

# Water Quality Modeling for Integrated Management of Urban Stream Networks

Yoon Jeong Yeon, Dong Hee Kim, and Jung Lyul Lee

**Abstract**—This study presents a water quality Management program for Urban River Networks (WAQUMURIN). The model analyzes a variety of water quality problems in urban stream networks linked by ponds, lakes, and reservoirs, which are subdivided into unit reach cells. A mass balance is performed in each cell for the nonconservative contaminants loaded from point and nonpoint sources on land. The model was designed by GUI to provide a practical program for management purposes. To test the performance of the model, it was applied to the Han River network in the city of Seoul, Korea, which has eight stream branches. The test was conducted for BOD load and compared with measured data.

**Index Terms**—Cascade model, BOD, GUI, Seoul.

## I. INTRODUCTION

Many different types of water quality models are available nowadays; however, it is not easy to select an appropriate model that consistently achieves maximum simplicity with the required degree of accuracy and detail. The decision for which model to use should be made carefully to avoid over complication of the model by eliminating physical, chemical, or biological relationships that do not significantly affect the simulation objectives.

Many water quality models currently exist, such as QUALs, CE-QUAL-W2, MIKE 11, SWAT, WASP, HSPF, ELCOM-CAEDYM, and EFDC [1], [2]. Most of these models involve the use of numerical methods for solving partial differential equations describing mass conservation and hydrodynamic motions for computing unsteady flow, discharge, and water level in streams. In a few special cases, it is possible to solve the equations analytically.

Of the existing models, QUAL2E and QUAL2K have been widely used in water quality prediction and pollution management. The US Environmental Protection Agency released a series of QUAL models such as QUAL2E, QUAL2EUNCAS, QUAL2K, and QUAL2Kw. These models allow for the simulation of up to 15 parameters associated with water quality, in any combination chosen by the user (DO, BOD, temperature, algae as chlorophyll a, organic nitrogen as N, ammonia as N, nitrite as N, nitrate as N, organic phosphorus as P, dissolved phosphorus as P, coliform bacteria, one arbitrary nonconservative constituent solute, and three conservative constituent solutes).

Even for one-dimensional, steady-state models, both

advective and dispersive modes of transport are considered in mass balance, which can be expressed as

$$V = \frac{\partial c}{\partial t} = -\frac{\partial \left( \frac{A_c E \partial c}{\partial x} \right)}{\partial x} dx - \frac{\partial ((A_c U))}{\partial x} dx + V \frac{dc}{dt} + s \quad (1)$$

where  $V$  is the volume,  $c$  is the concentration of the constituent,  $A_c$  is the element's cross-sectional area,  $E$  is the longitudinal dispersion coefficient,  $x$  is the distance (in the direction of flow from the load point),  $U$  is the average velocity, and  $s$  is the external sources (positive) or sinks (negative) of the constituent [1].

In this study, we present a water quality model, WAQUMURIN for the purpose of urban wastewater management. It was developed using a MATLAB GUI and designed to identify how urban pollution affects water quality in a semi-steady state and to predict pollution transport and fate in complicated urban stream systems.

With a goal of use in practical management, the present model includes BOD and DO dynamics; nutrients and eutrophication; and bacterial, organic chemical, and heavy metal contamination. The model was run for predicted BOD levels in the Han River basin of Seoul, Korea, as a case study and the results were compared with measured data.

## II. MODEL DESCRIPTION

The model was designed to have two functions for managing water quality in complicated urban river networks: one was to estimate the water quality and the other was to manage the maximum amount of waste load, such as from combined sewer overflows. The model begins on the main menu page, as shown in Fig. 1, where the mesh formulation of cell size, cell property, flow input, flow confirmation, waste load, and water quality calculations are determined.

### A. Mesh Cell Formulation

The model uses an  $n \times n$  mesh cell system in which cells are linked by a combination of rivers, lakes, and estuaries from upstream to downstream. Unlike the finite difference approach, a cell is not divided by a uniform length size but rather is assigned a length size based on one or a combination of the following: uniform hydraulic characteristics, location of point sources, zone of lateral nonpoint sources, monitoring position, or zone of interest. The cell properties are defined in advance for the simulation.

Fig. 2 is an example of a long lake in a stream with the converging lake upstream and diverging lake downstream. The lake is divided into three yellow colored cells in this

Manuscript received December 18, 2015; revised April 21, 2016. This work was supported by Graduate School of Water Resources, Sungkyunkwan University.

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example. River, lake, estuary, and land cells are cyan, yellow, green, and brown colored, respectively.

