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Methods on load estimation for the implementation assessment in the management of total maximum daily loads

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ABSTRACT

The annual amount of water pollution discharge load is utilized to assess its implementation of the load allotment on each unit watershed in the management of total maximum daily loads (TMDLs). The amount of the discharge load might be changed as the rainfall changes in the area with the combined sewer system. In order to evaluate the implementation properly, the effects of rainfall changes should be considered in the estimation of the discharge load. It is necessary to standardize the annual discharge load to be calculated at the same rainfall condition as that of the reference year. But the calculation process is very difficult and might have some limitations. This study investigated and developed two methods in order to estimate the discharge load in a relatively simple way. The load conversion method (LCM) is designed to calculate the differences in discharge due to rainfall changes and to convert the discharge load of the current rainfall condition into that of the reference rainfall condition. The multi-regression equation method (MREM) is to predict the discharge load directly on reference rainfall conditions using a multi-regression equation. These methods were applied to examine the calculation results. LCM showed a more precise result with an error of –0.06%, while MREM –0.18%. Judging from the application results of this study LCM may be useful as a tool for estimating the discharge load for evaluation preferably in the TMDL process.

Keywords: Water pollution discharge load; Unit watershed; Total maximum daily loads; Combined sewer system; Rainfall changes; Load evaluation

1. Introduction

A total maximum daily load (TMDL) is the greatest amount of pollutant loading that a waterbody can receive without violating water quality standards [1]. The objective of a TMDL is to allocate allowable loads among different pollutant sources so that the appropriate control actions can be taken and water quality standards achieved [2]. In Korea, TMDL was introduced as a part of the water pollutant reduction policy [3] and has been in effect since 2004 with a single target material, biological oxygen demand [4]. The annual amount of water pollution discharge load from each unit watershed is compared with its load allotment which is based on the rainfall condition of the reference year in the basic plan of TMDL [5].

Surface runoff during rainy days flows into the sewer pipe in the area with a combined sewer system (CSS). Combined sewer overflow (CSO) water, composed of a mixture of municipal wastewater and urban runoff, is discharged into the natural environment during rainy days in case the interceptor or the transport capacity of the sewer system is insufficient [6–8]. Pollutant's discharge load due to CSO is changeable depending on annual rainfall conditions and will increase as rainfall increases [9].

The annual pollution load in urban runoff is lower than the annual pollution load in sanitary wastewater in areas

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with low precipitation but it is higher in areas with high precipitation [10].

In the area with CSS, the annual amount of the discharge load might be changed as the rainfall changes even though there is no change in the size of water pollution sources. Without considering the rainfall effects on the discharge load in the estimation process, the evaluation for the implementation of the load allotment would not be properly carried out. The most influencing factors on the estimation of the discharge load are the precipitation height and its duration time [11]. It is necessary to standardize the discharge load for evaluation to be calculated at the same rainfall condition as the reference year. But there might be limitations in the calculation process. The objective of this study is to investigate and develop methods that can be used in the estimation of the discharge load for the implementation assessment in the management of TMDLs.

2. Materials and methods

2.1. Rainfall variables relating to discharge load

CSO increases the pollutant discharge during the rainy days in a given area. A combined sewer network is not only a transport system but also a physical and chemical reactor that has the potential to alter the quality of urban waters by its characteristics [12]. It is very difficult to identify and estimate precisely the amount of discharge load, which depends generally on rainfall conditions and the regional characteristics of the drainage area [13]. Technical guidance [14] describes that overflow discharge will occur over the rainfall intensity of 10 mm/d and the discharge load is calculated on the basis of mass transfer in the area with CSS as shown in Fig. 1 [15]. Domestic, industrial and livestock wastewater flows into the sewer pipe on dry days. And stormwater is added on rainy days. Overflow discharge occurs when the sewer influx into the sewer pipe is larger than the sewer transfer flow to sewer treatment plants. Infiltration and exfiltration are assumed to make no difference between dry and rainy days.

