Economic analyses for optimizing the construction of separate sewer in a hybrid sewer system
Home-Ming Chen and Shang-Lien Lo

ABSTRACT
Metropolitan Taipei located in north Taiwan uses a hybrid sewer system consisting of mostly separate sewer for the populated regions, and partly combined sewer for less populated regions. This study used the concept that Marginal Cost of Control (MCC) equals to Marginal Benefits of Control (MBC) to establish the method for studying the optimal household connection percentage, and the most cost-effective construction of the separate sewer in the hybrid sewer system. Results indicate the improvement of the receiving water quality in a cost-effective analysis manner. The most cost-effective sanitary sewer construction can be reached when the stream Biochemical Oxygen Demand (BOD₅) meets the river quality standard, which can be applied in other cities and existing systems.

Key words | household connection percentage, hybrid sewer system, marginal benefits of control, marginal cost of control, separate sewer

INTRODUCTION
There are two major types of sewers. The combined sewer collects both domestic wastewater and stormwater but using weirs to separate dry weather flow to the wastewater treatment plant; the separate sewer consisting of separate sanitary and separate storm sewer. The separate sanitary sewer is specifically designed for domestic wastewater whereas a separate storm sewer is used for stormwater or rainwater (Van der Tak et al. 1993). Although the separate sewer is generally more expensive than the combined sewer (Rauch et al. 2002; Toffol et al. 2007), it may not be the preferable system for protecting river water quality. This is due to the fact that non-point source pollution such as surface runoff from the street that possibly carries various pollutants is discharged directly into the river (Brombach et al. 2005; Toffol et al. 2007). Even though this is the case, by the end of 20th century, many countries in central Europe still adopted the separate sewer whenever possible (Achleitner et al. 2007; Toffol et al. 2007). The household connection percentage of a separate sanitary sewer is calculated by dividing the total number of household connections by the total number of households (Tchobanoglous 1981). More households connected generally results in decreasing pollution input to the environment with improved quality of the surface water for densely populated areas (Buerge et al. 2006). A separate sanitary sewer costly to build and the construction may last 20 or 30 years. The long-term impact of household connection percentage on the stream quality can be analyzed based on cost-effectiveness and environmental benefits (Benedetti et al. 2008).

Taipei used to have a traditional simple combined sewer for collecting urban surface drainage and domestic wastewater to improve environmental quality; however, since water pollution in river streams were still serious, methods were newly deployed to improve water quality. In recent years, separate sanitary and storm sewers have been built to serve more serious polluted regions, which are also densely populated regions. Increasing the household connection percentage has shown to improve the receiving water quality. The city later expanded to annex some...
suburban regions that are in remote locations with less residential density than urban regions. Constructing separate sanitary sewer to serve these suburban regions is not cost-effective; therefore the city has adopted the combined sewer to serve these remote regions. Hence, Taipei is managing a hybrid sewer system that consists of separate sewer to serve the well developed and densely populated regions and simple combined sewer to transport the wastewater of remote and less populated regions to the wastewater treatment plant. The wastewater treatment plant adopts the conventional activated sludge process to meet the effluent standards. The current question in mind is what percentage of separate sewers should be constructed for the city. Evaluating the most cost-effective percentage for the separate sewer is a top priority for completing and managing the city’s hybrid sewer system. The economic analysis carried out in this study will cover ratios of separate and combined systems in the hybrid system without dealing with the collection and treatment of storm water.

MATERIALS AND METHODS
Development of TCC to complete MCC

The Total Cost of Control (TCC) for constructing a sewer network (including household connection), the basic term for the cost-effectiveness analyses, is defined as the cumulative costs including operational cost for previous years plus the cost for the current year as shown by Equation (1). The Marginal Cost of Control (MCC) is the TCC for each unit of environmental quality improvement; it is the slope of the TCC curve as shown by Equation (3). Thus, the MCC can be obtained by taking the first derivative of a TCC curve with respect to unit quantity of pollution. When TCC rapidly increases, the MCC also escalates leading to a positive MCC slope.

