The Economics of Stormwater BMPs in Tehran, Iran

Sakineh Tavakoli[1] , Masoud Tajrishy[2]

[1] Sharif University of Technology, Tehran, Iran, sakineh.tavakoli@gmail.com
[2] Sharif University of Technology, Tehran, Iran, tajrishy@sharif.edu

ABSTRACT

Stormwater runoff has a lot of negative quantitative and qualitative effects on the surrounding environment. Best Management Practices (BMPs) are innovative technologies that can control these effects within natural and economic limitations.

Three types of BMPs are discussed in this study; swale, bioretention systems and pond. They have different installation costs and pollutant removal efficiency. The main objective of this paper is to find out the minimum cost combinations of these three BMPs, to reduce the concentration of total suspended solids, total phosphorous and total nitrogen in order to achieve water quality standards for urban streams.

Two models are used for this purpose: watershed and economic Models. Watershed model (MUSIC) provides stormwater and pollutant simulations and calculates BMP's pollutant removal rates. The outputs of watershed model serve as inputs to economic model (GAMS) which provides minimum cost optimization procedure. Another input for economic model is BMP's life cycle cost. Structural stormwater BMPs demand initial capital investments for design and construction and annual operating and maintenance costs.

Results show that swales are the least expensive BMPs to construct and maintain. These results can be used for decision making and help to find a balance between environmental protection and urban development.

KEYWORDS

BMP, GAMS, life cycle costs, MUSIC, Stormwater runoff, Tehran

1 INTRODUCTION

Urban development by increasing the construction of buildings and pavements increases imperviousness and leads to enhance flow velocities and stormwater runoff volume. This can cause flooding and increase loading on receiving waters. The most negative effect of urbanization is water quality degradation.

The original purpose of storm water management was to control stomwater quantity to prevent flooding. But by increasing the awareness about the effect of water quality problems on receiving waters, water quality control became a part of management plans. Nutrients such as nitrogen and phosphorus and suspended solids are of primary concern.

Pollution due to stormwater runoff can be recognized as non-point source pollution. Management of non-point source pollution of stormwater runoff is a complex decision making problem for planners and municipalities. Because of high uncertainties in water and hydrology, nature and lack of sufficient knowledge, selection of proper management is complicated. Non point source pollution can be controlled by various Best Management Practices (BMPs). By increasing the worldwide use of these practices, calculating their removal efficiency becomes more important.

Some management approaches use optimization procedure to design and implement management practices. Chen (2006) uses linear programming as the optimization procedure to find the most cost effective combination of four BMPs: Pond, Wetland, Infiltration and Filtering systems.

There is a need for evaluating best management practices costs. Current knowledge about their cost effectiveness is little. Weiss et al (2007) collected construction and annual operation and maintenance cost data for dry extended detention basins, wet basins, sand filters, constructed wetlands, bioretention filters and infiltration trenches.

In this work three BMPs are discussed: swales, bioretention Systems and ponds. The purpose is to find the minimum cost combination of these practices to reduce total phosphorus, total nitrogen and total suspended solids to achieve water quality standards in Maqsudbeig watershed in north of Tehran.

Two models are used for this purpose. Watershed model (MUSIC) is used for calculating pollutant removal rates of stormwater BMPs and these outputs along with some others such as BMPs costs and area requirements serve as inputs for economic model. GAMS is used as an optimization model to solve Linear Programming that is developed for the purpose.

2 METHODOLOGY

Each BMP has special removal efficiency, cost and physical requirements such as slope, soil characteristics, minimum installation area, groundwater depth and etc. So, it is first necessary to define which BMPs can be implemented in the study area. Next removal efficiencies of these BMPs can be determined by watershed model. Then the optimization procedure will find the best possible solution of the problem.

2.1 Best Management Practices

2.1.1 swale

Vegetated swales are open channel systems that utilize vegetation to capture and treat stormwater runoff. Swales should have limited longitudinal slopes and low velocities for better performance. The channel cross section is typically trapezoidal (City of Clarksville Street Department, 2004). In this paper two typical sizes for swale are considered: One with 3m top width, 0.5m bottom width and 100 m length and the other with 1.5m top width, 0.2m bottom width and 100m length.

2.1.2 Bioretention system

Bioretention areas are shallow detention areas that capture stormwater runoff and store it temporarily. They consist of a sand bed, mulch layer, ponding area, planting soil and vegetation and can provide stomwater runoff treatment. Bioretention systems promote filtration of stormwater through the filter medium (City of Clarksville Street Department, 2004). Bioretention system with length of 10m and width of 5m is the typical size which is considered here.

