

The allocation of resources to stormwater pollution control

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Abstract Limited resources for ameliorating stormwater pollution in urban areas raises the issue of selecting and implementing appropriate methods of pollutant reduction. An effective stormwater management programme should consist of strategies that will achieve the goal at the minimum cost, thereby making the best use of limited available resources. This paper presents an optimization scheme that sizes various stormwater pollution control options. The options include a wide range of strategies, from street sweeping to constructed wetlands. The objective is to select the most effective strategies for limited funds. The nonlinear problem is solved using LINGO, a nonlinear problem solver. A heuristic method is used to select various possible options. The algorithm is applied to Plumpton Park in Blacktown, a suburb in Western Sydney, Australia.

INTRODUCTION

Stormwater should be managed in an integrated and ecologically sustainable manner with one aim being to reduce the amount of pollution and the peak flow and volume. The development of better stormwater management options has occurred over the past decade, and this has led to the introduction of a combination of structural and non-structural strategies to improve the quality of stormwater (Gentle, 1996; Gentle *et al.*, 1997).

The management of stormwater is an extensive and costly exercise, and most local councils and water authorities do not possess the funds for adequate stormwater management. The objective of this study is to develop a technique to optimize different stormwater management strategies for maximum pollutant reduction within a fixed expenditure. A second optimization was performed which showed the cost of removing a set percentage of pollutant.

The Plumpton Park catchment is located in the city of Blacktown, approximately 40 km west of Sydney. The catchment is separated into two sub-catchments, one 60 ha, and the other 15 ha. Land use distribution of the larger of sub-catchment consists of 65% residential and 35% commercial and parkland, while the smaller sub-catchment has 100% residential land use (Hunter & Constandopoulos, 1997). The catchment has hillslope gradients of generally less than 5%. Average rainfall in the area is approximately 800 mm year⁻¹.

The only management strategy in place at present is a constructed wetland at the confluence of the two sub-catchments. It was constructed in 1993 and consists of three main parts, a gross pollutant trap, a trash rack and the wetland pond. The gross pollutant trap is on the main catchment inlet, and the trash rack is on the smaller catchment inlet.

The annual pollutant loads for the catchment have not been extensively studied although results from preliminary studies have been published. The following values are based on the amount of pollutants retained in the gross pollutant trap at the main inlet on the constructed wetland. The information was collected by G. Hawkes from Blacktown City Council (Table 1).

Table 1 Annual pollutant loads (Gentle, 1996).

Pollutant	Load removed GPT (kg year ⁻¹)	Pollutant removal efficiency	Annual pollutant load (kg year ⁻¹)
Total nitrogen	25.2	10%	252
Total phosphorus	5.4	10%	54
Suspended solids	36 000	70%	51 450

For this report, the pollutants found in stormwater have been separated into five groups:

- (a) Suspended solids, generally sediments and other small particles.
- (b) Nutrients, mainly nitrogen and phosphorus.
- (c) Litter and refuse.
- (d) Bacteria and pathogens.
- (e) Toxicants, such as pesticides and heavy metals.

MANAGEMENT STRATEGIES

Management strategies that prevent or reduce pollution of water can be physical, structural or management related, used singly or in combination (Table 2, Hunter (1998)). A single management option will not be suitable to all situations, and careful evaluation of the site is required before development of a stormwater pollution management strategy can be devised (EPA, 1996).

Table 2 Various management strategy efficiencies.

Management strategy	Pollutant removal efficiency (%):		
	Suspended solids	Total phosphorus	Total nitrogen
Structural strategies			
Gross pollutant trap	70	10	10
Wet detention basin	85	45	50
Constructed wetland	70	85	95
Litter boom	70	10	10
Grassed swale	70	30	30
Infiltration trench	50	35	50
Porous pavement	90	80	65
Non-structural strategies			
Public information programme	0	21	0
Street sweeping	30	30	30

Optimization

The linear solver in LINGO (a nonlinear problem solver) is LINDO, which uses the revised Simplex Method. LINGO's nonlinear solver employs both a Successive Linear Programming (SLP) algorithm and a Generalized Reduced Gradient (GRG) algorithm. Integer programming is performed by using the branch-and-bound-and-cut method (Lindo Systems, 1996). The solver used for the optimization process is the successive linear programming algorithm and the generalized reduced gradient algorithm.

