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A Lifecycle Cost-based Design Optimization Model for Stormwater Management Systems

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This chapter presents a novel approach to optimizing the design of stormwater management systems based on lifecycle cost. A new mathematical model coupled with PCSWMM, and Genetic Algorithms are employed to search for a global optimal design solution for a new stormwater management system. The model also ensures that the global optimization meets a set of design constraints including design guidelines and objectives.

With the implementation and integration of graph theory and search algorithms in the advanced optimization model, this mathematical model can not only identify the best mix of pipe sizes for a given layout of pipes, but can also configure and size new stormwater management network components in a formal way rather than in an intuitive fashion. A deterministic method that can construct a multi-root shortest-path tree is developed for a network configuration. The method is based on a modified form of Dijkstra's algorithm. A layered assignment method is also developed for pipe sizing and pipe slope determination.

Lifecycle cost is used as the evaluation function for design optimization. An environmental cost, viz. flood damage lifecycle cost, is evaluated in the design optimization process as well. A detailed design configuration and a unit cost database are used instead of an empirical cost estimation function to conduct the cost estimation. The approach implemented in this study makes the cost consideration more comprehensive and the result more accurate than the traditional approach. The model thus improves the design quality significantly.

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3.1 Introduction

Design optimization is a process of searching for a feasible and economic solution that achieves multiple design objectives and at the same time satisfies all design and feasibility constraints. Urban stormwater networks are directly related to economic development, historical preservation, human health protection and environmental protection. For urban stormwater, the goal is to reduce urbanization impacts by meeting approximate pre-development conditions subject to budgetary constraints.

Cost analysis is a major issue in the design and decision-making process because achieving the lowest cost is always the ultimate goal for an optimal design solution. The monetary budget of the organization responsible for stormwater management is always a strict decision constraint, and limits the capital (construction), operating and maintenance expenses.

Stormwater management systems, like other infrastructure systems, are usually expensive and expected to continue to function for a number of decades. For example, the common serviceable expectation of a stormwater pipe system is 70 to 120 years. In Detroit, the 100 y old brick pipe system is still in service. By the future value factor of $(1+i)^n$, it can be easily understood that the proportion of the operation and maintenance (O&M) cost in the total cost of a project becomes more significant as the project moves forward. Furthermore, because of aging and deterioration problems, the performance of any infrastructure will gradually degrade and need more frequent inspections and renewals. This will also contribute to an increase of the O&M cost. Life cycle cost modeling can provide more accurate information on these problems for decision making in the early stage of an infrastructure project, help make appropriate investment decisions, and reduce costs in the long run.

Unfortunately, most research to date has focused on capital cost only. This was largely due to the lack of well-maintained data on the O&M cost thus making a life cycle cost study inadequate, with a high level of uncertainty. Additionally, many design optimization tools use empirical cost functions rather than conduct accurate cost estimation by using detailed design configurations.

This chapter presents a new holistic approach to optimizing the design of urban stormwater systems based on lifecycle cost. A mathematical model for searching a globally optimized stormwater sewer system and BMP configuration is developed. Genetic algorithms are implemented in the model for design optimization, and the model integrates with PCSWMM, which is used to examine the design performance.

This study can be divided into two major parts: (i) Design Optimization Model and (ii) Lifecycle Cost Analysis Model. The two models are conceptually independent of each other. However, because the design optimization model needs feedback from the lifecycle cost analysis model, data exchange between the two models is necessary. In real applications, the two parts are integrated using XML and XML style sheets.

3.2 3-D Optimization Design Model (3DOM)

Pipe systems with the functions of conveying flows and connecting facilities are major components of any urban water management system. Since pipes direct flow both horizontally and vertically, a stormwater management system is a three-dimensional network.

Three-dimensional network optimization problems have not been extensively studied. The additional dimension introduces complexity and creates many more difficulties. It requires the simultaneous selection of the least-cost solution for the system plan layout and vertical design, subject to hydraulic, hydrology, quality and construction constraints and to the restrictions of real applications (Diogo et al, 2000).

3.2.1 Three-Dimensional Design Optimization Problem

In stormwater management system design, the design objectives are to:

1. approximately meet pre-development conditions in terms of peak flow,
2. avoid surcharging under specific design storms, more specifically avoid the hydraulic grade line rising above basement floor level, underpass road elevations, etc., and
3. minimize life cycle cost.