2.1.3 Pond

Stormwater Ponds have a permanent pool that store stormwater temporarily and treat it. Physical settling and biological uptake by plants are two main mechanisms for stormwater treatment (City of Clarksville Street Department, 2004). Pond with 15m length and 4m width is the typical size which is considered in this study.

Each BMP has different design requirements and in each subcatchment there is limited space for installing stormwater BMPs; based on these two factors four typical sizes have been chosen in this study as considered above.

2.2 Study area

The methodology is applied on Maqsudbeig watershed in Elahiyeh the north of Tehran, Iran. Tehran, the capital of Iran, has a total population of 8 million people spread over an area of 868 square kilometers. Tehran has a semi-arid climate and average annual precipitation of 250 mm. Figure 1 shows the study area. Maqsudbeig stream located in this watershed, collects surface runoff and also has aesthetic objectives. The river meanders over approximately 3.3 kilometers. There is no point source pollution in this part of the river and non-point source pollution resulting from stormwater runoff is the main source of pollution.

Figure 1. Study area

Some measurements on water quality parameters have been done on the river. Mean pollutant concentrations measured are 946 mg/L for Total Suspended Solids (TSS), 8.35 mg/L for Total Phosphorus (TP) and 3.94 mg/L for Total Nitrogen (TN) (Kazemi, 2011).

2.3 Economic model

Urban activities have different negative impacts on the surrounding environment. How to reduce these impacts best has a specific importance for planners and governments. The economic model employs the cost effectiveness methods to select the minimum cost strategies while keeping environmental standards.

Two main issues that should be considered in the economic model are costs of stormwater BMPs and their associated pollutant removal efficiencies. These are two groups of inputs for economic model. The structure of economic model is illustrated below.

2.3.1 Model objectives

The objective is to find out the minimum cost combination of BMPs. The total cost is a function of number of BMPs and their corresponding cost. The objective can be expressed with equation (1):

$$TotalCost = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{p} C_{ijk} X_{ijk} \qquad (1)$$

Where:

C_{ijk}: Total cost of k number combination of BMP i installed in subcatchment j;

X_{ijk}: The number of k number combination of BMP i installed in subcatchment j, a binary variable;

i: type of BMPs;

j: indication of subcatchment;

k: number of BMPs combination (contribute to form X_{ijk}).

2.3.2 Model constraints

- pollutant removal efficiencies

Each BMP has different removal efficiency. Removal efficiency for all BMPs is calculated with watershed model that will be illustrated later. The optimum combination of BMPs must satisfy water quality standard as equations (2) to (4):

$$I_{TP}(\prod_{i=1}^{m}\prod_{j=1}^{n}\prod_{k=1}^{p}\left(1-a_{ik}\right)^{X_{ijk}} \le I_{s,TP} \qquad (2)$$

$$I_{TN}(\prod_{i=1}^{m}\prod_{j=1}^{n}\prod_{k=1}^{p}\left(1-b_{ik}\right)^{X_{ijk}} \le I_{s,TN} \qquad (3)$$

$$I_{TSS}(\prod_{i=1}^{m}\prod_{j=1}^{n}\prod_{k=1}^{p}\left(1-d_{ik}\right)^{X_{ijk}} \le I_{s,TSS} \qquad (4)$$

Where:

I_{TP}: initial concentration of total phosphorus, before implementation of stormwater BMPs;

I_{TN}: initial concentration of total nitrogen, before implementation of stormwater BMPs;

I_{TSS}: initial concentration of total suspended solids, before implementation of stormwater BMPs;

$I_{S,TP}$: standard concentration of total phosphorus that is expected to achieve after stormwater BMPs implementation;

$I_{S,TN}$: standard concentration of total nitrogen that is expected to achieve after stormwater BMPs implementation;

$I_{S,TSS}$: standard concentration of total suspended solids that is expected to achieve after stormwater BMPs implementation;

a_{ik}: total phosphorus removal rate of k number combination of ith BMP (%);

b_{ik}: total nitrogen removal rate of k number combination of ith BMP (%);

d_{ik}: total suspended solids removal rate of k number combination of ith BMP(%);

- The installation area for a BMP

Each BMP has a specified area requirement to install. On the other hand, the total area available for installing a special kind of BMP in a subcatchment is estimated. The area needed for installing a BMP should not exceed the available area. Equation (5) shows this constraint.

$$\sum_{k=1}^{p} X_{ijk} S_{ik} \le A_{ij} \qquad \forall_{i,j} \tag{5}$$

where:

S_{ik}: area of k numbers of BMP i;

A_{ij}: area available for BMP i in subcatchment j.