Inflow and overflow associated with the sewer pipe are calculated on the monthly basis. Inflow due to surface runoff in a month is calculated by the simple method [Eq. (1)]:

$$\mathrm{IQ} = \frac{c \times \mathrm{Rh} \times A}{\mathrm{Rd}} \tag{1}$$

where c is inflow factor, Rh and Rd are rainfall amount and the number of the rainy days respectively for the month, and A is drainage area. Pollution load from non-point sources flowing into the sewer pipe on a rainy day is calculated by the following equation:

$$\mathrm{IL} = c \times \mathrm{ul} \times \mathrm{mR} \tag{2}$$

where ul is the unit load of land use and mR is the monthly rainfall ratio of a year. Overflow discharge from the sewer pipe is calculated with the ratio of overflow (oR) to total inflow load and the number of rainy days (Rd) by the total days of the month (Md) as in Eq. (3).

$$\mathrm{OL} = \mathrm{TIL} \times \mathrm{oR} \times \frac{\mathrm{Rd}}{\mathrm{Md}} \tag{3}$$

From the judgment of the above equations, the rainfall variables, rainfall amount and the number of rainy days, are directly related to the calculation of the quantity of overflow discharge and these two rainfall variables can be used as factors to developing estimation methods of the discharge load for the implementation assessment.

2.2. Strategies for estimation of the discharge load

The discharge load for evaluation should be calculated in the same rainfall condition as the reference year. In order to make the same condition, the raw rainfall data of the current year should be transformed into the rainfall condition of the reference year. However, the process of data transformation is very difficult and might have some limitations. Alternatively, the same rainfall conditions can be involved in the calculation of the discharge load instead of data transforming.

To calculate the discharge load on the rainfall condition commensurate with that of the reference year in a simple way, structural and non-structural methods were investigated and developed. One, a structural method, is the load conversion method (LCM) to calculate the differences in discharge on rainfall changes and to convert as much as the difference in discharge which is corresponding to rainfall differences. The other, a non-structural method, is the multi-regression equation method (MREM) to use a statistical

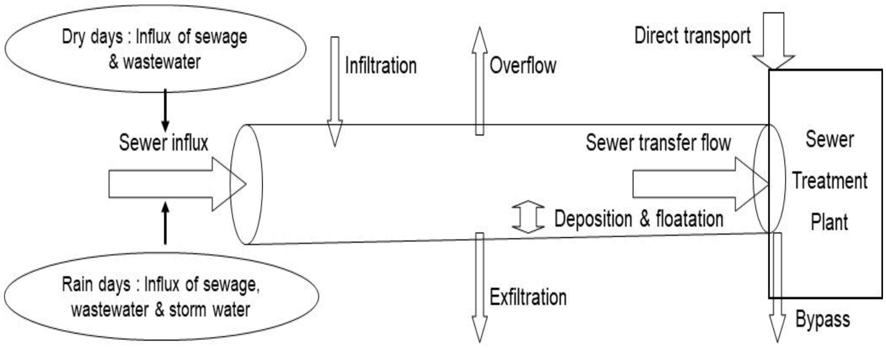

Fig. 1. Mass transfer path in the combined sewer system.

multi-regression equation and to predict the discharge load of reference rainfall.

The 2007 data of Daejeon City were used to identify changes in the discharge load due to changes in rainfall and rainfall days. Based on the number of base rainfall (1561.0 mm) and the number of base rainfall days (49 d), the rainfall was increased by 100 mm and the rainfall by 7 d respectively.

When rainfall increases, daily rainfall increases proportionally, and when rainfall decreases, rainfall decreases proportionally to the daily rainfall for the number of rainfall days exceeding 10 mm/d (the rainfall was fixed at 10 mm/d on a rainfall day less than or equal to 10 mm/d, and the rainfall or its scope was adjusted accordingly).

As the number of rainfall day increases, the number of rainfall day is increased by 20 mm/d or more, divided into scenario stages (the next day of the rainfall day is designated as an increased rainfall day for the most similar situation to the current situation and the rainfall of 20 mm or more is allocated by 1/2 each). When the number of rainfall days decreased, the number of rainfall days per month decreased proportionally.

The types of changes in the discharge load were reviewed for 5 y from 2004 to 2008 for the Daejeon area in order to identify changes in the discharge load, and the data on the source of pollution and the discharge load was used in 2007.

