IMPLEMENTATION OF GIS BASED WATER QUALITY INDICES FOR WATER QUALITY MANAGEMENT

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ABSTRACT: Water quality modelling is an ideal tool of simulating physical, chemical and biological changes occurring in water systems. It has been utilized in a number of GIS-based water quality management and analysis applications. However, there is a need of a decision making process to translate the modelling result into an understandable form thereby implement the modelling results to the real world. This paper outlines a new water quality index called the QUAL2E's water quality index (QWQI) based on the water quality modelling using QUAL2E. The development mainly includes four steps: variable selection, sub-index development, weight assignment and sub-index aggregation. An experiment of applying the index and GIS to the Sapgyo River in Korea was implemented. Different from other water quality indices for general water uses, the index is specifically used for the simulated water quality indicators. The index can provide a simple and easy-to-understand decision support. Furthermore, interfacing with GIS, the decision analysis can be performed within a spatial environment. However, more study needs to be made in the future including the improvement of aggregation function.

KEY WORDS: water quality index, water quality modelling, QUAL2E, GIS

1. INTRODUCTION

Water quality modelling is an ideal approach to simulate physical, chemical and biological changes occurring in water bodies (James, 1984). It involves the prediction of water pollution using mathematical simulation techniques. So far, a number of water quality models have been widely applied into the assessment of water quality (Cox, 2003).

Among the existing water quality models, QUAL2E is the most popular one developed and released by USEPA (United States Environmental Protection Agency) in 1985. It is an enhanced steady-state model mainly used to simulate the inflow and water quality of rivers and streams. QUAL2E has been actively applied to the water quality simulation of dendriform rivers and streams mixed with branching tributaries over the years. Ning et al. (2001) assessed a pollution prevention program by the QUAL2E simulation analysis. Park and Lee (2002) implemented a water quality modelling of the Nakdong River in Korea by means of QUAL2E. McAvoy et al. (2003) made a risk assessment approach for untreated wastewater using QUAL2E.

Meantime, with the aid of GIS, water quality modelling can be interfaced with a environment allowing users to create interactive quires, spatial analysis and cartographic outputs. Grunwald and Qi (2006) carried out a water quality modelling in the Sandusky watershed of the USA based on the Soil and Water Assessment Tool (SWAT) and GIS. Paliwal et al. (2007) simulated the water quality of the Yamuna River in India by QUAL2E within a GIS.

However, the management of water quality today is more requiring easy-to-understand and intellectual decision making support for national and local governments. This requires more applicable and effective water quality assessment functions and user-oriented frameworks. Although the approach of water quality modelling provides reasonable simulation of water quality changes in water systems, a decision making process that can give deliberate and optimal judgments and decisions based on modelling results is needed for governments especially for non-expert users.

Viewing from the multi-criteria decision problems on water quality, water quality index (WQI) is an available tool of translating multiple variables into a single suitable criterion and establishing background levels of water quality based on the water quality standards for a given aquatic system (Ott, 1978). By means of the background levels for different regulatory policies, the quality of water can be judged by "good", "bad", "acceptable" or "polluted". Since the Horton's Quality Index is the first formal water quality index (Horton, 1965), a number of water quality indices have been developed for general and specific water uses.

However, all the indices were made to handle the monitored water systems. They are hardly able to work on the water without known quality data. Therefore, in this paper, a new water quality index called the QUAL2E's water quality index (QWQI) is proposed for the water quality simulated by QUAL2E.

2. STUDY SITE AND QUAL2E MODELING

As shown in Figure 1(a), the study area is the main stream of Sapgyo River, which is the biggest tributary of the Geum River system in Korea. Flowing in a north-eastern direction, the main stream is about 31 kilometers long. Along the river, there are a number of point sources (e.g. population, industry, livestock, and fishery) and non-point sources (e.g. landuses) that discharge water pollutants into the river. The water quality of the river had declined in the last ten years. Hence, it is a challenge to systematically manage and analyze the water pollution of this site, and to make decisions and plans to decrease water pollutants and to improve water quality.