- Water quality standard constraint

Water quality standards are the base of quality-based programs for pollution control. According to water body usage, standards set criteria to protect it from polluting. Pollutant concentration criteria that were used in economic model are 35 mg/L for TSS, 0.1 mg/L for TP and 1.5 mg/L for TN (Leib and Browne, 2002).

2.4 Cost estimation

Costs of stormwater BMPs are developed based on literature and cost estimating tools. Here, total cost is the sum of capital cost and annual operation and maintenance cost over a 20 year life cycle period.

2.4.1 Total Capital Cost

Total capital cost consists primarily of land cost and construction cost. One of the capital costs component is land cost that depends on site specific characterization and surrounding land use. Land costs significantly vary from site to site. Therefore, land cost is not considered in life cycle cost in this paper.

2.4.2 Design, permitting and contingencies costs

Design, permitting and contingencies costs include costs for design and planning, site investigation and unexpected costs that might occur during construction of a stormwater control practice. These costs usually are considered as a percentage of total construction cost. In Iran, design cost is calculated for a unit surface area as well as construction cost. Furthermore, cost of permitting is not included in the life cycle cost of a practice. In this paper, design cost is included in initial construction cost and contingencies costs are expressed as 5% of total construction cost. (Narayanan and pitt, 2005 ; Shoemaker et al, 2009).

2.4.3 Operation and Maintenance costs

Operation and maintenance costs (O&M) are post construction activities and ensure the proper performance of a constructed BMP and prevent problems such as odour, turbidity, trash and sediments. Operation and maintenance cost is expressed as a fraction of construction costs. Based on EPA report on O & M costs, it is assumed 6% of construction cost for swales and bioretention systems and 4.5% for wet ponds (Sample et al, 2003).

2.4.4 Total Present Costs

The total present cost is the sum of present construction, design and contingencies costs and the equivalent present cost of annual operation and maintenance costs. For converting annual O&M costs to a present cost, it is needed to calculate interest and inflation rate based on historical data. Then the present worth can be calculated by equation (6) and (7):

$$P = A * E \tag{6}$$

$$E = \left[\frac{\left(\frac{1+r}{1+i} \right)^{n}}{r-i} \right] \tag{7}$$

where P: present worth of annual O&M costs; A: annual O&M costs; r: inflation rate(20%); i: interest rate(12%) and n: number of years (i.e. 20 year life period of BMPs).
Total Present Cost for BMPs is shown in Table 1.

Table 1. Total present costs of BMPs

BMP	Design and construction costs (million Rial[*])	Annual O & M costs (Million Rial)	Longevity (year)	Total Present Cost (Million Rial)
3m width swale	46.1	2.4	20	134.5
1.5m width swale	19.1	1	20	54.9
Bioretention Systems	36	2	20	110.8
Wet Pond	29.2	1.2	20	74.2

[*] Iranian Rials (IRR), 1 USD= 13000 Rial

2.5 Watershed model

MUSIC (Model for Urban Stormwater Improvement Conceptualization) was used to assess the BMPs pollutant removal efficiencies. MUSIC serves as a decision support system to help watershed managers to predict stormwater treatment measures effects on receiving waters (CRCC, 2005).

In this work watershed model was made based on 3 years precipitation-evapotranspiration data during 2004-2006. Pollutant removal efficiencies of Stormwater BMPs are calculated based on input and output pollutant concentrations to a BMP (or a group of BMPs) and serves as inputs to economic model. Most studies use literature to find out various BMPs' efficiencies in reducing different pollutants. But usually a wide range of efficiencies are attributed to a special BMP and it is hard to select an exact value. So, simulation with site specific conditions was chosen in this study. To find more accurate results, each type of BMPs were simulated for combination of one, two and more. The reason is that removal rate for combination of two typical swales is not twice the one swale and we considered the point with notation “k” in the economic model. Simulation was done until maximum 16 combinations for each type of BMP, because results show that combination of 16 BMPs can reduce approximately 100% of the pollutant. Table 2 shows removal rates of TSS for different combination of BMPs. Removal rates of TP and TN are calculated similarly.