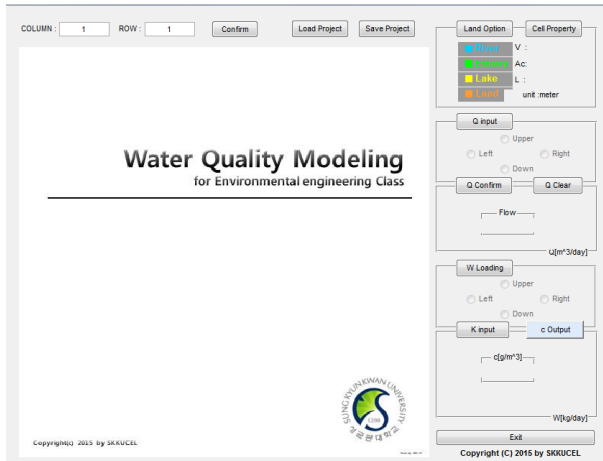


Fig. 1. Model program layout.

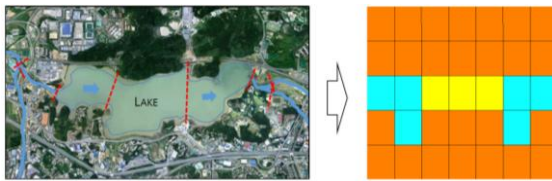


Fig. 2. Mass balance of unit mesh for a lake.

Once the grid structure is formulated, a preprocessing of each cell is required because water quality or waste loading can be obtained based on flow information and the volume of the lake cell or length and cross-sectional area of the river cell. The pre-process is shown in detail in Fig. 3.

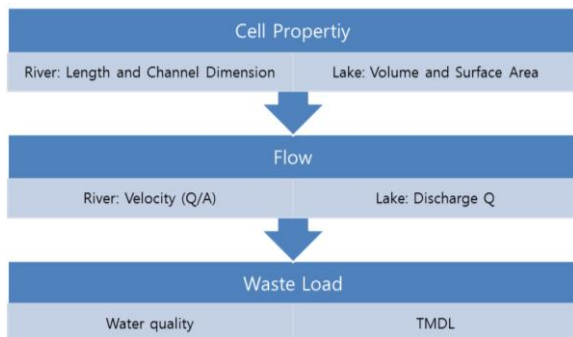


Fig. 3. Model pre-process.

### B. Flow Input and Confirmation

Water quality is normally determined according to flow conditions even though the same waste load is given. The present model was operated under the assumption of a steady state, thus uniform discharge was assigned to each mesh from the most upstream cell. However, in a cell where rivers converge, the upstream discharge of each branch was used to determine the downstream flow after convergence. Similarly, in a cell where a river diverges, a division ratio was used. Both of these scenarios are informed by a pop-up window as shown in Fig. 4. The flow confirmation was done by systematically moving downstream cell by cell from the most upstream cell as shown in Fig. 5.

### C. Water Quality Estimation in Lake

Using the assumptions for a well-mixed reactor, the concentration in a lake cell was estimated as

$$C_{out} = \frac{(C_{in}Q + W_p + W_N)}{Q + kV} \quad (2)$$

where  $C_{in}$  is the concentration at the lake entrance,  $C_{out}$  is the concentration at the lake outlet,  $W_p$  and  $W_N$  are the waste loads of point and nonpoint sources respectively,  $Q$  is the flow discharge,  $k$  is the reaction factor, and  $V$  is the lake volume. The theoretical locations of,  $C_{in}$ ,  $C_{out}$ ,  $W_p$ ,  $W_N$ , and  $V$  are shown in Fig. 6.

### D. Water Quality Estimation for a River Point Source

Factories and sewage treatment plants are two common types of point source.

$$C_{out} = C_{in} \exp\left(-\frac{kL}{u}\right) \quad (3)$$

where  $C_{in}$  is the concentration at the upstream reach end,  $C_{out}$  is the concentration at the downstream reach end,  $L$  is the length of the unit reach,  $u$  is the mean velocity, and  $k$  is the reaction factor.

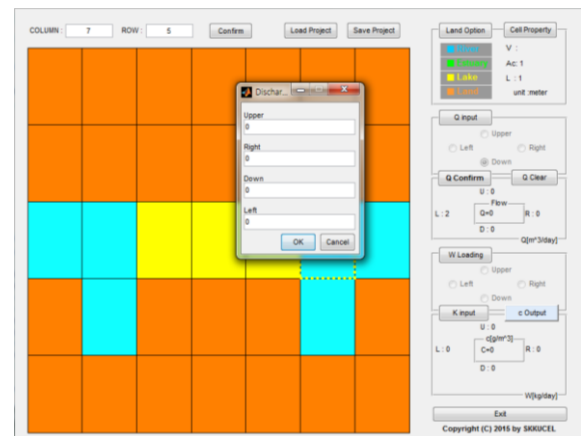


Fig. 4. Pop-up window showing the flow process.