The first objective can be achieved by the optimization of BMPs (e.g. storage facilities, infiltration facilities, permeable pavements etc.) and the second objective can be achieved by the optimization of the conveyance system. The third objective is conducted through the above two optimization processes.

In order to simplify the optimization problem, we transform the multi-objective optimization into a single-objective optimization problem by treating the first two objectives as two additional constraints. If the design solution does not satisfy the two objectives, it is an infeasible solution. The feasibility of all solutions must be ensured during the above optimization

processes. Therefore, the design constraints and objectives can be mathematically stated:

$$\text{Minimum LCC} = C_{\text{cap}} + \text{LCC}_{\text{O\&M}} + \text{LCC}_{\text{flood}} \quad (3.1)$$

$$C_{\text{cap}} = \sum_{i=1}^m uc_i^P(D_i) \cdot P_i(L_i, D_i, E_i) + \sum_{k=1}^n uc_k^N(A_K) \cdot L_k + \sum_{j=1}^k uc_j^B \cdot V_j(x_j, y_j) \quad (3.2)$$

$$\text{LLC}_{\text{O\&M}} = \sum_{n=1}^N C_{\text{O\&M}_n} \times (1 + \text{discountrate})^{-n} \quad (3.3)$$

$$\text{LLC}_{\text{flood}} = \sum_{n=1}^N C_{\text{flood}_n} \times (1 + \text{discountrate})^{-n} \quad (3.4)$$

Subject to

$$\begin{aligned} Q_j^{\text{post}} &\leq Q_j^{\text{pre}} & j = 1, 2, \dots, R \\ S_k &= 0, & \forall j \\ p_i &\in \{T\} & \forall i \\ p_j &\in \{T^?\} & \forall j \end{aligned}$$

where:

- LCC = lifecycle cost of the whole system
- C_{cap} = capital cost of the whole system
- $\text{LLC}_{\text{O\&M}}$ = lifecycle O&M cost of the system
- $\text{LLC}_{\text{flood}}$ = flood damage cost of the system
- $C_{\text{O\&M}_n}$ = O&M cost of the n th year during the service period (N years) of this system
- C_{flood_n} = flood damage cost of the n th year during the service period (N years) of this system
- P_i = construction quantity for pipe i , which is function of length, diameter and elevation of the crown invert
- L_i = length of pipe i
- D_i = diameter of pipe i
- E_i = crown elevation of pipe i (Note that the crown elevation instead of buried depth is used as decision variable since the ground elevation is given by GIS data)

- uc_i^P = unit cost of the pipe i , which is function of pipe diameter
 A_k = the size of manhole, which could be the diameter of the manhole
 L_i = the vertical length of manhole k
 uc_k^N = is the unit cost of the manhole k , which is function of manhole size
 V_j = the explanatory variable of the BMP i which can be used to define the size of the BMP. It can be volume of storage, length of swale, or surface area of sand filter.
 S_k = the surcharging occurred in node k .
 x_i, y_i = the two parameters which can be used to determine the size of BMP (i.e. the surface area and depth of a storage).
 Q_j^{post} = the peak flow rate at j th outlet in post-development condition
 Q_j^{pre} = the peak flow rate at j th outlet in pre-development condition
 R = the number of roots (outlets) where pre and post runoff condition must be met
 uc_j^B = the unit cost of the BMP j
 T and T' = the set of design constraints for pipe design and BMP design respectively
 p_i and p_j = the corresponding network parameters of design constraint for pipe i and BMP j respectively (i.e. the pipe diameter and slope, the width, depth and side slope of the storage etc).

In order to reduce the complexity of the model, the routing algorithms are operated in two-phases. First, a modified 2-D routing is performed that determines the topologies of the network system with modified minimum pipe length. This is followed by a detailed routing phase, where the final network system configuration, including the factors of pipe size, slope, roughness, pipe type etc., is determined in terms of layers, and track assignments. Thus the network design optimization model is decomposed into two sub-models: network layout optimization module (LOM) and network detailed design module (DDM).

Network Layout optimization module (LOM)

The network layout problem can be formally represented in graph theoretic notation as a weighted graph, with the components (e.g. manholes and BMPs) as nodes, and the conduits connecting them as edges. The weights of the edges represents the costs of the conduits, and the weights of the nodes represents the costs of nodes, which can be either the cost of the manhole or the cost of BMPs.