The optimization criterion determines the strategies that will be optimized by the mathematical programming process. For the optimization process, the following management strategies were selected based on the quality of the information obtained on their efficiencies, as well as the frequency of their use in other catchments. The strategies included in the objective function, are:

- gross pollutant trap (GPT),
- constructed wetland (CW),
- wet detention pond (WDP),
- grassed swales (GS),
- public information programme (PIP), and
- street sweeping (SS).

The optimization process involved two distinct methods:

- Optimizing a combination of these strategies to maximize the amount of pollutants removed, limited by budgetary constraints.
- Minimizing the cost of removing a percentage of the total pollutant load from the catchment.

Both of the optimization methods were performed for three different pollutants, i.e. optimization of suspended solids removal, optimization of total nitrogen removal, and optimization of total phosphorus removal. A sensitivity analysis was performed to investigate the effects of removal costs if the removal efficiencies are reduced.

The following assumptions were made:

- The pollutant removal is linearly related to the size of the strategy compared to the size of the catchment.
- The cost of the strategy is linearly related to its size.
- All of the strategies have a useful life of 15 years.
- The proper maintenance will be carried out for the full 15 year period.

The strategies are applied sequentially, i.e. a strategy can only remove pollutants not previously removed by a previous strategy. The public information programme would be applied first and street sweeping would occur after that as these are preventative strategies, and then the grassed swales would be used. The gross pollutant traps are included next, then constructed wetlands and wet detention ponds.

The costs were converted to present worth (1998). The present value of the strategies is listed in Table 3. A discount rate of 5% over 15 years was applied to the capital and maintenance costs. A sensitivity analysis was performed to examine the effects of an increase in the discount rate.

During the preliminary optimization, a method of Linear Programming was applied. The results from the linear programming were not satisfactory and were only

Table 3 Present worth (1998) with a discount rate of 5% (\$A, Australian dollars).

Strategy	Present worth
Gross pollutant trap	\$A 11 858.81 per m ²
Constructed wetland	\$A 64.14 per m ²
Wet detention pond	\$A 54.14 per m ²
Grassed swale	\$A 11 103.73 per ha
Public information programme	\$A 2503.52 per ha
Street sweeping	\$A 12 669.62 per ha

approximations of the maximum for the objective function. The linear programming procedure involved substituting estimates of the objective function, and then reconstituting the local solution back into the problem.

The nonlinear method allowed for a one-step solution to the problem and this method was selected for the optimization process.

Optimization method A

The objective function:

$$Z = \Sigma (\text{Remaining Pollutant Load}) \times (\text{Efficiency of Strategy}) \times (\% \text{ covered by the strategy})$$

A sample objective function, which maximizes total phosphorus removal, is:

$$\begin{aligned} \text{Maximize} \quad & (\text{Efficiency of PI}) \times (\% \text{ catchment covered by PI}) + (\text{Remaining Total P Load}) \times (\text{Efficiency of SS}) \times (\% \text{ catchment covered by SS}) + \\ & (\text{Remaining Total P Load}) \times (\text{Efficiency of GS}) \times (\% \text{ catchment covered by GS}) + (\text{Remaining Total P Load}) \times (\text{Efficiency of GPT}) \times \\ & (\% \text{ catchment covered by GPT}) + (\text{Remaining Total P Load}) \times (\text{Efficiency of CW}) \times (\% \text{ catchment covered by CW}) + (\text{Remaining Total P Load}) \times (\text{Efficiency of WDB}) \times (\% \text{ catchment covered by WDB}) \end{aligned}$$

Subject to:

Cost Constraint – This constraint is based on the costs of the strategy being used over the entire catchment:

$$C_1 \times \text{PI} + C_2 \times \text{SS} + C_3 \times \text{GS} + C_4 \times \text{GPT} + C_5 \times \text{CW} + C_6 \times \text{WDB} \leq X$$

Catchment Constraint – This constraint represents the maximum limit of the catchment in a decimal form. The value for all of the strategies below is 1, which represents 100%:

$$\begin{aligned} \text{PI} & \leq 1 \\ \text{SS} & \leq 1 \\ \text{GS} & \leq 1 \\ \text{GPT} & \leq 1 \\ \text{CW} & \leq 1 \\ \text{WDB} & \leq 1 \end{aligned}$$

This optimization program is a linearly constrained model as all of the constraints are linear.

Optimization method B

The objective function is the cost equation, and it will be minimized.

$$Z = \Sigma (\text{Cost of Strategy}) \times (\% \text{ covered by the strategy})$$

A sample objective function that minimizes the cost of total phosphorus removal is:

$$\text{Minimize } C_1 \times \text{PI} + C_2 \times \text{SS} + C_3 \times \text{GS} + C_4 \times \text{GPT} + C_5 \times \text{CW} + C_6 \times \text{WDB}$$

Subject to:

Catchment Constraint –

$$\begin{array}{lcl} \text{PI} & \leq & 1 \\ \text{SS} & \leq & 1 \\ \text{GS} & \leq & 1 \\ \text{GPT} & \leq & 1 \\ \text{CW} & \leq & 1 \\ \text{WDB} & \leq & 1 \end{array}$$

Efficiency Constraint –

$$\begin{aligned} & (\text{Efficiency of PI}) \times (\% \text{ catchment covered by PI}) + (\text{Remaining Total P Load}) \times \\ & (\text{Efficiency of SS}) \times (\% \text{ catchment covered by SS}) + (\text{Remaining Total P Load}) \times \\ & (\text{Efficiency of GS}) \times (\% \text{ catchment covered by GS}) + (\text{Remaining Total P Load}) \times \\ & (\text{Efficiency of GPT}) \times (\% \text{ catchment covered by GPT}) + (\text{Remaining Total P Load}) \times \\ & (\text{Efficiency of CW}) \times (\% \text{ catchment covered by CW}) + (\text{Remaining Total P Load}) \times \\ & (\text{Efficiency of WDB}) \times (\% \text{ catchment covered by WDB}) = X \end{aligned}$$

where X represents the percentage of pollutants removed by the combination of strategies.

This model is an example of a nonconvex model, as the constraint is not linear in nature.

RESULTS

Optimization method A

The first optimization method determined the maximum pollutant removal for a given sum of money. The optimization process considered all combinations of the six strategies, which are approximately 64 sets of calculations for each pollutant removal optimization (Table 4).

The nonlinear program focusing on total phosphorus found that a public information programme should be implemented over 100% catchment as a non-

Table 4 Global optimums for method A optimization.

	Phosphorus removal	Suspended solids removal	Nitrogen removal
Optimized for phosphorus removal	90.15%	79.58%	95.93%
Optimized for nitrogen removal	89.09%	85.48%	96.51%
Optimized for suspended solids removal	48.97%	92.59%	53.61%

structural strategy, and a minor wet detention basin should be constructed to serve approximately 37.5% of the catchment, and the entire catchment should drain through a constructed wetland. This would remove 227 kg of total nitrogen, 51 kg of total phosphorus and 40 944 kg of suspended solids from the annual loads. The constructed wetland should have an area of 2% of the catchment, or 15 000 m² and wet detention basin with an area of 5625 m².

The nonlinear program focusing on total nitrogen found that the following strategies should be employed. A minor wet detention basin should serve approximately 60% of the catchment, and a constructed wetland should be constructed to service 100% catchment. This combination of strategies would remove 224 kg of total nitrogen, 52 kg of total phosphorus and 43 980 kg of suspended solids from the annual pollutant loads. The constructed wetland should have an area of 15 000 m² and wet detention basin with an area of 9000 m².

