Cost Effectiveness of Urban Runoff and Combined Sewer Control Options

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The negative long term impacts of urban runoff discharges and combined sewer overflows (CSOs) have been widely documented over the past twenty years. Short term and long term impacts can have a negative impact on public water supply, recreational water use and aquatic species. In order to reduce negative impacts, control options can be applied to reduce pollutant mass into receiving water bodies. To achieve maximum effectiveness, a series of source and “end-of-pipe” control options can be applied.

A methodology was developed to assess the effectiveness of a variety of control options. The methodology employed a statistical modeling approach. The statistical approach is meant to be used in preliminary and planning level studies. The approach utilized involved the definition of the statistical properties of rainfall. Closed-form equations have been developed in the past to determine the long term effectiveness of extended detention ponds, wet ponds, and underground storage tanks in removing suspended solids (Guo, 1992). These models were extended to predict the long term effectiveness of wet detention ponds, underground storage tanks, infiltration basins, porous pavements, and outfall treatment in removing both particulate and soluble pollutants (Moroz, 1994).

The least cost for a particular level of service for a control option was determined from available cost data. Capital, operating and maintenance, and land costs were all included in the tabulation of the total cost of a particular option. Cost-effectiveness curves were then generated for each option and level of service.

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The results of the analyses on urban drainage control options determined that infiltration ponds with sand base and wet ponds were the most cost-effective options for reducing pollutant loadings from urban drainage discharges. Both options were found to be effective in removing suspended solids, BOD₅, nutrients, heavy metals, and fecal coliform loadings from urban drainage.

The results of the analyses on combined sewer control options determined that outfall treatment with roof disconnection would be the most cost-effective option in removing suspended solids, BOD₅, and fecal coliforms. However, sensitivity analyses showed that, under some circumstances, other options were the most cost-effective.

16.1 Background

Over the last 20 years, the negative impacts of urban runoff and CSOs on water bodies have been studied intensively. Short term impacts, associated largely with bacteria and dissolved oxygen, negatively impact public water supply, recreational use (Hvitved - Jacobsen, 1986) and aquatic species diversity. Long term impacts are typically associated with suspended solids, nutrients, and heavy metals. The presence of these pollutants in receiving waters may result in gill damage to some fish species, excessive algae growth and reductions in aquatic species due to heavy metals ingestion.

In order to reduce these negative impacts, numerous control options have been proposed to reduce urban runoff and CSOs. Control options can be divided into two categories: source controls and downstream controls. Often a comprehensive control strategy will involve both types of control measures. Source control typically involves reducing urban runoff volumes entering a drainage system and includes such options as roof leader disconnection. Downstream controls involve “in pipe” or “end-of-pipe” controls and concentrate on the treatment of discharges entering receiving waters.

16.2 Methodology

In order to assess the effectiveness of a variety of control options, a statistical modeling approach was utilized. Statistical models were developed in order to describe the efficiency of control options in removing suspended solids, BOD₅, nutrients, bacteria, and heavy metals. These models are derived from the probability density functions of the following rainfall event characteristics (Adams, et al., 1986):

$$f_v(v) = \zeta e^{-\zeta v}, \zeta = \frac{1}{v} \quad (16.1)$$

$$f_b(b) = \psi e^{-\psi b}, \psi = \frac{1}{b} \quad (16.2)$$

$$f_t(t) = \lambda e^{-\lambda t}, \lambda = \frac{1}{t} \quad (16.3)$$

where:

- v = the rainfall event volume (mm),
- b = the interevent time (hrs), and
- t = the event duration (hrs).

The values of the parameters used in the present study are $\zeta = 0.193$ /mm, $\psi = 0.0142$ /hr, and $\lambda = 0.288$ /hr and were derived from the Toronto Bloor Street Meteorological station. Through the application of derived probability theory, Guo (1992) developed the following equation to predict the long term effectiveness of extended detention ponds and underground storage tanks in removing suspended solids:

$$C_p = E_d \Omega \left(\frac{1}{\lambda} - \overline{T_d} \right) \frac{\xi}{\phi C_1} \times 100 \quad (16.4)$$

where:

- C_p = the pollution control effectiveness
- E_d = the average removal efficiency,
- Ω = the outflow rate (mm/hr),
- C_1 = a constant dependent upon the value of depression storage,
- $\overline{T_d}$ = the average settling time, and
- $(1/\lambda - T_d)$ = the time in which dynamic settling occurs.

The final expression for T_d has been derived by (Guo, 1992) as follows:

$$\begin{aligned} \overline{T_d} = & \frac{S}{C_1^2 C_4^2} [(\Omega + C_3) C_2 C_3 - C_3] (1 - C_1 C_3) \\ & + \left(\frac{1}{\lambda} - \frac{1}{\lambda} C_1 C_4^2 \right) (1 - C_1 C_4) - \frac{S}{\Omega} C_1 C_2 C_3 C_4 \end{aligned} \quad (16.5)$$

where:

$$C_1 = e^{-C_1 S_d} \quad (16.6)$$

$$C_2 = e^{-\psi \frac{S}{\Omega}} \quad (16.7)$$

$$C_3 = e^{-\lambda \frac{S}{\phi}} \quad (16.8)$$

$$C_4 = \frac{\lambda \phi}{\lambda \phi + \zeta \Omega} \quad (16.9)$$

$$C_5 = \frac{\phi}{\psi \phi + \zeta \Omega} \quad (16.10)$$

and:

ϕ = the runoff coefficient,
 S = the storage volume in mm, and
 S_d = the depression storage in mm.