In graph theory, a typical problem input can be stated: there is graph

$$G = (V, E)$$

Where:

$$v_i \in V \text{ is a vertex in the vertex-set } V, \text{ and}$$

$$e_{ij} = (v_i, v_j) \in E \text{ is an edge-set } E.$$

Let c_{ij} be the weight or cost of an edge e_{ij} . The number of outlets in the network k is given.

The output consists of disjoint subsets V_1, V_2, \dots, V_k such that

$$\bigcup_{n=1}^k V_n = V, \text{ and } \forall e_{ij} \text{ subject to } [v_i] \neq [v_j],$$

$$C = \sum c_{ij} \text{ is minimized.}$$

$V_n = [v_i]$ represents the subset containing v_i , and C is the overall cost of the system.

Note that in the network design problem, we do not have any edge in the input graph, only vertex sets and outlets are given. Therefore the model must produce the edge, validate the edge for feasibility, and evaluate the cost of the edge.

The manhole spacing defines the edge. There is a maximum distance requirement between any two connected manholes. If the length of a pipe, which connects two manholes, exceeds the maximum value required by the design code, the solution is infeasible. One manhole can only connect with other manholes within the maximum distance. This constraint is the key to constructing a connected input graph.

In this study, we assume that the network can be treated as a tree-like graph. The problem in the LOM can therefore be termed a minimum spanning tree problem. But there is one slight difference between the network layout problem and the typical minimum spanning tree problem in graph theory. The latter only has one root in the tree structure, whereas a drainage system usually can have multiple roots.

Among many available algorithms for solving minimum spanning tree problems, Dijkstra's algorithm has been proven to be effective for searching least-cost spanning tree (Li et al., 1990; Minieka, 1978 cited by Li et al., 1990; Ahuja et al., 1993). Dijkstra's algorithm solves the problem of finding the shortest path from the root node S to all other nodes in a graph with non-negative edge lengths. Dijkstra's algorithm can be explained as follows:

1. For a set composed of K nodes, randomly select one. Place it in the root node subset S (i.e. size is 1). The remaining nodes are stored in subset \bar{S} (i.e. size is $K-1$);
2. For each node in subset \bar{S} , select the node with the least distance to the nodes in subset S . Place the selected node into the subset S and eliminate the selected node from subset \bar{S} .
3. Repeat 2 until all nodes have been placed into the subset S .

Implementing Dijkstra's algorithm requires that the cost between each two nodes be given. Since sewer systems preferably flow by gravity, negative slopes certainly increase the excavation cost, so that we can use a modified length to represent the cost between any two nodes (or manholes). The modified length is the physical distance between two particular nodes plus the elevation difference between them. This algorithm starts by forming a minimum spanning tree from the root-set. Because it is a deterministic algorithm in nature, we certainly can get the least-cost tree once the cost between each two nodes is given.

Vertical configuration problem

In network (vertical) configuration design, we have to consider the hydraulic and construction constraints and the restrictions of real applications. The set of design constraints considered in this model is as follows:

- a. minimum pipe slope, which is a function of pipe size,
- b. maximum construction slope,
- c. minimum pipe cover,
- d. maximum pipe cover,
- e. hydraulic continuity through manholes (downstream pipe crown elevations equal to or lower than those of the upstream pipes),
- f. downstream section progression (pipe diameters do not decrease in a downstream sense), and
- g. commercially available pipe type and pipe size.

In order to maintain the diversity of design alternatives, the size and slope of all conduits are set randomly while subject to the design constraints above. A layered assignment method is developed for this purpose.

Layer assignment method:

Each node is assigned an integer value, which defines the distance from the particular node to its root. The roots have a layer number of 0 and the farthest nodes have the largest layer number. Because a sewer system is a directed network, each edge in the network has its direction toward the roots. Therefore, once the network connectivity is given, the upstream node and downstream node of each edge are known as well. This observation helps us form an algorithm to determine the layer number for each node, called the layering rule. The common layering rule is that the layer number of each upstream node is the number of its downstream node +1. For example, the layer number of the root is 0 and first upstream node of a root is 1. If a node does not have any upstream node, we term it a leaf node. In the layered assignment method, we reverse the common layering rule. Each leaf node is assigned number 0 and each root node has the largest layer number in its path. Pipe sizing and pipe slope determination start from leaf nodes and are conducted layer by layer until the root is reached.