As a result of higher cost and long term for separate sewer construction, there is not immediate effectiveness of environmental quality improvement and river pollution control (Braden & Johnston 2004). The effectiveness of pollution prevention and control, indexed by the improvement of environmental quality or reduction of environmental damages (Downing 1984). The concentration of pollutants in the receiving water is shown to decrease in proportion to the progress of sewer construction (Yamada et al., 1993; Ning et al. 2001).

Reductions of environmental damages can be expressed in monetary values, which are summed up to obtain the Total Benefits of Control (TBC) curve. With improved environmental quality, the TBC curve will increase at a reduced increasing rate. If the environmental quality reaches a certain level, further increase of additional benefits becomes negligible leading to a flat TBC curve. Since the Marginal Benefits of Control (MBC) is the slope of TBC, a decreasing TBC curve will result in negative values of the rate of MBC. According to “Environmental Economics and Policy” the most efficient pollution control should conform to two basic principles: (1) TBC being greater than TCC, and (2) MCC being the same as MBC, such that the optimal level of control discharge and the optimal allocation of resources could be achieved (Downing 1984). Results of the above notions indicate that the intersection of the MCC curve and the MBC curve is the optimal quantity of pollution discharge. This will be the basis for obtaining the optimal pollution of the receiving water body in this study.

Hence, the cost to be investigated in this study is the aforementioned TCC for constructing the collection network whereas MCC is the first derivative of TCC with respect to quantity of pollutant (Equation (3)). The process of analysis is shown by Equations (1–3); the analyses of MCC are represented by Equations (4–7).

\[ \text{TCC}(t) = \text{TCC}(t - 1) + P \]  
\[ t = 1 \text{ to } n \text{ (this case from year 1993 to 2005).} \]  
\[ P = \text{Prior Cumulative Budget.} \]

\[ Q = Q_{ds} - Q_{us} \]  
\[ Q \text{ is the average stream pollution quantity.} \]  
\[ Q_{us} \text{ is the pollution observed at an upstream point.} \]  
\[ Q_{ds} \text{ is the pollution observed at a downstream point.} \]  
\[ Q_{us} (\text{BOD}_5 \text{ 10}^3 \text{kg yr}^{-1}) = 3.1536 \times 10^3 \times q_{us} (\text{BOD}_5 \text{ mg l}^{-1}) \times F_{sus} \text{ (cms).} \]  
\[ Q_{ds} (\text{BOD}_5 \text{ 10}^3 \text{kg yr}^{-1}) = 3.1536 \times 10^3 \times q_{ds} (\text{BOD}_5 \text{ mg l}^{-1}) \times F_{sd} \text{ (cms).} \]  
\[ q_{us} \text{ and } q_{ds} \text{ are the concentrations of BOD}_5 \text{ at the upstream and downstream points.} \]
respectively, \( F_{75us} \) indicate the 25 percentile annual river flow rate.

\[
\text{MCC} = \frac{\partial \text{TCC}}{\partial Q}
\]  

(3)

Development of TBC with scenario analysis to complete MBC

The scenario analysis is a process of analyzing future events based on alternative scenarios with the objective to confirm the consistency between the forecasting assumptions and results. It provides simple and clear descriptions of future events. For calculating TBC, only water quality improvement is considered while the other benefits are ignored; benefits such as (1) protecting human health, and (2) promoting productivity for animals and plants (Downing 1984), appears to be inadequate but will be compensated using multipliers to adjust the overall benefit by water quality improvement. Hence, the scenario analysis assumes that TBC is a multiple number of \( \text{tbc} \) (Equation (5)), which is the basic unit of benefit calculated by only considering the receiving water quality improvement. The 5.56(US$/kg) of BOD\(_5\) reduction benefit is based on the sewage treatment cost in US$ 1.0 m\(^2\) day based on the average cost of four BOT (build–operate–transfer) sewer systems in Taiwan analyzed by using the Cost-Based Method for environmental degradation with benefit transfer method (direct benefit transfer). The calculation of 5.56(US$/kg) is shown between Equations (5) and (6).