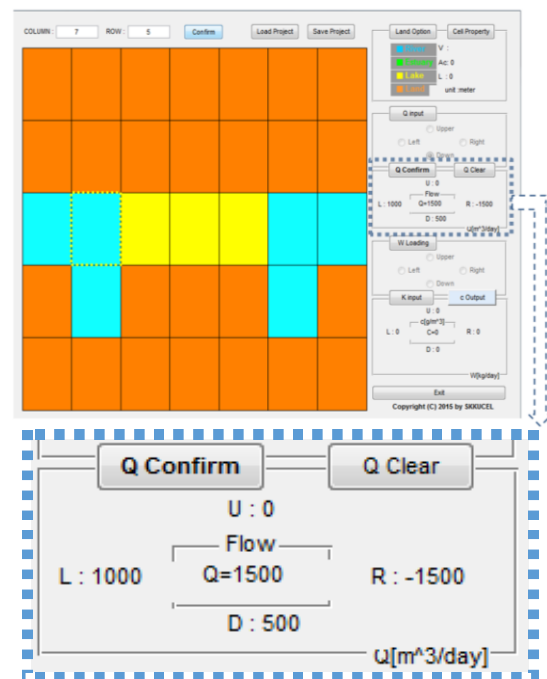


Fig. 5. Flow confirmation for converging channel (positive: inflow; negative: outflow).



the main Han River) and a flow of 11,733,461 m<sup>3</sup>/day outflows to the Gayang Bridge (the most downstream cell). Therefore, a flow of 328,529 m<sup>3</sup>/day is added from the Seoul basin to the Han River.

### C. Waste Load Input

The long-term average concentration of BOD has shown a consistent decreasing trend for 37 years. However, BOD shows an increasing trend along the main stream of the Han River as it flows downstream, whereas the BOD influx from Paldang Dam has maintained a decreasing trend because the nonbiodegradable materials in the Paldang Dam area are controlled [3]. BOD concentration from the Paldang Dam was 1.2 mg/L in 2012 [4].

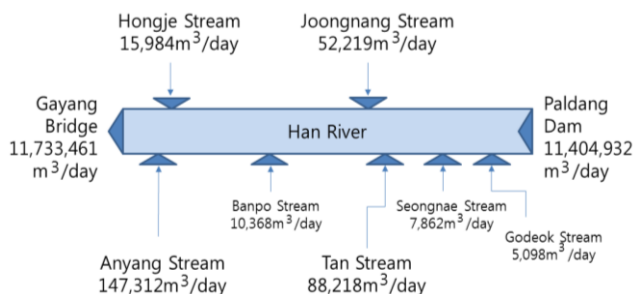


Fig. 10. Flow conditions in the Han River for Q<sub>355</sub> flow.

Pollution load is estimated in three steps: generation, discharge, and inflow into the stream, and each step is accomplished using numerous data sources, such as population census data, land use status, quantity and quality data for industrial and livestock wastewater, wastewater discharge inventory for each industry, ratio of collection to treatment, and status of wastewater treatment systems.

The generated BOD load was estimated as 764,642 kg/day, with each person generating approximately 76 g/person/day in 2013. The discharged BOD load was estimated as 84,880.32 kg/day, and point and nonpoint source loads in the Seoul basin were estimated to be 40,365.59 kg/day and 44,514.73 kg/day, respectively, in 2013. Seoul uses mainly combined sewer systems (96.38%), but separated sewer systems (3.60%) have also been adopted. In addition, a small amount of wastewater remains untreated (0.02%). The distribution of pollution load in Seoul is listed in Table I.

TABLE I: POLLUTION LOAD (KG/DAY) DISTRIBUTION IN SEOUL [5]

Pattern	Generated Load	Discharged Load	
		Point Source	Nonpoint Source
Household	689,252	23,445	16,400
Livestock	196	0	18
Industry	46,003	458	16
Land	29,168	16,463	28,081
Landfill	24	0	1
Total BOD load	764,643	40,366	44,515

Current wastewater facilities in Seoul have a total daily capacity of 5.81 million tons. Sewage treatment areas have been divided into four based on a facility's location as shown in Fig. 8. The Joongnang and Nanji WWTPs are located in the east and west sides of the northern zone of the Han River respectively. The Tancheon and Seonam WWTPs are located in the east and west sides of the southern zone respectively. In