Optimization Algorithm

The pipe sizing and pipe slope determination optimization problem is an *NP-hard* problem (nondeterministic polynomial time complete problem) due to the large number of system components as well as the number of available pipe sizes and types. For example, if a network contains 30 pipes with a set of 14 discrete pipe diameters and there are 3 BMPs options, then the available design combinations will be $3 \times 2 \times 1 \times 14^{30} = 1.452085942E35$. Therefore, it is crucial to select suitable algorithms for identifying the best solution in such a huge search space.

We chose genetic algorithms (GA) to perform design optimization in this model. Inspired by Charles Darwin's theory of evolution, the genetic algorithms mimic the natural selection process to solve the optimization problem. They are typical heuristic methods for problem solving. Complex combinatorial and organizational problems can be solved with many variants, by employing the analogy with nature's evolution. In every generation, a new set of artificial creatures (strings) is created using bits and pieces of the fittest of the old; an occasional new part is tried for good measure. While randomized, genetic algorithms are no simple random walk. They efficiently

exploit historical information to speculate on new search points with expected improved performance (Goldberg, 1989).

The general genetic algorithm procedures are:

unrated population → *fitness function* → *rated population* →
selection function → *population of parents* → *reproduction*
function → *population of parent copies* → *mutation operations* →
unrated population.

As such, the optimization is then become an iterative and routine job. There are a few rules to set up an encoding schema for a tree-like problem - the schema should be:

1. capable of representing all possible trees and only trees, to the extent that no-trees must not be represented,
2. unbiased in the sense that all trees are equally represented, and
3. able to go back and forth easily between the encoded representation of the tree and the tree's representation in a more conventional form suitable for evaluating the fitness function and constraints.

One of the classical theorems in graphical enumeration is Cayley's theorem that there are k^{k-2} distinct labeled trees on a complete graph with k nodes (Balakrishnan, 1997). Prüfer provided a constructive proof of Cayley's theorem by establishing a one-to-one correspondence between such trees and the set of all strings of $k-2$ digits (Batko, 1999). This means that we can only use $(k-2)$ digit permutation to uniquely represent a tree where each digit is an integer between 1 and k inclusive. This permutation is usually known as the Prüfer number.

Figure 3.2 shows a network schematic with 16 nodes. Table 3.1 provides the representation of the network in Prüfer number. The first line illustrates the position of each node in the network. The root nodes don't appear in this line. The second line is the real Prüfer number. It describes the corresponding downstream node of each node in the first line.

In this model, we use the modified Prüfer number to represent the network Connectivity. Table 3.2 shows the representation of the network as a modified Prüfer number. All nodes including roots are presented in Table 3.2. The root nodes, however, have been assigned a special number -1 , so that the computer program can recognize it as a root node.

In order to find the best layout, this research has been done in two phases. The first phase is using GA only without Dijkstra's Algorithm implementation. The second phase implements the modified Dijkstra's

Algorithm with GA. In the first phase, the best layout of a simple network was reached after 40 generation (with 20 chromosomes of each generation) as shown in Figure 3.2. This layout thereafter obtained by modified Dijkstra's Algorithm, and further to prove it to be the best layout of the studied network. The Modified Prüfer Number which is used to represent the best layout or the best network connectivity is then written to a text file as shown in Figure 3.3.

After the network connectivity is established, it can be extended to construct the chromosome by inserting the essential parameters we set up in detailed design model. Then the chromosome is the representation of the network-detailed-design.

The GA encoding for the problem is straightforward. A simple string representation is typically used in which each gene represents the logic value to be applied to a particular input of the network (in this case the stormwater management system) at a specific time. Standard crossover and mutation operators can therefore be used.

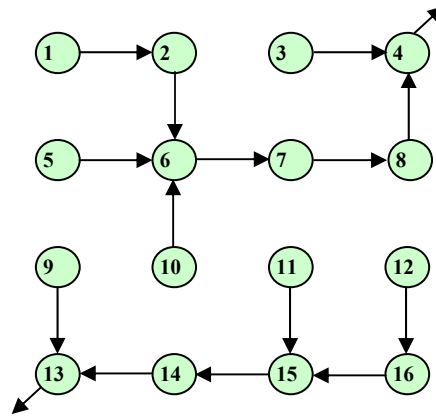


Figure 3.1 Network Schematic.

