Waste load allocation for water quality management of a heavily polluted river using linear programming

J.H. Cho*, K.H. Ahn, W.J. Chung*** and E.M. Gwon*****

* Department of Environmental Engineering, Kwandong University, Yangyang-Up, Yangyang-Gun, Gangwon-Do 215-800, Korea (E-mail: *jhcho@kwandong.ac.kr*)

** Future Technology Research Division, Korea Institute of Science and Technology, 39-1, Hawolkok-dong, Songbuk-ku, Seoul 136-791, Korea (E-mail: *khahn@kist.re.kr*)

*** Department of Environmental Engineering and Biotechnology, Myongji University, San 38-2, Namdong, Yongin, Kyunggi-Do 449-728, Korea (E-mail: *wookjin@myongji.ac.kr; emgwon@myongji.ac.kr*)

Water Science and Technology **Vol 48 No 10 pp 185–190** © IWA Publishing 2003

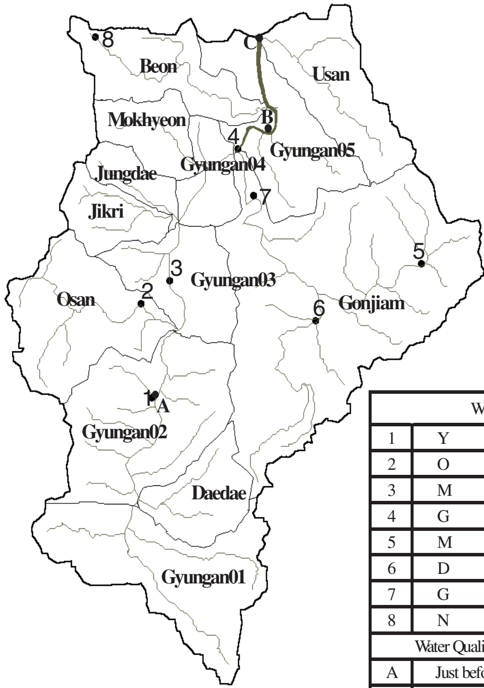
Abstract A waste load allocation model using linear programming has been developed for economic water quality management. A modified Qual2e model was used for water quality calculations and transfer coefficients were derived from the calculated water quality. This allocation model was applied to the heavily polluted Gyungan River, located in South Korea. For water quality management of the river, two scenarios were proposed. Scenario 1 proposed to minimise the total waste load reduction in the river basin. Scenario 2 proposed to minimise waste load reduction considering regional equity. Waste loads, which have to be reduced at each sub-basin and WWTP, were determined to meet the water quality goal of the river. Application results of the allocation model indicate that advanced treatment is required for most of the existing WWTPs in the river basin and construction of new WWTPs and capacity expansion of existing plants are necessary. Distribution characteristics of pollution sources and pollutant loads in the river basin was analysed using Arc/View GIS.

Keywords GIS; Gyungan River; linear programming; waste load allocation model; water quality goal

Introduction

The heavily concentrated population in the capital region of South Korea causes problems. Lake Paldang is a key source of the public water supply for the capital region. Gyungan River has a significant effect upon the water quality of Lake Paldang. The schematic diagram of the Gyungan River Basin is presented in Figure 1 and the total area of the river basin is 558 km^2. Rapid housing and development in the large area of the river basin results in rapid population growth, which contributes to substantial heavy pollutant loads. Although eight wastewater treatment plants are currently operating in the river basin, the wastewater treatment capacities of the plants are insufficient. Annual mean water qualities of the year 2000 at the Gyungan Bridge in the middle part of the Gyungan River were BOD 8.6 mg/L, TN 12.75 mg/L, and TP 0.678 mg/L. High levels of nutrients in the river cause eutrophication in Lake Paldang. Therefore, waste load reduction is required for comprehensive water quality management. However, it is necessary to consider the regional equity due to the fact that two cities (Yongin and Gwangju City) are located in the river basin.