2012, the Joongnang WWTP discharged a BOD load of 1,344,338 m<sup>3</sup>/day with 7.2 mg/L of BOD after treatment, the Nanji WWTP discharged a BOD load of 620,987 m<sup>3</sup>/day with a BOD concentration of 6.8 mg/L, the Tan WWTP released a BOD load of 793,618 m<sup>3</sup>/day with a BOD concentration of 4.3 mg/L, and the Seonam WWTP released a BOD load of 1,661,500 m<sup>3</sup>/day with a BOD concentration of 7.1 mg/L. The Nanji and Seonam WWTPs are located downstream of the Gayang Bridge as shown in Fig. 8. Fig. 11 shows the BOD load to the Han River in 2012 [4].

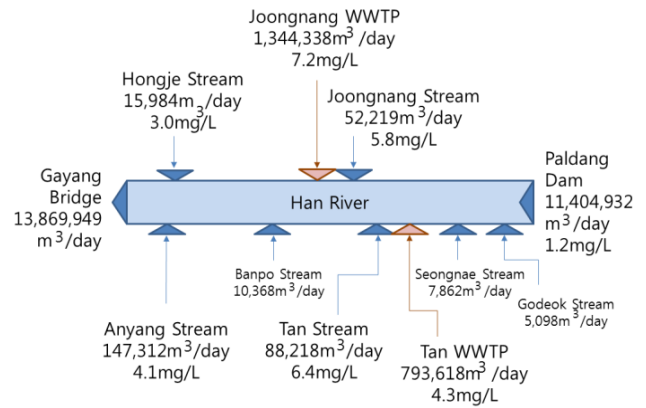


Fig. 11. BOD load to Han River.

### D. Comparison with BOD Concentrations

The BOD concentrations were monitored at eight points along the mainstream Han River as listed in Table II and shown in Fig. 8. The upstream zone of the Han River was considered Grade 1 (the best water quality) for BOD concentration (<2 mg/L) as Paldang Dam and AS had 1.2 mg/L, JS had 1.5 mg/L, GU had 1.7 mg/L, and TD had 1.8 mg/L. The middle zone was considered Grade 2 for BOD concentration (<3 mg/L) as BK and YD had 2.6 mg/L and 2.7 mg/L, respectively. The downstream zone was considered Grade 3 (average water quality) for BOD concentration (<5 mg/L) as GY had 3.1 mg/L, NR had 3.2 mg/L, and Haengju had 4.0 mg/L. Table II shows the model results obtained from the flows and the BOD loading conditions of streams from Fig. 11 compared with measured BOD data. The calculated values from the model underestimated the measured BOD values in the downstream zone. This may be due to BOD loads from the Nanji and Seonam WWTPs diffusing upstream through the Han River.

TABLE II: COMPARISON BETWEEN MEASURED (2012) AND CALCULATED CONCENTRATIONS OF BOD

Locations	Position Symbol	Measured Data (mg/L)	Model Results (mg/L)
Amsa	AS	1.2	1.2
Guui	GU	1.7	1.4
Jamsil	JS	1.5	1.4
Ttukdo	TD	1.8	1.7
Bokwang	BK	2.6	2.2
Noryangjin	NR	3.2	2.5
Yeungdeungpo	YD	2.7	2.6
Gayang	GY	3.1	2.6

Water quality of the Han River has been greatly improved by treating pollutant loads to the river. However, there are still some difficulties in getting the effluent water to meet water quality standards when the rainfall seasonally exceeds the capacity of the sewer system. This is because the combined sewer system occupies 96% of the total sewer system of Seoul, and therefore pollutants are occasionally discharged directly into the Han River and its tributaries without any treatment when the sewer system is inundated with stormwater [6].

The seasonal variation of BOD in the Han River is as follows: spring>winter>summer and fall, although the amount of water discharged at Paldang Dam is systematically controlled. For integrated management purposes, the studied model easily and quickly simulates urban river networks using a GUI interface and is helpful for rapid understanding of water quality conditions.

#### IV. CONCLUSION

This study presents a water quality model for urban stream networks. The model predicts contaminant concentration in urban stream networks, which are subdivided into unit reach meshes, thus accomplishing mass balance in each cell for nonconservative contaminants loaded from point and nonpoint sources on land. The model was developed by a GUI to provide a practical use for management purposes. To test the performance of the model, it was applied to the Seoul basin of the Han River network, which has eight stream branches.

#### ACKNOWLEDGEMENT

This work was financially supported by Graduate School of Water Resources, Sungkyunkwan University.

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