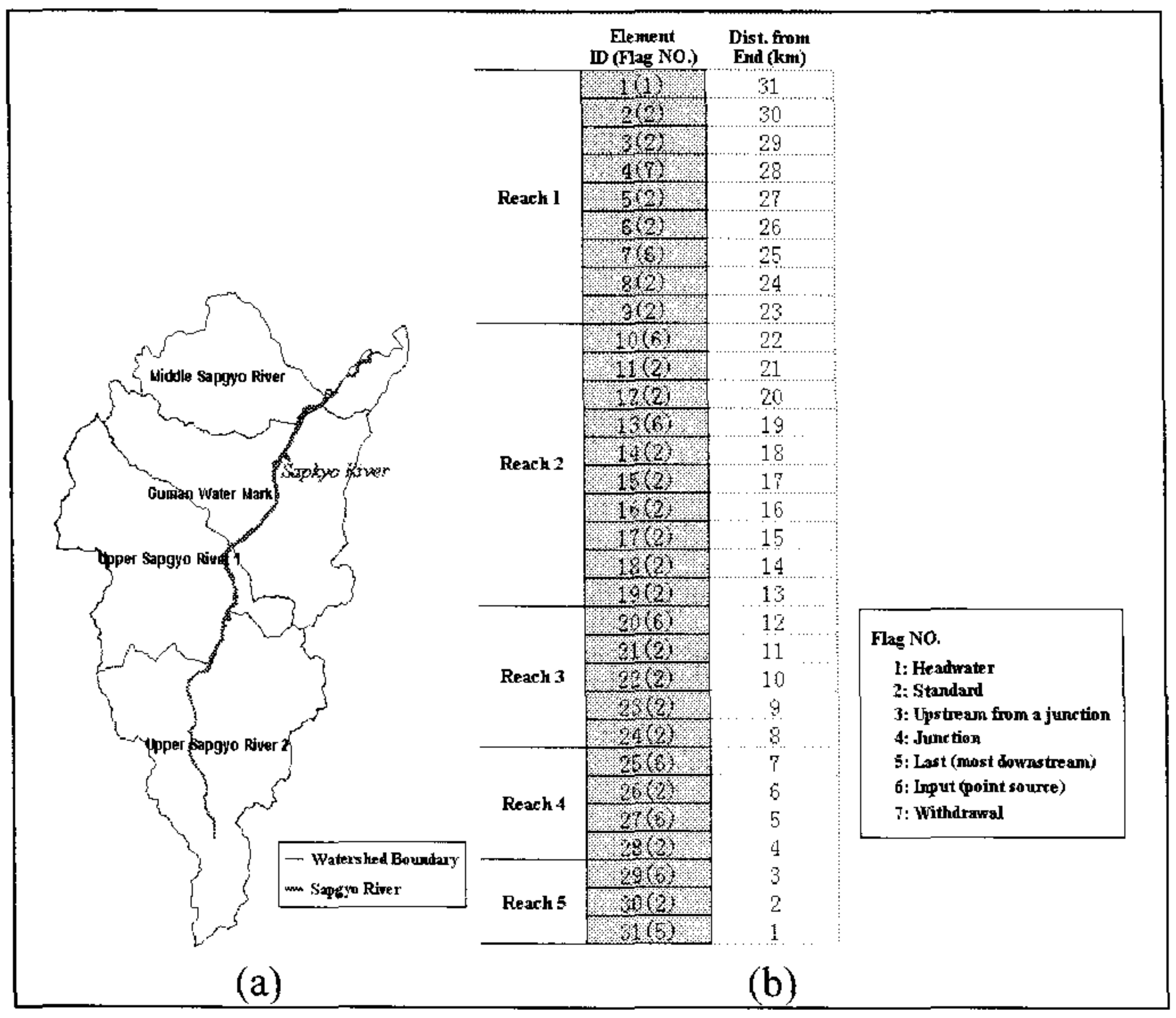

Figure 1. Conceptual Model of Sapgyo River.

By means of QUAL2E, the main stream was divided into 5 reaches and further subdivided into totally 31 elements as shown in Figure 1 (b). Each element was given a sequence number and a flag number which means the element type. The input at the headwater element (element 1) was the major input data. In addition, there were several other inputs from tributaries and pollution sources along the main stream. These loads were used to represent point source discharges into the stream and losses from the stream. Thus, for each element, the water quality indicators including BOD, T-N, and T-P were simulated by a set of formulations defined in QUAL2E. The modeling result of 2004 is listed in Table 1.

Table 1. QUAL2E Modeling of Sapgyo River (2004).