Water quality parameters considered in this allocation were BOD, TN and TP. To achieve the water quality goal of 1 mg/L BOD (1st level of river water quality standard in Korea), which is the original water quality goal established by The Ministry of Environment (1999), is impossible in actuality. Therefore, the water quality goal of BOD was adjusted to 3 mg/L (2nd level of river water quality standard in Korea) in this study. Because water quality goals of TN and TP for Gyungan River were not predetermined by The Ministry of Environment, they were established in this study as the concentration that



WWTP		
1	Y	ongin
2	O	po
3	M	aesan
4	G	wangju
5	M	ansun
6	D	ochuk
7	G	onjiam
8	N	amhan
Water Quality Check point		
A	Just before Yongin WWTP	
B	Seoha ridge B	
C	Gwangdong Bridge	

Figure 1 Gyungan River Basin

is judged to cause eutrophication in retarded streams of Korea (Kim, 1997). Water quality goals of TN and TP in this study were 2.9 mg/L and 0.1 mg/L, respectively.

Waste load allocation model

Linear programming (Arbabi and Elzinga, 1975), nonlinear programming (Fujiwara, 1990), dynamic programming (Klemetson and Grenny, 1985) and integer programming (Bishop and Grenny, 1976; Burn, 1989) have been used to solve waste load allocation problems in some river basins. In this study, linear programming was used to allocate the BOD, TN and TP load in the Gyungan River Basin. The effect of the waste load reduction in each sub-basin upon the water quality checkpoints of the mainstream was estimated as a transfer coefficient (Bishop and Grenny, 1976; Burn, 1989). Constraints of the optimisation problem were constituted to achieve the water quality goal of the checkpoints using transfer coefficients. The objective function focused on minimising the total waste load reduction of the river basin. This optimisation problem was solved using the revised simplex algorithm of IMSL.

$$\text{Minimise} \quad \sum_{i=1}^{m} X_i$$

$$\text{Subject to} \quad \sum_{i=1}^{l} T_{ij} X_i \geq \Delta c_j \qquad j = 1, 2, 3, 4, [...], n$$

where $0 \leq X_i \leq V_i \qquad i = 1, 2, \ldots, m$

m = No. of sub-basins and wastewater treatment areas
n = No. of water quality check points
X_i = Waste load reduction at each sub-basin and wastewater treatment area, kg/d
T_{ij} = Transfer coefficient, (mg/L)/(kg/d)

Δc_j = Difference of water quality goal and calculated water quality at check point j, mg/L
U_i = Maximum waste load reduction at each sub-basin and wastewater treatment area, kg/d

Application of waste load allocation model

Pollutant load estimation and water quality model

Gyungan River Basin was divided into 39 drainage areas by Arc/View spatial analyst. These 39 drainage areas were merged into 13 sub-basins, which are divided by The Ministry of Environment, Korea. A 100 m × 100 m grid-based database was made from the unit load and the information of the pollution source using Arc/View GIS. Pollutant loads from point and diffuse sources were estimated by the grid-based database. From nine water quality survey results of Gyungan River Basin, annual mean DRs (Delivery Ratios) were estimated for tributaries of the river (Novotny and Olem, 1994). The DRs of urban areas were larger than rural areas.

For the water quality calculation of the waste load allocation model, Qual2e model (Brown and Barnwell, 1987) was used. We modified the Qual2e model to consider the BOD increase caused by algae. The modified Qual2e model was applied to the 34.5 km section of the Gyungan River; 37 point sources and incremental inflows were considered in the model. Depth–discharge equations and velocity–discharge equations were used for the hydraulic calculation. The model was calibrated using data sets observed in April 2001 and a complementary water quality data set observed by The Ministry of Environment for 6 years (Oct. 1996–2001). Verification was done with data sets observed in July 2001 and the 6 years of data from The Ministry of Environment.

Scenarios for waste load allocation

Two scenarios were proposed for water quality management of the Gyungan River, in which eight existing WWTPs (Wastewater Treatment Plants) are operated with secondary treatment.

Scenario 1: Advanced treatment by coagulation, rapid sand filtration and activated carbon adsorption was considered in addition to the existing secondary treatment. Maximum waste load reduction at each wastewater treatment area was determined by the combined processes (existing secondary treatment + coagulation + rapid sand filtration + activated carbon adsorption). At least secondary treatment is done at all plants. Activated sludge treatment was assumed for the untreated area, in which population density is relatively high. Storage facility was assumed for the waste load reduction of the area where the portion of the nonpoint pollutant load was high.