Table 3.1 Prüfer Number representation.

1	2	3	5	6	7	8	9	10	11	12	14	15	16
2	6	4	6	7	8	4	13	6	15	16	13	14	15

Table 3.2 Modified Prüfer Number representation.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
2	6	4	-1	6	7	8	4	13	6	15	16	-1	13	14	15

3.3 Lifecycle Cost Analysis Model

Lifecycle Cost (LCC) modeling is an economic method to determine the total cost of a stormwater management system over its economic life or full life cycle. In general terms, LCC includes the initial cost, maintenance cost, operating costs, replacement or repair cost, disposal cost, and other costs such as taxes, depreciation, and additional management costs. In other words, LLC modeling combines the estimated capital, maintenance, operating and replacement costs over the entire lifecycle of an infrastructure facility into a single value, which takes into account all expenditures occurring at different stages in the lifecycle of the infrastructure.

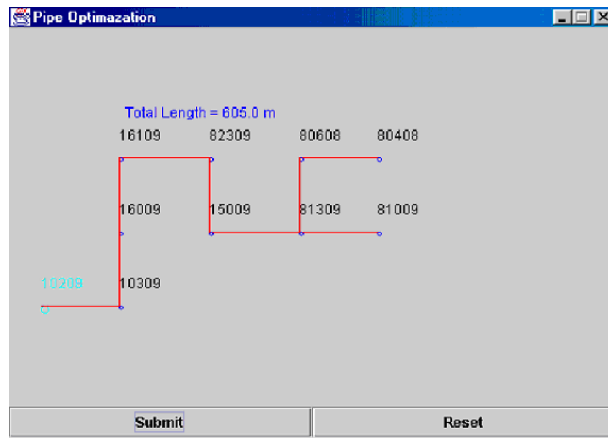


Figure 3.2 The best layout of a network

Index	Upstream Nodes	Downstream Nodes	TreeIndex
0	16100	16000	1
1	16000	10300	3
2	15000	82300	5
3	10300	10200	4
4	10200	outfall	-1
5	82300	16100	0
6	81300	15000	2
7	81000	81300	6
8	80600	81300	6
9	80400	80600	8

STOP

Figure 3.3 Tree representation file.

In this study, the LCC Model is subdivided into two sub-models: Capital Cost Model and O&M Cost Model.

3.3.1 Capital Cost Sub Model

To perform the capital cost calculation, we must have the construction quantity data and unit cost data. The capital cost calculation is conducted in two phases: construction quantity calculation first and then applying the unit cost to the capital cost calculation. Unit cost data can be obtained from some typical commercial cost databases (e.g. RS Means unit cost database), or non-commercial cost database or the users own cost database. In this study, unit cost data are mainly obtained from the RS Means database.

A database connection sub-module is developed for this purpose, and Figure 3.4 shows the unit cost data retrieved from RSMeans database using the database connection sub-module. The network detailed configuration data can be obtained from the network vertical design and the construction quantity calculation is then performed.

In the construction phase, the stormwater sewer system project can be broken down into unit processes: pipe trench excavation, pipe installation, backfill and compaction, manhole installation. The quantities of pipe trench excavation, backfill and compaction, pipe installation are related to each other.

The cross-sectional shape of the trench is dependent upon several factors (American Iron and Steel Institute, 1980):

1. the design depth below surface (pipe crown elevation),
2. the shape of the conduit structure,

3. the type of soil encountered,
4. foundation material present in the bottom of the trench, and
5. procedures used in placement of backfill around the conduit structure.

The width of the trench box bottom is determined by the outside pipe diameter as illustrated in Table 3.3. And Table 3.4 illustrates the relationship between soil type and trench side slope ratio.

As long as the soil type and pipe size and pipe crown are known, the trench cross-section shape can be determined. Applying the pipe length with the trench cross-section area, the trench quantity can be obtained. The backfill and compaction quantity equals to the trench quantity minus the product of pipe length and pipe outside diameter. Once the construction quantities are known, the unit cost can be assigned to each unit process and facility component (i.e. conduit, manhole, BMPs). The summation of the products of the quantities multiplied by the corresponding unit costs is the bare capital cost.