The analyses are carried out using the following TBC values:

For scenario \( n_0: \text{TBC} = n_0 \times \text{tbc} (n_0 = 1, 2, 3, 4, 5, 6...; n_0 \text{ is integer}). \)

For other scenario \( n_1, n_2: \text{TBC} = n_1, n_2 \times \text{tbc} (n_1, n_2 \text{ are integers}; n_1 > 1, n_2: 1–9). \)

\[
\Delta Q = Q_1 - Q_2
\]  

(4)

\( \Delta Q \) is reduction of BOD\(_5\) (10\(^3\) kg yr\(^{-1}\)) for the current year. \( Q_1 \) is average stream pollution for the reference year (1993) of base in BOD\(_5\). \( Q_2 \) is average stream pollution for the current year in BOD\(_5\).

\[ \text{tbc(benefit)} = \sum \Delta Q \times 5.56 \]  

(5)

Average BOD\(_5\) reduction benefit (US$ kg\(^{-1}\)) = (1.0 US$) ((Influent BOD\(_5\) of 200 mg l\(^{-1}\))\(^{-1}\) – (Effluent BOD\(_5\) of 20 mg l\(^{-1}\))\(^{-1}\) = 5.56 US$ kg\(^{-1}\).

\[
\text{TBC} = N \times \text{tbc}
\]  

(6)

\( N = 1, 1.1, 1.2, \ldots, 2, \ldots (0.1 \text{ interval}). \)

\[
\text{MBC} = \frac{\partial \text{TBC}}{\partial Q}
\]  

(7)

Correlation between MCC and MBC

When MCC = MBC finds optimal level of control discharge (\( Q^* \)).

\[
R = f(Q)
\]  

(8)

Where: \( R = \) household connection percentage (%); \( Q = \) average stream pollution. And \( Q = Q^*, R = R^* \). Where: \( R^* = \) optimal household connection percentage.

\[
\text{TCC} = F(R)
\]  

(9)
When \( R = R^* \), \( TCC = TCC^* \). Where \( TCC^* \) = economic optimization cost of construction. According to the total procedures by the study, a flow chart is shown in Figure 1.

## RESULTS AND DISCUSSION

### Case study and analyses

The applicability and validity of the method for optimizing the household connection percentage are confirmed using the water quality data of K River that flows directly through Taipei. A 15.3 km stretch of K River between the upstream Bridge N station and the downstream Bridge B station was selected as a closed system for conducting the study. The study catchment is \( 1.94 \times 10^4 \) ha (71.6% of the whole city), (Figure 2). The whole catchment region is surrounded by hills and mountains; separate sewer is provided to residents living in most sub-catchments with residential density \( (\geq 300 \text{ persons/ha}) \). Some sub-catchments that are adjacent to the surrounding hills and mountains have lower residential density \( (<300 \text{ persons/ha}) \) and pollutions, they are served by simple combined sewer.

The benefit of constructing the separate sewer for improving K River water quality between Bridge N station and Bridge B station is evidenced by the river water quality monitoring results published by Taiwan Environmental Protection Administration between 1993 and 2005 (Figure 3). The difference in pollution observed between the water quality monitored at Bridge N station and Bridge B station is assumed to come from the city.

During the initial stage of collection (prior to 2000), the separate sewer was constructed in catchments where the residential density is high and the pollution is serious. Thus, an increasing TCC will show obvious benefit of significantly lowering the river BOD\(_5\). Subsequent construction of the sewer will gradually extend into the less developed and remote sub-catchments with low residential density and pollution potential. Although the newly constructed sewer may continually improve the overall environmental quality, it does not show obvious further improvement of the water quality because the pollution discharge has already passed the optimal level. The construction cost is proportional to the scale of sewer system coverage regardless of decreasing marginal benefit. Hence, once the optimal or the most cost-effective household connection percentage is reached, no more separate sewer should be constructed. The remaining regions not served by the separate sewer will only need to be provided with the less costly simple combined sewer. Determination of this optimal household connection percentage based on cost-effectiveness considerations will be presented in the following sections.

According to the BOD\(_5\) of N station and B station and the average river pollution shown in Figure 4, the trend of average river pollution is lowered from 1993 to 2000 with
the lowest in 2000. After 2002, the decreasing trend of average river pollution becomes less obvious and more stable represents that the system is working in a steady state after 2002.