The reason for choosing the baseline scenario is that the error rate is very low and the accuracy is so high that it can be usefully used as a method for calculating the load of the assessment emission.

3. Results and discussions

3.1. Changes of annual discharge load

Discharge load in an urban area is composed of direct discharge from water pollution sources and overflow discharge from combined sewer pipes during the transportation of wastewater to the sewer treatment plant. The changes of annual discharge load were reviewed with regard to rainfall amount in the area with CSS. Fig. 2 shows the annual inflow load flowing into the sewer pipe and the overflow discharge from the pipe between the year 2004 and 2008 in Daejeon Metropolitan City which is one of the largest city located in the central part of Korea with its population of 1,344,881 and drainage area of 210 km^2 [16–20]. By the reference year of 2004, the yearly ratio of inflow load varied from –10.1% to 6.4% and marked an average of 5.8%. On the other hand, the yearly ratio of overflow discharge varied from –20.7% to 29.9% and a marked an average of 19.4%. The figure showed that overflow discharge increases somewhat proportionally when rainfall amount increases by the year. It can be said that the change of overflow discharge was not much related to the size of inflow load and this variation in overflow discharge, much greater than that of inflow load, is mainly due to the amount of annual rainfall.

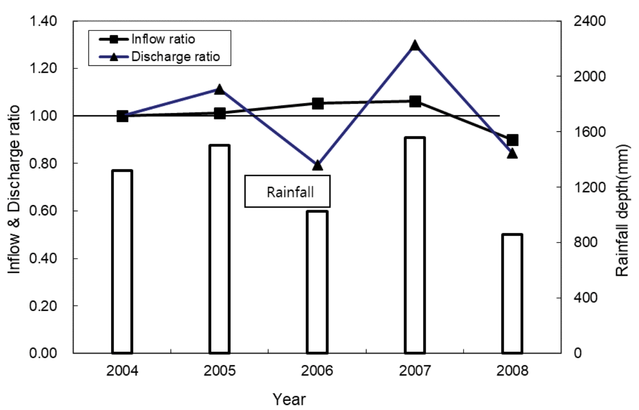

Fig. 2. The annual inflow load and the outflow discharge with regard to rainfall amount (Daejeon Metropolitan City).

3.2. Estimation methods of the discharge load for evaluation

3.2.1. Load conversion method

The estimation process of the discharge load for evaluation by LCM involves several tasks, including constructing a series of rainfall scenario, calculating pollutant discharge loads for all the scenario, drawing a curve for rainfall vs. pollutant discharge and calculating differences in pollutant discharge on different rainfall conditions as shown in Fig. 3.

A series of rainfall scenarios are constructed to fit the graph for rainfall vs. discharge load. The discharge load for each scenario is calculated generally including the rainfall condition of the current year. Five scenarios for rainfall amount and rainfall day changes were constructed respectively and the values of discharge load on each scenario were arranged to draw the curves in the Daejeon Metropolitan City area (Tables 1 and 2). The current rainfall condition for the year 2007 falls on scenario 3. The overflow discharge increases nearly as much as two times the rainfall amount increases in this area and changes oppositely at similar rates as the rainfall day changes.

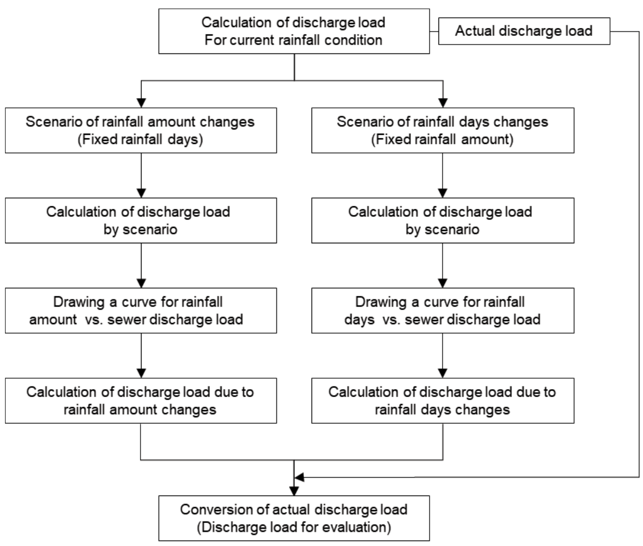

Fig. 3. The procedure for the estimation of discharge load by LCM.