The screenshot shows a 'Database Browser' window with the following details:

- Database URL: jdbc:mysql://localhost/rsmeans
- User ID: root
- SQL Command: select * from seq;

lineNumber	Description	Crew	Cre...	D...	ManHours
023154000...	EXCVTNG BULK, BKHO, HYD, CRWLMNT, 1C...	B12A	1.00	6...	0.027
023154000...	EXCVTNG BULK, BKHO, HYD, CRWLMNT, 1.5...	B12B	1.00	8...	0.020
023154000...	EXCVTNG BULK, BKHO, HYD, CRWLMNT, 2C...	B12C	1.00	1...	0.015
023154000...	EXCVTNG BULK, BKHO, HYD, CRWLMNT, 3.5...	B12D	1.00	1...	0.010
023154400...	EXCAVATING HAND PITS, 6' DEEP, SANDY SOIL	CLAB	1.00	8...	1.000
023154400...	EXCAVATING, STRUCTURAL, HAND, PITS TO ...	CLAB	1.00	4...	2.000
023155050...	FILL, SPREAD DUMPED MTL BY DOZER, NO ...	B10B	1.00	1...	0.012
023155050...	FILL, SPREAD DUMPED MTL BY HAND, NO C...	CLAB	1.00	1...	0.667
023155050...	FILL 4" GRVL UNDER FL SLABS, COMPACTD	B37	1.00	1...	0.005
023155050...	GRAVEL UNDER FLOOR SLAB, 6" DEEP, COM...	B37	1.00	8...	0.006
023159000...	EXCAV TRENCH, COMMON EARTH, 1'-4' DEE...	B11C	1.00	1...	0.107
023159000...	EXCAV TRENCH, COMMON EARTH, 1'-4' DEE...	B11M	1.00	2...	0.080
023159000...	EXCAV TRENCH, COMMON EARTH, 4'-6' DEE...	B11M	1.00	2...	0.080
023159000...	EXCAV TRENCH, COMMON EARTH, 4'-6' DEE...	B12J	1.00	2...	0.080
023159400...	EXCAV UTIL TRNCH COMMON EARTH, CHAIN...	B53	1.00	8...	0.010
023159400...	EXCAV UTIL TRNCH COMMON EARTH, CHAIN...	B53	1.00	7...	0.011
023159400...	EXCAV UTIL TRNCH COMMON EARTH, CHAIN...	B53	1.00	7...	0.011
023159400...	EXCAV UTIL TRNCH COMMON EARTH, CHAIN...	B53	1.00	6...	0.012
023202000...	HAUL EARTH 6CY DUMP TRUCK 1 MILE ROU...	B34A	1.00	2...	0.033
023202000...	HAUL EARTH 6CY DUMP TRUCK 4 MILE ROU...	B34A	1.00	8...	0.094
023202000...	HAUL EARTH 12CY DUMP TRUCK 4MILE RO...	B34B	1.00	1...	0.053
023202001...	GRADING DUMPED EARTH AT EMBANKMENT...	B10B	1.00	1...	0.012
025209000...	WELL, DOMESTIC, DRILLED & CASED, 4 TO 6"	B23	1.00	1...	0.250

Figure 3.4 RSMeans database.

Table 3.3 Trench bottom widths for various diameters of buried pipe.
(Source: Goldman et.al, Means Estimating Handbook, 1990).

Outside Diameter in Inches	Trench Bottom Width Feet
24	4.1
30	4.9
36	5.6
42	6.3
48	7.0
60	8.5
72	10.0
84	11.4

There are other important costs occurring before the system starts operation. These costs include the design and consultancy cost, constructor overhead, taxes, and other costs that can be treated as contingency costs. Because the RS Means unit cost already includes constructor overhead, we only consider the design consultancy cost, contingency cost and tax in this study. Design consultancy and contingency cost are assigned 15% of the bare cost, while tax is considered to be 7% of the bare cost, applicable in Ontario, Canada. In the design model, the rate of design consultancy and contingency and the rate of tax are input variables.

Table 3.4 Soil type and side slope ratio (source:aisi, 1980).