**TCC, TBC, MCC and MBC curves**

The optimal quantity of pollution discharge is the intersection of MCC and MBC curves while TBC must be greater than TCC. If only the improvement of river water quality is considered, these simplifications cause a much greater TCC than TBC. According to Equations (3) and (6), the slopes of the TCC and TBC curves are obtained and plotted versus the average pollution discharge to yield the MCC and MBC curves (scenario 1). There is a great difference between the theoretical and actual curves, so the optimal environmental quality point can not be found.

The Scenario Analysis Method used in previous sections assumes that the total benefit consists of only the river water quality improvement; but the benefit of promoting human health and productivity for animals and plants should be considered as well. These benefits are assumed to be proportional to the average BOD$_5$ reduction for water quality improvement. Thus in this study, the average BOD$_5$ reduction benefit ($5.56$ US$ kg^{-1}$) will be multiplied by a number, e.g. 1, 1.1, 1.2, 1.3, 1.4 etc. to yield terms designated as 1-benefit, 1.1-benefits, 1.2-benefits, 1.3-benefits or 1.4-benefits etc. Using the multiplier will simplify the estimation but adequately include the benefits concerning human health and biological productivity in the final cost. The screening results shown in Figures 5 and 6 (scenario 6.9 and scenario 10.9) demonstrate that this approach is practical to yield significant results. Although BOD$_5$ reduction is beneficial for improving water quality and promoting human health, but these results should be further analysis.

When TCC is greater than TBC, the intersecting point of MBC curve and MCC curve is not taken as the optimal environmental quality point. The curves shown in Figures 5 and 6 are similar to the theoretical curves. From $8.743 \times 10^6$ kg yr$^{-1}$ (scenario 6.9) to $4.902 \times 10^6$ kg yr$^{-1}$ (scenario 10.9), the optimal level of control discharges for scenario 6.9 and scenario 10.9 can be determined. When the optimal household connection percentage is reached, the TCC will become the optimal TCC.

The relationship between the household connection percentage and the average river pollution can be analyzed using regression analyses. As shown in Figure 7, the range of
optimal household connection percentage is between 57.64% and 65.19% of the separate sewer. From Figures 3 and 4, this percentage is close to the level of household connection percentage in 2002 and 2003 as evidenced by stable BOD5 values and average river pollution quantity. The validity of optimal household connection percentage between 57.64% and 65.19% has implemented from Figures 3 and 4, as the steady state of separate sewer indexed by river pollution control is obvious from 2002 (57%) to the later years.

From the economical point of view, the total cost for constructing a sewer system should include all resources involved, e.g. land, labor and capital. Since the sewer system is buried underground, the cost for acquiring land to construct the system is no longer significant. Thus, only labor and capital costs are included in the construction cost. Additionally, the overall benefit should include human health, reproduction of plants and animals and improvement of landscape. However, these benefits cannot be realistically quantified in engineering and cost-effective terms. With the improvement of river water quality or landscape being the main focus, using the concept of multi-benefit and scenario analysis appears to be a realistic and acceptable approach. Although these benefits could be quantified, but this is also beyond the scope of this study.

CONCLUSIONS

The validity and applicability of the method proposed in this study has been demonstrated with case studies while optimal level of control discharge on analyzing the optimal household connection percentage to assessing economic cost for constructing the separate sewer. For more accurate benefit, other factors such as human health protection, animal and plant production should be quantified and the Scenario Analysis Method is applied for evaluating the total benefit TBC. Once the economic cost of construction is reached, the expensive separate sewer will not be constructed. Instead, the remaining sewer will be switched over to less expensive combined sewer such that the whole system becomes a hybrid sewer system. Results of the analyses show that during the initial stage of separate sewer construction, more connection will greatly reduce the river BOD5 pollution. However, during the later stage, further increase of household connections will work in a steady state to improve the river quality. The river water quality (BOD5) is improved from near “serious pollution” to “moderate pollution” and starts to approach “light pollution” when the optimal household connections is reached. The analysis of other parameters, e.g. precipitation (mm), settlement patterns, rainfall patterns will be considered and ensure the result in the future work. The other similar cities can adopt the method to search the optimal household connection percentage of separate sewer in a hybrid sewer system while the steady state of separate sewer indexed by river pollution to achieve optimal construction approach.

REFERENCES