(unit: mg/l)

ID	BOD	T-N	T-P	ID	BOD	T-N	T-P
1	5.75	2.565	0.098	17	3.34	7.326	0.326
2	5.42	2.543	0.095	18	3.20	7.290	0.322
3	5.10	2.521	0.091	19	3.06	7.255	0.319
4	4.78	2.499	0.088	20	2.81	8.272	0.270
5	4.50	2.479	0.086	21	2.80	8.176	0.265
6	4.23	2.463	0.084	22	2.79	8.086	0.261
7	4.81	7.108	0.353	23	2.79	8.001	0.258
8	4.59	7.062	0.342	24	2.78	7.920	0.255
9	4.38	7.018	0.333	25	2.84	7.928	0.241
10	4.49	7.586	0.367	26	3.03	7.994	0.247
11	4.30	7.543	0.358	27	2.96	7.961	0.236
12	4.12	7.500	0.350	28	3.15	8.029	0.244
13	3.96	7.482	0.347	29	2.85	7.545	0.218
14	3.80	7.442	0.341	30	2.95	7.612	0.219
15	3.64	7.402	0.336	31	3.04	7.680	0.221
16	3.48	7.364	0.331				

3. QUAL2E'S WATER QUALITY INDEX (QWQI)

In this study, a new water quality index called QUAL2E's water quality index (QWQI) was developed to provide simple description of the simulated water quality from QUAL2E. Unlike the pre-existing water quality indices, the QWQI has a specific availability to the water that has not been monitored but can be simulated by water quality modelling. Normally, the development of a WQI includes four steps: variable selection, sub-index description, weight assignment and sub-index aggregation (Boyacioglu, 2007).

3.1 Variable Selection

QUAL2E involves 15 water quality indicators including DO, BOD, temperature, chlorophyll, organic nitrogen, ammonium nitrogen, nitrate, nitrite, organic phosphorus, phosphate, coliform, one arbitrary non-conservative constituent and three conservative constituents. The total amount of the different existent nitrogen can be indicated by T-N (total nitrogen). Similarly, the total amount of the different existent phosphorus can be indicated by T-P (total phosphorus). Each indicator may be optional for the modelling purpose. For example, the water quality modelling of Sapgyo River's main stream involved 6 indicators including temperature, BOD, DO, T-N, T-P and chlorophyll. Among the 6 indicators, DO, temperature and chlorophyll are not directly related to the water quality. DO is the measure of oxygen contained in the water. Temperature is used to determine the tendencies of water quality which normally changes with temperature. Chlorophyll is only used to measure the algal concentration influenced by nitrates and phosphates. By contrast, BOD, T-N and T-P are the important indicators of oxygen depletion caused by water pollutants. In a sense, to simplify the description of the simulated water quality by QUAL2E for general water uses, BOD, T-N and T-P are the major indicative parameters. Hence, these three indicators were selected as the variables of QWQI.

3.2 Sub-Index Description

The QWQI was developed based on the water quality standards of Korea (KOWACO, 2001). The standards consist of five classes, orderly the Class I, II, III, IV and V. The five-class standards of BOD, T-N and T-P are listed in Table 2.

Table 2. Standards of BOD, T-N and T-P in Korea.

Variable	I	II	III	IV	V
BOD	<1	<3	<6	<8	<10
T-N	<2	<4	<6	<10	<15
T-P	<0.1	<0.3	<0.5	<1.0	<1.5

Brown et al. (1970) presented a water quality index called the National Sanitation Foundation's Water Quality Index (NSF WQI), which is similar in structure to Horton's index. It is the most widely used of all existing water quality indices. By means of the NSF WQI, each classified group in this study was represented by a numerical range, e.g. Class I (91-100), Class II (71-90), Class III (51-70), Class IV (26-50), and Class V (0-25). These fixed values are not the real quality values but the descriptors of quality. The five classes can be described as "Excellent", "Good", "Medium", "Bad" and "Very bad", respectively. Finally, a set of sub-index functions were defined to transform the variables to their sub-index values that have a numerical range of 0 to 100.

Table 3. Sub-index functions for QWQI.