Table 1
Discharge load and its variation on each scenario of rainfall amount changes

Characteristics	Scenario of rainfall amount changes				
	S–1	S–2	S–3	S–4	S–5
Rainfall amount (mm/y)	1,365.2	1,461.0	1,561.0	1,661.0	1,761.0
Rainfall days (d/y)	49	49	49	49	49
Overflow discharge load (kg/d)	956.7	1,103.3	1,255.4	1,407.5	1,559.6
Variation of rainfall amount (%)	–12.5	–6.4	0.0	6.4	12.8
Variation of overflow discharge load (%)	–23.8	–12.1	0.0	12.1	24.2

Table 2
Discharge load and its variation on each scenario of rainfall day changes

Characteristics	Scenario of rainfall day changes				
	S–1	S–2	S–3	S–4	S–5
Rainfall days (d/y)	35	42	49	56	63
Rainfall amount (mm/y)	1,561.0	1,561.0	1,561.0	1,561.0	1,561.0
Overflow discharge load (kg/d)	1,592.2	1,423.8	1,255.4	1,087.0	938.9
Variation of rainfall days (%)	–28.6	–14.3	0.0	14.3	28.6
Variation of overflow discharge load (%)	26.8	13.4	0.0	–13.4	–25.2

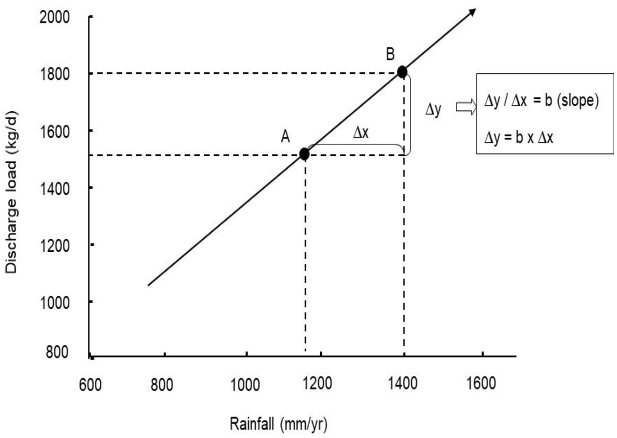

Fig. 4. The difference in pollutant discharge on different rainfall conditions.

An analytical graph for the rainfall amount vs. overflow discharge load from combined sewer pipes is shown in Fig. 4. The figure provides how to get a difference in pollutant discharge on different rainfall conditions. When point *A* is the pollutant discharge on the rainfall condition of the current year and *B* of the reference year, Δy is the difference in pollutant discharge due to the rainfall changes between 2 y. Slope "*b*" can be obtained from a graph for the rainfall amount vs. pollutant discharge and another slope "*b*" from another graph for the rainfall days vs. pollutant discharge. The difference in pollutant discharge Δy for the difference in rainfall amount and $\Delta y'$ for the difference in rainfall days can be calculated by the following equations:

$$\Delta y = b \times \Delta x = b\left(R_0 - R_1\right) \quad (4)$$

$$\Delta y' = b' \times \Delta x' = b'\left(R_0' - R_1'\right) \quad (5)$$

where Δx is the difference between the rainfall amount of the reference year (R_0) and of the current year (R_1), and $\Delta x'$ is the difference between the rainfall days of the reference year (R_0') and of the current year (R_1'). Discharge load for evaluation (L_0) which is considered to be discharge load on the equal rainfall condition to the reference year can be calculated by converting the actual discharge load of the current year (L_1) as in Eq. (6).

$$L_0 = L_1 \pm \Delta y \pm \Delta y' \quad (6)$$

3.2.2. Multi-regression equation method

The procedure for the calculation of the discharge load for evaluation by MREM is shown in Fig. 5. This method requires the formation of a multi-regression equation. One independent variable of pollutant discharge load and two dependent variables of rainfall amount and rainfall days applied to form a multi-regression equation on the basis of the current year. The equation is, then, applied to predict pollutant discharge load for the same rainfall condition as the reference year.