Scenario 2: Advanced treatment could be done as mentioned in Scenario 1, but regional equity was considered for this scenario. Constraint equations were constituted on condition that effluent water qualities of all WWTPs are to be equal.

Treatment efficiencies (Metcalf and Eddy, 1991; EPA, 1997) of each treatment process were used for calculating the maximum waste load reduction at each WWTP. Checkpoints of the water quality goal were just before the Yongin WWTP, Seoha Bridge and Gwangdong Bridge as shown in Figure 1.

Results and discussion

Waste load allocation was completed for 12 sub-basins excluding Usancheon sub-basin. Allocation has also been completed for eight wastewater treatment areas, in which existing WWTPs are in operation and are included in the sub-basins. Table 1 shows the reduction rates of emitted pollutants loads calculated for the 12 sub-basins and the 8 WWTPs. Reduction rates of WWTPs are those of additional treatment caused by advanced treatment. Final effluent water qualities of WWTPs are also shown in parentheses.

Table 1 Calculated waste load reduction rate in the Gyungan River Basin

Sub-basins and wastewater treatment areas	BOD (%)		TN (%)		TP (%)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Gyungan 01	–	–	20.6	–	72.1	67.7
Daedae	–	–	56.0	–	–	–
Gyungan 02	1.4	1.4	16.4	4.4	10.4	13.0
Osan	–	–	56.0	–	–	–
Gyungan 03	10.6	10.6	27.6	20.9	6.4	6.4
Jungdae	–	–	56.0	–	–	–
Jikri	–	–	56.0	–	–	–
Gyungan 04	–	–	56.0	–	–	–
Mokhyeon	–	–	56.0	–	–	–
Gonjiam	–	–	6.9	–	–	–
Gyungan 05	–	–	18.1	–	–	–
Beon	–	–	–	–	–	–
Yongin WWTP	39.6 (13.9)	67.5 (7.5)	65.4 (13.9)	79.7 (8.1)	80.3(0.550)	88.3 (0.329)
Opo WWTP	–	–	55.4 (8.2)	43.9 (8.1)	–	64.5 (0.329)
Maesan WWTP	84.0 (1.1)	–	55.3 (7.1)	48.8 (8.1)	89.5(0.040)	9.1 (0.329)
Gwangju WWTP	84.0 (1.4)	16.9 (7.5)	55.4 (6.6)	45.0 (8.1)	89.6(0.091)	62.2 (0.329)
Mansun WWTP	77.0 (2.8)	30.9 (7.5)	50.6 (5.4)	23.2 (8.1)	81.3(0.359)	76.0 (0.329)
Dochuk WWTP	–	–	–	25.4 (8.1)	–	67.7 (0.329)
Gonjiam WWTP	83.9 (1.2)	–	55.3 (8.2)	55.8 (8.1)	89.5(0.146)	76.3 (0.329)
Namhan WWTP	–	10.4 (7.5)	–	–	–	79.3 (0.329)

* Calculated effluent water qualities of each WWTP are shown in parentheses

In Scenario 1, advanced treatment is necessary for Yongin, Maesan, Gwangju, Mansun and Gonjiam WWTPs to achieve the water quality goal of 3 mg/L BOD. It is sufficient for Opo, Dochuk and Namhan WWTPs to operate under their present treatment methods. In Scenario 2, higher advanced treatment is required for the Yongin WWTP, whose treatment capacity is much larger than other plants. For Opo, Maesan, Dochuk and Gonjiam WWTPs, it is sufficient to operate under their present treatment methods. In Scenario 1, 13.2% of total emitted BOD load in Gyungan River Basin has to be reduced, and in Scenario 2, 14% of total emitted BOD load must be reduced.