Material Description	Angle of Repose	Slope (Horiz to Vert)
Rock and Cemented Sand	90°	Vertical
Compacted Angular Gravels	63°	½:1
Compacted Angular Sands	34°	1½:1
Weathered Loose Sands	27°	2:1

3.3.2 O&M Cost Sub Model

All O&M costs can be broken down into four categories: inspection cost, operational cost, repair cost, and others. Typically, the inspection and operational costs occur every year, but unevenly through the lifecycle of a system. Because of aging and deterioration, more frequent inspections and renewals are required as time passes. The problem not only results in inspection and operational costs growing with increase in the service year, but also results in some repair and replacement costs or other unpredictable costs, termed “other costs”. In the first few years, say 10 or 15 years, the system usually functions well and does not require repair. However, after the first stage, repair cost will occur routinely.

Table 3.5 shows an example of O&M cost for a system which is of 75-y service period. It represents one hypothetical scenario. In this example, the inspection cost is a yearly cost ranging from 20000 to 40000. Repair practices only occur after the system has been in service over 10 years, and occur once in 5 years. The discount rate for O&M cost is 0.05.

The O&M cost is usually taken to be a proportion of capital cost in project preliminary and feasibility study phases. This study provides two approaches for the user to construct their own O&M cost model. Each cost in each category (i.e. inspection cost, operational cost) for each year can be either a certain value or a proportion of a base cost. In the above example, the inspection cost is given as a certain value and the repair cost is given as a percentage of capital cost. Normally, the base cost is capital cost.

3.3.3 Flood Damage Cost

Rapid urbanization results in more frequent flooding and much more severe flooding damages. These impacts can be considered to be environmental costs. The major purpose of an urban stormwater management system is to reduce flood damages and eventually, minimize the environmental impact resulted from urbanization. The methodology to conduct flood damage cost assessment is:

1. Simulate the N -year rainfall event, and obtain the surcharging data at each manhole. The N value depends on municipal design code. If the design code requires the stormwater management system to control the 5-y storm to pre-development levels, $N = 5$.
2. If the maximum surcharging elevation is beyond the elevation of the basement, the difference between the maximum surcharging

elevation and the basement elevation is the depth of flood surrounding the house. The flood cost calculation then applies to this house.

Table 3.5 Example XML file of O&m cost parameters.

```

<?xml version="1.0" encoding="UTF-8"?>
<OMCostParameter>
<Category>
<Inspection Interval="1" From="1" To="10" Type="Cost Value"><![CDATA[20000]]>
</Inspection>
<Inspection Interval="1" From="11" To="30" Type="Cost Value"><![CDATA[30000]]>
</Inspection>
<Inspection Interval="1" From="31" To="75" Type="Cost Value"><![CDATA[40000]]>
</Inspection>
<Repair Interval="5" From="11" To="30" Type="Percentage"><![CDATA[0.010]]></Repair>
<Repair Interval="5" From="31" To="55" Type="Percentage"><![CDATA[0.05]]></Repair>
<Repair Interval="5" From="56" To="75" Type="Percentage"><![CDATA[0.1]]></Repair>
<Operating Interval="1" From="1" To="75" Type="Cost Value"><![CDATA[0.0]]></Operating>
<Others Interval="1" From="1" To="75" Type="Cost Value"><![CDATA[0.0]]></Others>
</Category>
<Interest Type="Year"><![CDATA[0.05]]></Interest>
<LifeCycle Unit="Year"><![CDATA[75]]></LifeCycle>
</OMCostParameter>

```

3. Obtain the total flood cost by summing the flood cost of each house.
4. The probability of an N -year rainfall event occurring in each year is $1/N$. Apply $1/N$ to the total flood cost to estimate the annual flood cost.
5. Use one feasible network configuration solution to conduct the flood damage analysis on the N -year storm event. Apply the probability of the N -year event to obtain N -year event flood annual cost (NFC).
6. Use a feasible network configuration solution to conduct flood damage analysis on 2-y, 5-y, 10-y, 25-y, 50-y, 100-y, 500-y rainfall event and regional storm including N -year storm event. Apply probability of each storm event and summarize all the above to obtain the total annual flood damage cost (TFC).
7. The flood damage cost factor is assigned the value of TFC/NFC .
8. Assume the lifecycle of the whole system is M years. Adjust the annual N -year flood damage cost by the flood damage cost factor to obtain the annual flood cost. Apply annual flood cost to M years and obtain the lifecycle flood cost in present value.