Table 2. TSS removal rates for different BMPs

Combination	BMP			
	3 m width swale	1.5 m width swale	Bioretention Systems	Wet Pond
1	42%	28%	24%	7%
2	55%	34%	29%	12%
3	62%	35%	33%	12%
4	71%	38%	38%	16%
5	81%	42%	44%	17%
6	85%	42%	51%	27%
7	86%	45%	53%	29%
8	86%	47%	55%	30%
9	90%	51%	59%	32%
10	90%	51%	65%	32%
11	92%	57%	67%	41%
12	93%	64%	70%	48%
13	95%	77%	79%	67%
14	100%	100%	91%	83%
15	100%	100%	99%	100%
16	100%	100%	100%	100%

3 RESULTS

After collecting all data that are needed for economic model, the optimization procedure is conducted. GAMS is used to solve the Integer Linear Programming model developed in this study. Results show that, ignoring land cost, Swales are the least cost BMPs to construct and maintain in our study area. As Table 3 shows, 300 m^2 of 3 m width swale and 1350 m^2 of 1.5 m width swale which cost 628.6 million Rials can achieve water quality standards.

Table 3. Final results of economic model

BMP	k	Number	Area (m^2)	Removal Rate (%)			Cost (Million Rial)
				TSS	TP	TN	
3 m width swale	1	1	300	42	54	32	134.5
1.5 m width swale	1	7	1050	28	48	30	494.1
	2	1	300	34	54	36	
Bioretention Systems	-	0	0	0	0	0	0
Wet Pond	-	0	0	0	0	0	0
Total	-	9	1650	-	-	-	628.6

This study is an optimization problem and has only one optimum solution, but for better understanding the results, several random combinations are defined and shown in table 4. For each combination removal rates of TSS, TP and TN are calculated. Some combinations don't meet the standards for these pollutants. For those combinations which meet standards, total cost is calculated and is compared to optimum solution in figure 2.

Table4. Definition for random combinations and their ability for meeting standards

Combination	Definition	Does the combination meet standards?
a	300m^2 of 3m width swale+150m^2 of 1.5m width swale+50m^2 of bioretention+60m^2 of pond	No
b	1200m^2 of 1.5m width swale	No
c	900m^2 of 3m width swale+150m^2 bioretention	No
d	600m^2 of 3m width swale+300m^2 of 1.5m width swale+100m^2 of bioretention+120m^2 of pond	No
e	1200m^2 of 1.5m width swale+ 150m^2 of bioretention	Yes
f	2400m^2 of 1.5m width swale	Yes
g	300m^2 of 3m width swale+750m^2 of 1.5m width swale+250m^2 of bioretention	Yes

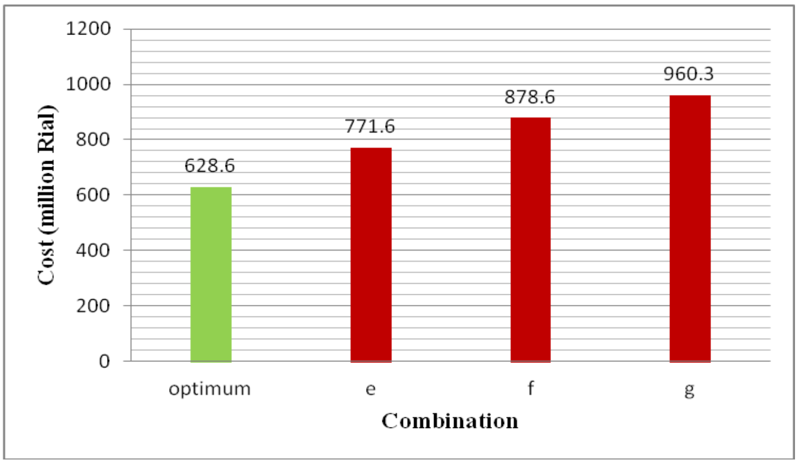

Figure2. total cost for different combinations

In three upcoming figures pollutant removal rates of these combinations and their total construction and maintenance costs are shown. As the figures show, there is not a significant relashionship between removal efficiencies and total cost of combinations. To achieve water quality measures combinations should reduce pollutant concentrations to standard values that are discussed earlier, therefore there is a minimum reduction amount for each pollutant that every combination must satisfy in order to be an acceptable option. The red line in figures 3 to 5 shows minimum acceptable removal rate for TP, TN and TSS respectively.