Using the same methodology, a series of equations were developed to predict the long term effectiveness of wet detention ponds, underground storage tanks, infiltration basins, and porous pavements in removing both particulate and soluble pollutants from stormwater (Moroz, 1994).

In the study of CSOs, analytical models previously derived to determine pollutant control efficiencies of storage and interception capacity (Li, 1991) were extended to predict the efficiency of outfall treatment in removing particulate and soluble pollutants (Moroz, 1994).

Tables 16.1 and 16.2 present the suspended solids removal equations derived for both urban runoff control and CSO control options, respectively.

16.3 Cost of Control Options

In order to determine cost-effectiveness, the capital, operating and maintenance and land costs were estimated for each control option. Data from recent studies conducted as part of the Remedial Action Plan Program in Ontario (CH₂M HILL, 1992) were used to estimate capital and operating and maintenance costs. Table 16.3 presents the cost equations used to estimate capital and operating and maintenance costs for each control option.

It was recognized that ponds and underground storage tanks would typically require a significant land area to construct. Therefore, land costs were calculated for ponds and underground storage tanks. An equation was developed relating land costs to runoff coefficient and storage volumes based on a regression analysis of existing data (Moroz, 1994). The following equation was derived:

$$C_{LC} = 29.816(\phi S)^{2.11}$$

(16.11)

where:

- C_{LC} = the land cost in 1995 dollars,
- ϕ = the runoff coefficient, and
- S = the storage volume of the pond in m³.

Table 16.1 Suspended solids removal for urban runoff control options.

Control Option	Removal Equation	Source
Extended Detention Ponds, Underground Storage Tanks	$E_d \Omega \left(\frac{1}{\lambda} - \overline{T_d} \right) \frac{\zeta}{\phi C_1} \times 100$	Guo (1992)
Infiltration Ponds, Porous Pavements	$1 - \frac{\frac{\lambda}{\Omega} \frac{\psi}{\Omega} + \frac{\zeta}{\phi} e^{-\left(\frac{\psi}{\Omega} + \frac{\zeta}{\phi}\right)S}}{\frac{\lambda}{\Omega} + \frac{\zeta}{\phi} \frac{\psi}{\Omega} + \frac{\zeta}{\phi}}$	Adams et. al. (1986)
Wet Detention Ponds	$\frac{e^{-\zeta\left(\frac{S}{\phi} + S_d\right)} \frac{SV_s A}{S + V_s} + (1 - e^{-\zeta\left(\frac{S}{\phi} + S_d\right)S})}{\frac{\phi}{\zeta} e^{-\zeta S_d}} \int_{b=0}^{b=\infty} \int_{v=0}^{v=\frac{S}{\phi} + S_d} f(v, b) dv db$	Moroz (1994)

Table 16.2 Suspended solids removal by CSO control options.

Control Option	Removal Equation	Source
Downstream Storage, Increased Interceptor Capacity	$1 - \frac{\frac{\lambda}{\Omega} \frac{\psi}{\Omega} + \frac{\zeta}{\phi} e^{-\left(\frac{\psi}{\Omega} + \frac{\zeta}{\phi}\right)S}}{\frac{\lambda}{\Omega} + \frac{\zeta}{\phi} \frac{\psi}{\Omega} + \frac{\zeta}{\phi}}$	Adams et al (1986)
Outfall Treatment	$n_s \frac{(R - Pu_1)}{R} + n_o \frac{(Pu_1 - Pu_i)}{Pu_1}$	Moroz (1994)

Table 16.3 Cost of control options (1995 Canadian dollars).

Extended Detention Ponds	$857V^{0.5461}$, V is the storage volume in m^3 .
Wet Detention Ponds	$1500V^{0.5461}$, V is the storage volume in m^3
Underground Storage Tanks	$4048V^{0.79}$, V is the storage volume in m^3
Roof Leader Disconnection	$0.827AR$, AR is the disconnected roof area in ha.
Porous Pavement	$1157SA_p + 180.75A_p$, A_p is the pavement area in ha. and S is the depth of stone in mm.
Increased Interceptor Capacity	$504,800Q^{0.67}$, Q is the interceptor capacity in mm/hr
Sewer Separation	$176,400A_s$, A_s is the area separated in ha.
Outfall Treatment	$17,493Q^{0.82}$, Q is the outfall treatment rate in mm/hr

16.4 Cost Effectiveness Analysis Methodology

The purpose of the cost-effectiveness methodology is to determine the least-cost option for a particular level of pollution control performance. Therefore, the methodology involves minimizing the cost of each option considered, subject to performance constraints. For two inputs, the cost-effectiveness curve can be developed from the expansion path by plotting the level of service versus the cost at each tangency point where tangency points represent the minimum cost to achieve the level of pollution control performance. For optimization problems with two or more variables, this procedure can also be applied. The cost minimization problem can be expressed mathematically as follows:

Minimize $C_T = f_c[(X_i - X_{io}), \dots (X_n - X_{no})]; i = 1, \dots n$ (16.12)

subject to: $Y_k(X_1, \dots X_n) = Y_{ko}; k = 1, \dots m$ (16.13)

$X_i \geq X_{io}, i = 1, \dots n$ (16.14)

where:

- C_T = the total cost of the control option,
- $f_c[(X_i - X_{io}), \dots]$ = the total cost of the control option dependent upon n variables,
- n = the number of variables,
- $Y_k(X_1, \dots X_n)$ = the k^{th} performance constraint,
- X_i = the total value of the i^{th} variable,

X_{io} = the existing value of the i^{th} variable, and
 m = the total number of performance constraints.

By employing the Lagrange multiplier method, the following Lagrange function can be formed by combining the objective function with the constraint equation:

$$Z = f_c[X_i - X_{io}, \dots, (X_n - X_{no})] + E_k(Y_k(X_i, \dots, X_n) - Y_{ko}) \quad (16.15)$$

where:

E_k = the k^{th} Lagrange multiplier or the marginal cost of an additional unit of Y_{ko} .

In order to optimize the performance, the objective function was differentiated with respect to variables $X_i, \dots, X_n$ and multiplier E_k and the derivatives set to zero. The resulting set of equations was then solved to determine the optimal mix of measures. The solution to this set of equations is the tangency point between the isoquant and isocost lines. Li (1991) developed this methodology for water quality analysis.

16.5 Cost Effectiveness Analysis Results

Cost-effectiveness curves were developed for each control options for each pollutant of interest. The following sections summarize the findings of the completed analyses.

16.5.1 Urban Drainage Control Options

Figures 16.1 and 16.2 present the cost-effectiveness curves for urban drainage control options in removing suspended solids and fecal coliforms respectively. The results of the analysis showed infiltration ponds with sand base and wet ponds were the most cost-effective options. Both of these control options are capable of removing suspended solids, BOD₅, nutrients, heavy metals, and fecal coliform from urban drainage. These control options probably could not both be utilized in a specific area, since infiltration ponds require high hydraulic conductivity soils in order to encourage infiltration while wet ponds normally require a low permeability clay lining in order to maintain a permanent pool of water. The results of analyses for other pollutants were found to be similar.

The analyses determined that storage tanks had limited effectiveness in removing fecal coliforms (maximum of 40%) due to the short residence time of these tanks. In addition, storage tanks had high costs. Furthermore, the analyses showed that even with a roof leader disconnection program in place, storage tanks still had a poor effectiveness in removing fecal coliforms.

Figure 16.1 Urban runoff control - cost effectiveness of suspended solids removal.

Figure 16.2 Urban runoff control - cost effectiveness of fecal coliform removal.

16.5.2 Combined Sewer Rehabilitation Control Options.

Figures 16.3 and 16.4 present the cost-effectiveness curves developed for the removal of suspended solids and fecal coliforms; respectively. The results of the analyses showed that outfall treatment with a roof leader disconnection program would be the most cost-effective option in removing a high percentage of suspended solids, BOD₅ and fecal coliforms. If lower removal rates are required (i.e. < 80%), downstream storage combined with increased interception capacity and roof leader disconnection was found to cost effective until the removal rate reached 80%. If removals above 80% were required, the cost effectiveness curve of this option became exponential.

Figure 16.3 Combined sewer control options - cost effectiveness of suspended solids removal.

Sensitivity analyses were completed in order to determine the circumstances which would favour another option. The results of the sensitivity analyses showed that only under extreme circumstances would outfall treatment with a roof leader disconnection program not be the most cost-effective option. These extreme circumstances included an existing interception capacity in excess of 80 times dry weather flow, a high cost to implement a roof leader disconnection program (i.e. \$100,000/ha), and a low efficiency for outfall treatment units. If the existing interception capacity was in excess of 80 times dry weather flow, downstream storage was found to be optimal. Increased interception capacity was found to be optimal if the efficiency of outfall treatment was below 23%.

Figure 16.4 Combined sewer control options - cost effectiveness of fecal coliform removal.

16.6 Conclusions

A statistical modeling approach was applied to a variety of control options in order to determine their effectiveness. Optimal cost information for each option was developed by solving a cost minimization problem. The statistical approach allows many options to be evaluated. In addition, a comprehensive sensitivity analysis was performed.

The results of the applied methodology indicated that in some cases, a combination of control options may be the most cost-effective. For urban drainage systems, it was found that wet ponds and infiltration ponds with sand base were found to be the most cost-effective options. Both of these options could not be implemented due to local soil conditions. For combined sewer rehabilitation, outfall treatment combined with a roof leader disconnection program was found to be the most cost-effective option under most circumstances. A series of sensitivity analyses determined the circumstances under which other control options could be considered most cost-effective.

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