The suspended solids nonlinear program calculated that the following strategies should be employed in the catchment. A gross pollutant trap should be constructed to service approximately 72% of the catchment and a wet detention basin should be constructed for the entire catchment. This combination of strategies would remove 21 357 kg of total nitrogen, 26 kg of total phosphorus and 47 638 kg of suspended solids from the annual pollutant loads. The gross pollutant trap should have an area of 48 m² and wet detention basin with an area of 15 000 m².

The implementation of these strategies would involve the upgrade of the constructed wetland and the construction of a wet detention pond. The calculations were based on a constructed wetland that is 2% of the total catchment size. The existing constructed wetland is 1.33% of the total catchment size. This means an additional 5000 m² of area would have to be added to the constructed wetland.

The general trend of all of the models was to discard street sweeping and grassed swales as viable management strategies.

Optimization method B

The second optimization method was used to determine the minimum cost for a percentage removal of pollutant. This method was optimized for total phosphorus, total nitrogen and suspended solids.

This optimization method was performed separately for each of the pollutants. Several combinations of strategies were used in this process, but each of the combinations gave a similar solution to the problem.

The least expensive removal of pollutants was achieved in all three pollutant cases when all management strategies were included in the calculations.

The phosphorus case used a constructed wetland and a public education programme as the primary strategies, and then it included a wet detention basin and then other strategies. The suspended solids case used a wet detention basin as its primary strategy, and then it included gross pollutant trap and then other strategies. The nitrogen case used a constructed wetland as the primary strategy, then a wet detention basin, followed by the rest of the strategies.

The general trend for this optimization was for the cost of removal to remain constant up to around 85% for suspended solids and phosphorus removal, and up to

around 95% for nitrogen removal. The costs of removal then increase dramatically to the total amount of pollutants able to be removed by the strategies, which were approximately 98%. Figure 1 shows the trend mentioned above. The public is unlikely to support such high costs for such a small improvement in water quality.

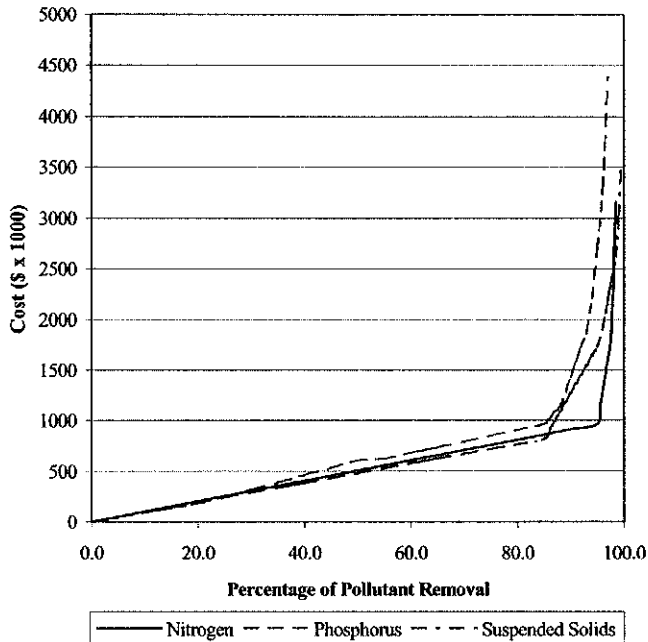


Fig. 1 Cost vs pollutant removal.

The sensitivity analysis was separated into two sections. The first part involved increasing the discount rate to investigate its effects on the cost of removing stormwater pollution. The second part of the sensitivity analysis involved reducing the effectiveness of the management strategies, and investigating its effects on the optimization results.

Sensitivity analysis for cost

For the analysis, the discount rate was increased to 10% and 15% (Table 5). The revised nonlinear programs yielded the results in Table 6. The values obtained in the sensitivity analysis vary by approximately 1–3% for every 5% the discount rate is increased. This small increase is insignificant, and shows the discount rate is a variable of minor importance in the optimization process.