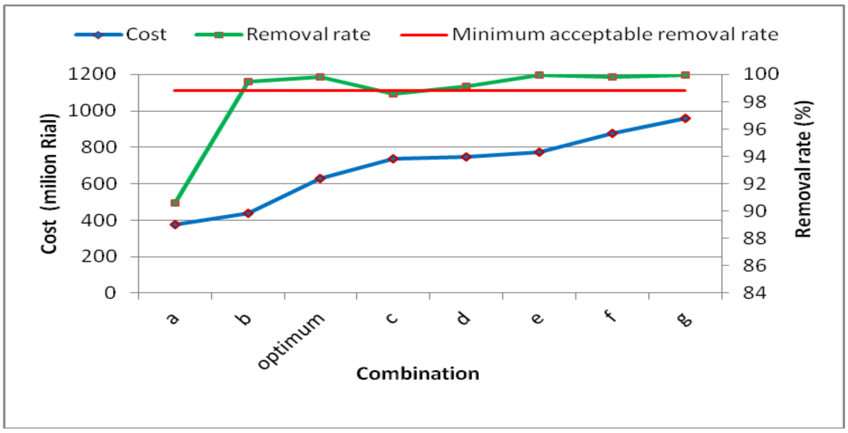

Figure 3. TP removal rate and total cost for different combinations

Figure 3 shows that combinations “a” and “c” don’t meet standard value for TP. Figure 4 shows that all the selected combinations satisfy TN standard. Figure 5 shows that combinations a, b, c and d cannot reduce TSS concentration to standard concentration. Thus only four combinations satisfy standard concentration for all three pollutants and among them the optimum combination has the lowest cost.

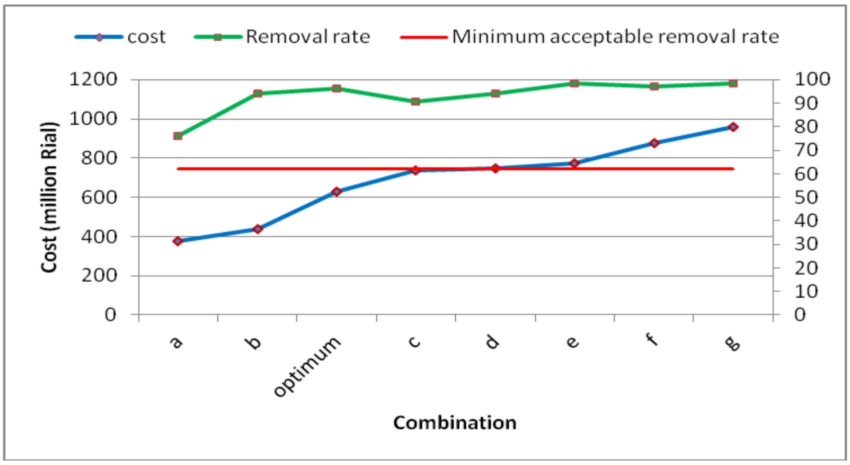

Figure 4. TN removal rate and total cost for different combinations

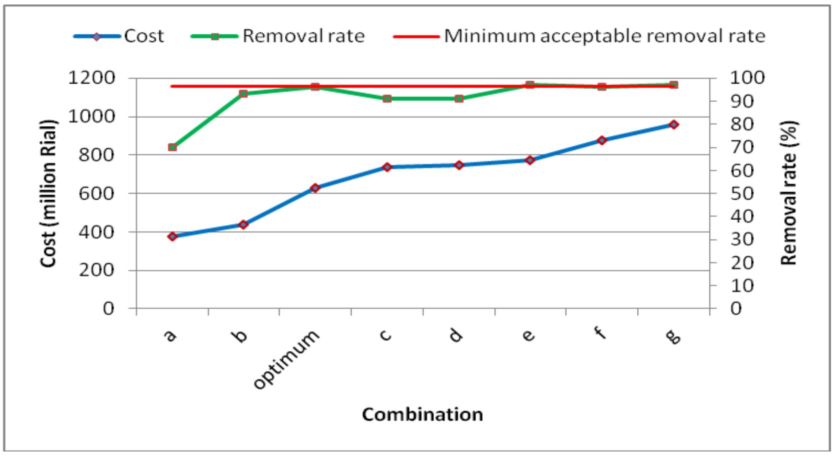

Figure 5. TSS removal rate and total cost for different combinations

4 CONCLUSION

The goal of this paper was to develop a methodology to find optimal solution for controlling non-point source pollution caused by urbanization. The general modelling approach involves a pollution simulation model and an optimization model.

Historical data was used to compare life cycle costs of stormwater BMPs, including swale, bioretention system and pond. Construction costs and annual O&M costs have been combined to estimate the total present cost of stormwater BMPs (in 2011 IRR) as a function of BMPs sizes. Effectiveness in reducing TSS, TP and TN concentration by each type of BMPs has been assessed by watershed model.

For the stormwater BMPs investigated, results show that, ignoring land costs, swales have been the least expensive BMPs to construct and maintain if appropriate land is available.

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