About 45% of the total emitted TN load in the Gyungan River Basin has to be reduced to achieve the water quality goal of 2.9 mg/L TN in Scenario 1. In treated areas, most of the WWTPs including Yongin WWTP have to upgrade with advanced treatment facilities. In untreated areas, where WWTPs are not constructed, untreated domestic and livestock wastewater must be treated as shown in Table 1. In Scenario 2, all WWTPs excluding Namhan WWTP have to lower the effluent TN concentration to 8.1 mg/L. 40.3% of the total emitted TN load in the river basin has to be reduced in Scenario 2. The total reduction rate of Scenario 2 is less than that of Scenario 1. This is caused by the fact that increase of the reduction load at the Yongin WWTP is less than the decrease of the reduction load at other WWTPs and untreated areas. However, it is difficult to meet the effluent TN concentration of 8.1 mg/L at the Yongin WWTP because influent TN concentration of the Yongin WWTP is very high (90.9 mg/L). In order to meet the effluent quality level of 8.1 mg/L, additional treatment in addition to the aforementioned physical advanced treatment is necessary at the Yongin WWTP.

The result of TP allocation shows that about 42% of the total emitted TP load in the Gyungan River Basin has to be reduced to achieve the water quality goal of 0.1 mg/L TP under Scenario 1. In Scenario 1, advanced treatment is necessary for Yongin, Maesan, Gwangju, Mansun and Gonjiam WWTPs to achieve the water quality goal of 0.1 mg/L TP. In untreated areas like Gyungan 01 sub-basin, where WWTPs are not constructed, domestic