The equation is formed to determine its coefficients *a*, b_1 and b_2, on the basis of current year rainfall condition as in the following equation:

$$Y = a + b_1 X_1 + b_2 X_2 \quad (7)$$

where Y is pollutant discharge, X_1 rainfall amount and X_2 rainfall days of the current year. The prediction of the discharge load for the reference year (Y_0) can be conducted by applying its rainfall data (X_{10} and X_{20}) using Eq. (8).

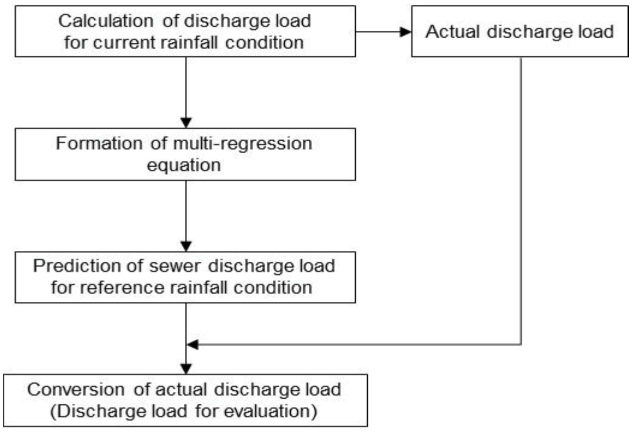

Fig. 5. The procedure for the calculation of discharge load by MREM.

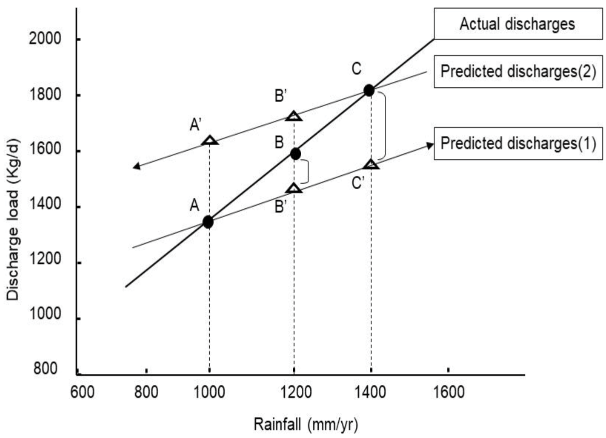

Fig. 6. Differences between the predicted and actual discharge load.

$$Y_0 = a + b_1X_{10} + b_2X_{20} \tag{8}$$

This prediction technique, however, involves the fundamental deficit and makes some differences between the predicted and actual discharge load. The differences were shown in Fig. 6. Predicted discharges by MREM will appear like *A*′, *B*′ and *C*′ when the actual discharges are *A*, *B* and *C*. The prediction results upward for larger rainfall conditions are likely to appear less than the actual values as in the predicted discharges (1). On the contrary, the prediction results downward for smaller rainfall conditions are inclined to appear more than the actual values as in the predicted discharges (2).

The differences are supposed to occur because the coefficients of the equation have not fitted for the rainfall condition of the reference year but for that of the current year. The differences might be somewhat corrected by analyzing the relationship between rainfall and load prediction. The more the rainfall increases, the more the load prediction ratio decreases under the condition that the rainfall amount is greater than the current condition, and the more the rainfall decreases, the more the load prediction ratio increases under the condition that the rainfall amount is smaller than the current condition (Fig. 7a). A power function curve can be obtained by converting the load prediction ratio into the load correction ratio (Fig. 7b) and used for the correction of the differences in the predicted values.

The corrected discharge load (Yo′) can be calculated by using the predicted discharge load (Yo) and the power function (pf) as in Eq. (9). This correction process by power function needs additional calculations. MREM might, then, be more complicated than LCM. It may remain somewhat deficits of MREM, thus this process would not be preferable in the calculation of discharge load for evaluation.