Sensitivity analysis for efficiency

For this analysis, the efficiencies of the management strategies were reduced by 5% and 50%, to investigate the effects of this on the cost of pollutant removal.

Table 5 Cost of strategies with increased discount rates.

Strategy	10% discount rate	15% discount rate
Gross pollutant trap	\$A 10 333.34 per m ²	\$A 9366.05 per m ²
Constructed wetland	\$A 55.82 per m ²	\$A 50.54 per m ²
Wet detention pond	\$A 45.82 per m ²	\$A 40.54 per m ²
Grassed swale	\$A 8884.86 per ha	\$A 7477.90 per ha
Public information programme	\$A 1893.34 per ha	\$A 1506.42 per ha
Street sweeping	\$A 9618.69 per ha	\$A 7684.11 per ha

Table 6 Percentage removal with revised costs.

	Phosphorus removal:		Suspended solids removal:		Nitrogen removal:	
	10%	15%	10%	15%	10%	15%
Optimized for phosphorus removal	90.90%	91.68%	83.17%	86.89%	96.29%	96.66%
Optimized for nitrogen removal	89.88%	90.72%	88.44%	91.63%	96.81%	97.12%
Optimized for suspended solids removal	61.02%	62.08%	95.19%	95.97%	64.56%	65.52%

This reduced efficiency could represent the effects of incorrect construction or application of the management strategy, or the failure to conduct proper maintenance at the correct time.

The effect on the first optimization method was a reduction in pollutant removal. Table 7 shows the results of the analysis with reduced strategy efficiencies compared with the original values. As expected, the optimal strategies were the same as for the fully efficient case (Table 8). All that changed was the amount of pollution removed.

Table 7 Comparison of values from sensitivity analysis—optimization A.

	Phosphorus removal:		Suspended solids removal:		Nitrogen removal:	
	Original	5% reduced	Original	5% reduced	Original	5% reduced
Optimized for phosphorus removal	90.15%	85.73%	79.58%	75.53%	95.93%	91.69%
Optimized for nitrogen removal	89.09%	84.86%	85.48%	82.00%	96.51%	92.73%
Optimized for suspended solids removal	48.97%	44.34%	92.59%	90.12%	53.61%	48.98%

DISCUSSION

The budget in optimization method A was assumed to be \$A 1 000 000 for construction costs, and \$A 40 000 per year maintenance costs, which corresponds with approximately \$A 1 400 000 at present value. This allowed for a pollutant reduction of between 90% and 95%.

Table 8 Comparison of values from sensitivity analysis—optimization B.

	Phosphorus removal:		Suspended solids removal:		Nitrogen removal:	
	Original	50% reduced	Original	50% reduced	Original	50% reduced
Optimized for phosphorus removal	90.15%	52.89%	79.58%	45.39%	95.93%	52.43%
Optimized for nitrogen removal	89.09%	50.36%	85.48%	51.77%	96.51%	55.47%
Optimized for suspended solids removal	48.97%	25.30%	92.59%	57.05%	53.61%	27.71%

The optimization method B showed a steep increase in costs after approximately 85% of pollutant removal was achieved. A removal efficiency of 85% would cost approximately \$A 962 000, which is only 69% of the original budget.

For both of the methods, the best option for pollution removal included a constructed wetland. The existing wetland in Plumpton Park is not functioning at its peak efficiency, due to the size and the infestation of carp. It should be upgraded in size to become a part of the management strategies determined in these processes.

CONCLUSION

This paper has outlined a method of selecting the pollution control strategies based on their costs and efficiencies. The results showed that for Plumpton Park a constructed wetland of area 15 000 m² and a minor wet detention basin of area 9000 m² would be the best management plan for the optimization method A (cost constraint). A constructed wetland would be the best option for the second optimization method (efficiency constraint).

The final selection of the management plan would depend on the funds that were available, and the amount of pollutants that were required to be removed.

This report has displayed a method of optimizing management strategies that may benefit the community and Local Government. This approach is a sound method of optimization, but further analysis of the effectiveness of the management strategies, and their associated costs must be done.

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