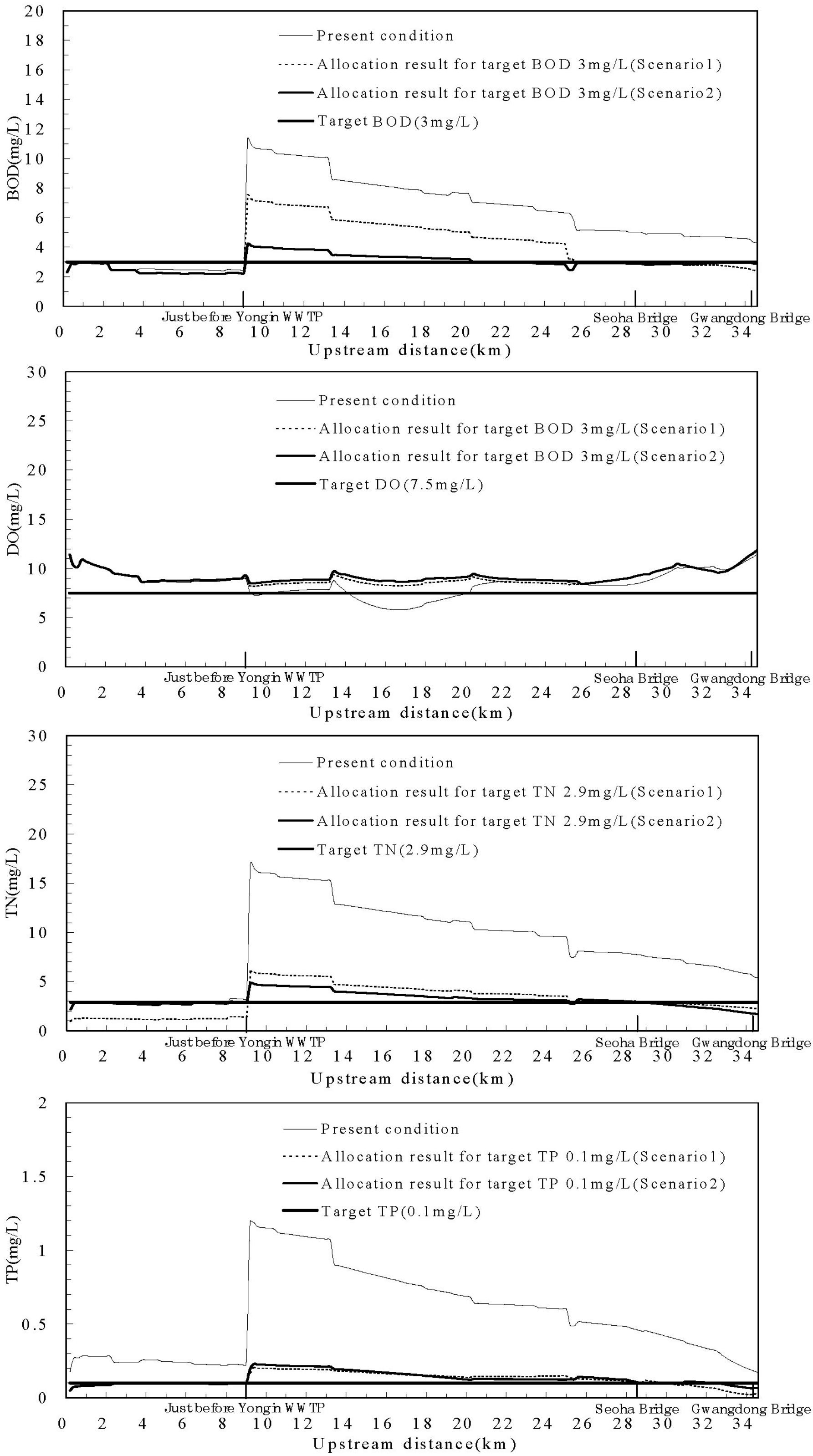


Figure 2 Water quality distribution calculated by waste load allocation

wastewater must be treated. In Scenario 2, effluent TP concentrations of all plants in the river basin must be lowered to 0.33 mg/L. Therefore, advanced treatment is necessary for all plants in the river basin. About 43% of the total emitted TP load in the river basin has to be reduced in Scenario 2.

Water quality distribution calculated by the result of waste load allocation is shown in Figure 2. We can identify the fact that water qualities of the three checkpoints (just before Yongin WWTP, Seoha Bridge, Gwangdong Bridge) are to be satisfied with the water quality goals of BOD, TN and TP. The river water quality seriously worsens after joining the effluent of the Yongin WWTP, but becomes gradually better as it flows to the lower part of the river because of dilution and self-purification.

Conclusions

To achieve the water quality goal of the Gyungan River, advanced treatment is necessary for most of the WWTPs in the river basin. Particularly, advanced treatment is required for the Yongin WWTP whose effect upon the river quality is substantial. In presently untreated areas, domestic wastewater of Gyungan 01 sub-basin and livestock wastewater of Gyungan 02 sub-basin have to be treated through the construction of new WWTPs and capacity expansion of the existing WWTPs. Under Scenario 2, in which regional equity is considered, more treatment costs are necessary than under scenario 1 because a lot of waste load reduction has to be done at the Yongin WWTP whose treatment capacity is larger.

References

Arbabi, M. and Elzinga, J. (1975). A general linear approach to stream water quality modelling. *Water Resources Research*, **11**(2), 191–196.

Bishop, A.B. and Grenny, W.J. (1976). Coupled optimization-simulation water quality model. *Journal of the Environmental Engineering Division, ASCE*, **102**(5), 1071–1086.

Brown, L.C. and Barnwell, T.O. Jr. (1987). *The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: Documentation and user manual*. Environmental Research Laboratory, Office of Research and Development, U.S. EPA/600/3-87/007.

Burn, D.H. (1989). Water-quality management through combined simulation-optimization approach. *Journal of Environmental Engineering, ASCE*, **115**(5), 1011–1024.

EPA (1997). *Technical guidance manual for developing Total Maximum Daily Loads, Book 2: Streams and rivers, Part 1: Biochemical oxygen demand/Dissolved oxygen and nutrients/ Eutrophication*. U.S. EPA 823-B-97-002.

Fujiwara, O. (1990). Preliminary optimal design model for wastewater treatment plant. *Journal of Environmental Engineering, ASCE*, **116**(1), 206–210.

Kim, S.W. (1997). *Total Load regulation for particular river basin*. Korea Environment Institute.

Klemetson, S.L. and Grenny, W.J. (1985). Dynamic optimization of regional wastewater treatment systems. *Journal WPCF*, **57**(2), 128–134.

Metcalf and Eddy (1991). *Wastewater Engineering: Treatment, Disposal, and Reuse*. 3rd edn, McGraw-Hill, New York, USA.

Ministry of Environment (1999). *Environmental statistics yearbook*. Republic of Korea.

Novotny, V. and Olem, H. (1994). *Water Quality: Prevention, Identification, and Management of Diffuse Pollution*. Van Nostrand Reinhold, New York, USA.