3.4 Conclusion

A GA-based design optimization model is employed to determine efficient stormwater management system configurations by finding an optimal design solution which satisfies both the design guidelines and design objectives. Lifecycle cost is used instead of capital cost as the evaluation function or objective function for design optimization. Flood damage lifecycle cost is also taken into consideration in the design optimization process. Detailed design configuration and a unit cost database are used to conduct the cost estimation, whereas the traditional approach in literature is to use empirical cost function to perform cost estimation. The approach implemented in this study is much more accurate than the traditional approach. This design model significantly thus improves the design quality.

References

- Ahuja, Ravindra K., Magnanti, Thomas L., Orlin, James B. (1993), "Network Flows Theory, Algorithms, and Applications", Englewood Cliffs, New Jersey: Prentice Hall, Inc., ISBN: 013617549, p109
- American Iron and Steel Institute (AISI), (1980). "Modern Sewer Design" (Canada Edition), Cambridge, Ontario: Corrugated Steel Pipe Institute.
- Arnell, N. W. (1989). "Expected annual damages and uncertainties in flood frequency estimation.", *Journal of Water Resources Planning and Management*, 115(1), 94-107.
- Balakrishnan, V. K.; (1997). "Schaum's Outline of Theory and Problems of Graph Theory", Publisher: Mcgraw-Hill, ISBN:0070054894
- Batko, Alex; (1999). "Project 16, Free Trees, Enumeration and Representation of", *Data Structure and Algorithms*, http://www.cs.mcgill.ca/~abatko/computers/free_trees/project/,
- Chao-Hsien Yeh and John W.Labadie (1997); "Multiobjective watershed-level planning of storm water detention systems", *J. Water Resour. Plan. Manage.*, 123(6), 336-343.
- Clark, Rober M. ; Sivaganesan, Selvakumar, Mano; Ari; and Virendra Sethi (2002). "Cost Models for Water Supply Distribution Systems", *J. Water Resour. Plan. Manage.*, 128(5), 312-321
- Coley, D. A. (1999). "An introduction to genetic algorithms for scientists and engineers", World Scientific, River Edge, N.J.
- Diogo, A. Freire (Univ of Coimbra); Walters, Godfrey A.; de Sousa, E. Ribeiro; Graveto, Victor M(2000); "Three-dimensional optimization of urban drainage systems"; *Computer-Aided Civil and Infrastructure Engineering*, v 15, n 6, Nov, 2000, p 409-426
- Dragan A. Savic and Godfrey A. Walters (1997); "Genetic Algorithms for Least-Cost Design of Water Distribution Networks"; *Journal of Water Resources Planning and Management*, 123(2), 67-77.

- Froise, S. & Burges, S. J., (1978) Least-cost design of urban-drainage networks, *Journal of Water Resources Planning and Management*, ASCE, 104(1), 75-92
- Hilton, A. B. Chan and Culver, T. B. (2000). "Constraint handling for genetic algorithms in optimal remediation design", *J. Water Resour. Plan. Manage.*, 126(3), 128–137.
- Goldberg, D. E. (1989) *Genetic algorithms in search, optimization, and machine learning*, Addison-Wesley, Reading, Mass., ISBN: 0201157675
- Goldman, Jeffrey M. (Editor); Mahoney, William D.; R S Means Company;(1990). *Means Estimating Handbook*, Publisher: Robert s Means Co; ISBN: 0876291779
- Laura J. Harrell, S. Ranji Ranjithan; "Detention Pond Design and Land Use Planning for Watershed Management", *Journal of Water Resources Planning and Management*, 2003, March/April, 98-106
- Li, G. & Matthew, R. G. S., (1990); "New approach for optimization of urban drainage system", *Journal of the Environmental Engineering Division*, ASCE, 116(5) (1990), 927-44
- Minieka, E. (1978). "Optimization algorithms for network and graphs", Dekker, Marcel, Inc., New York, N. Y.
- Sample, David. J.; Heaney, James P.; Wright, Leonard T. ; Fan, Chi-Yuan; Lai, Fu-Hsiung ; and Field, Richard ; (2003). "Costs of Best Management Practices and Associated Land for Urban Stormwater Control", *Journal of Water Resources Planning and Management*, Vol. 129, No. 1, pp 59-68
- Savic, Dragan A. and Walters, Godfrey A. (1997). "Genetic Algorithms for Least Cost Design of Water Distribution Networks", *J. Water Resour. Plan. Manage.* 123(2), 67-77.