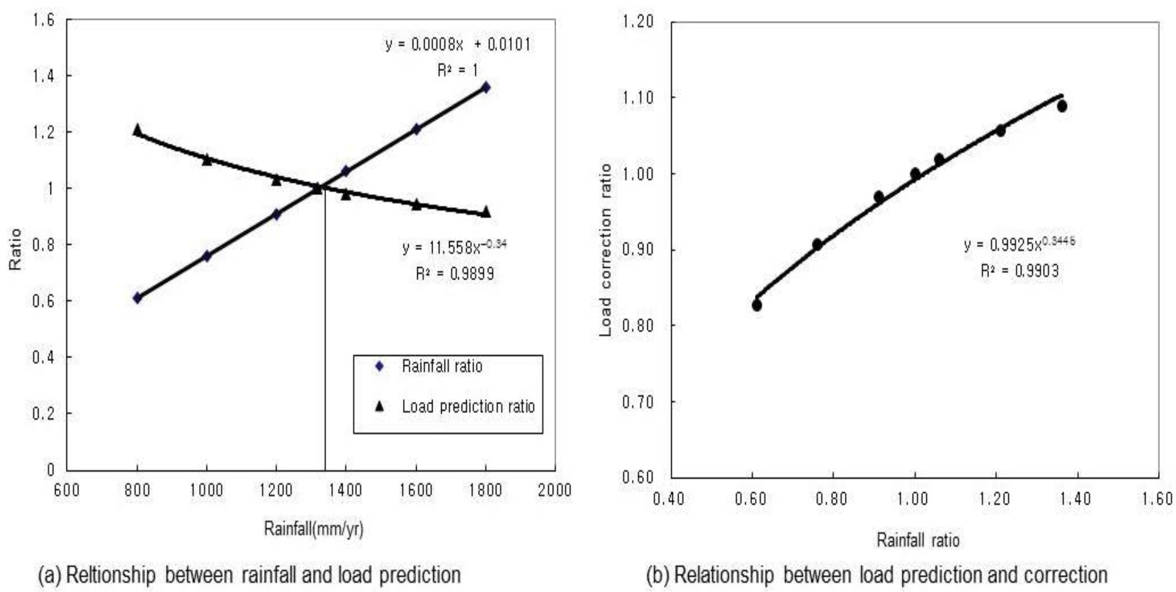

Fig. 7. A power function curve is derived from the relationship between rainfall and load prediction.

Table 3
Application results of calculating discharge load by LCM and MREM

	Discharge load (kg/d)	Difference (kg/d)	Error (%)
Reference	24,579.4	–	–
LCM	24,564.6	–14.8	–0.06
MREM	24,536.2	–43.2	–0.18

$$\text{Yo}' = \text{Yo} \times \text{pf} = \text{Yo} \times a\left(\frac{R_0}{R_1}\right)^b \tag{9}$$

3.3. Application results of the methods

The methods, LCM and MREM, developed in this study were applied to calculate discharge load for evaluation and to examine its applicability in the Daejeon Metropolitan City area. A reference discharge load which could be a criterion for the comparison of application results was calculated following the conventional method through transforming of rainfall data. Table 3 shows the application results of LCM and MREM. The discharge load was calculated by LCM at the amount of 24,564.6 kg/d with its error of –0.06%. LCM showed quite good accuracy in the estimation of the discharge load for evaluation. The discharge load was calculated by MREM at the amount of 24,536.2 kg/d with its error of –0.18%. MREM with its original deficits showed a considerable error and three times more difference than LCM in the prediction of discharge load in spite of its simplicity. The results suggest that LCM can be applied as a means of calculating the discharge load for evaluation.

4. Conclusions

Rainfall changes can affect the amount of water pollution discharge load in an area with CSS. In order to evaluate annual discharge load over its allotment, the effects of rainfall changes should be considered. This study investigated and developed two methods, LCM and MREM, to estimate the discharge load for evaluation with the consideration of the rainfall effects.

LCM, a structural method, is to calculate the differences in discharge on rainfall changes and to convert the discharge load of current rainfall condition into that of reference rainfall condition. MREM, a non-structural method, is to predict the discharge load of reference rainfall conditions using a multi-regression equation. The discharge loads for evaluation were calculated by two methods and the calculation results were examined. LCM made a more precise result and less error than MREM which involves original deficits in its formula. The results suggest that LCM can be used to the estimation of the discharge load for evaluation preferably, and expected to assess the annual discharge load more reasonably and objectively in the TMDL process.

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