Variable	Range	Sub-index function
BOD	$X=0$	$Y=100$
	$0<X<1$	$Y=-10X+100$
	$1\leq X<3$	$Y=-10X+100$
	$3\leq X<6$	$Y=-6.7X+90.1$
	$6\leq X<8$	$Y=-12.5X+125$
	$8\leq X<10$	$Y=-12.5X+125$
	$X\geq 10$	$Y=0$
T-N	$X=0$	$Y=100$
	$0<X<2$	$Y=-5X+100$
	$2\leq X<4$	$Y=-10X+110$
	$4\leq X<6$	$Y=-10X+110$
	$6\leq X<10$	$Y=-6.25X+87.5$
	$10\leq X<15$	$Y=-5X+75$
	$X\geq 15$	$Y=0$
T-P	$X=0.0$	$Y=100$
	$0.0<X<0.1$	$Y=-100X+100$
	$0.1\leq X<0.3$	$Y=-100X+100$
	$0.3\leq X<0.5$	$Y=-100X+100$
	$0.5\leq X<1.0$	$Y=50X-25$
	$1.0\leq X<1.5$	$Y=-50X+75$
	$X\geq 1.5$	$Y=0$

3.3 Weight Assignment

The weight of each variable for a water quality index is used to denote the variable's importance to overall water quality. The importance of each variable in the NSF WQI was developed by combining the opinions of 142 water experts. Each expert was asked to rate every variable according to its significance as a contributor to overall water quality. The rating was done by a scale of 1 (highest relative significance) to 5 (lowest relative significance). The final rates of the NSF WQI were defined by a final consensus of the opinions. According to the NSF WQI, the temporary weights and the normalized weights for QWQI were assigned as shown in Table 4. Comparing with BOD and T-P, T-N has a higher importance to overall water quality.

Table 4. Weight assignment for QWQI.

Variable	Significance ratings (NSF WQI)	Temporary weights	Final (normalized) weights
BOD	2.3	1.00	0.34
T-N	2.4	0.96	0.33
T-P	2.4	0.96	0.33

3.4 Sub-Index Aggregation

The aggregation of a WQI is mathematically combining all sub-indices to an overall index value. The aggregation function of QWQI was simply formulated as follows:

$$QWQI = \sum_{i=1}^{3} w_i I_i \qquad (1)$$

where w_i = weight of the i th variable

I_i = sub-index of the i th variable.

4. APPLICATION OF QWQI TO SAPGYO RIVER

By means of the QWQI, the water quality modelling result can be further indexed for decision. The sub-indices and aggregated indices for the result of QUAL2E modelling in this study are shown in Table 5. The QWQI indexing result was interfaced with a GIS as shown in Figure 2. Viewing the QWQI indexing result, some simple conclusions can be made as follows:

Table 5. QWQIs of Sapgyo River (2004).

ID	Sub-indices			QWQI	Class
	BOD	T-N	T-P		
1	51.6 (III)	84.4 (II)	90.2 (I)	75.2	II
2	53.8 (III)	84.6 (II)	90.5 (I)	76.1	II
3	55.9 (III)	84.8 (II)	90.9 (I)	77.0	II
4	58.1 (III)	85.0 (II)	91.2 (I)	77.9	II
5	60.0 (III)	85.2 (II)	91.4 (I)	78.7	II
6	61.8 (III)	85.4 (II)	91.6 (I)	79.4	II
7	57.9 (III)	43.1 (IV)	64.7 (III)	55.3	III
8	59.3 (III)	43.4 (IV)	65.8 (III)	56.2	III
9	60.8 (III)	43.6 (IV)	66.7 (III)	57.1	III
10	60.0 (III)	40.1 (IV)	63.3 (III)	54.5	III
11	61.3 (III)	40.4 (IV)	64.2 (III)	55.4	III
12	62.5 (III)	40.6 (IV)	65.0 (III)	56.1	III
13	63.6 (III)	40.7 (IV)	65.3 (III)	56.6	III
14	64.6 (III)	41.0 (IV)	65.9 (III)	56.9	III
15	65.7 (III)	41.2 (IV)	66.4 (III)	57.8	III
16	66.8 (III)	41.5 (IV)	66.9 (III)	58.5	III
17	67.7 (III)	41.7 (IV)	67.4 (III)	59.0	III
18	68.7 (III)	41.9 (IV)	67.8 (III)	59.6	III
19	69.6 (III)	42.2 (IV)	68.1 (III)	60.1	III
20	71.9 (II)	35.8 (IV)	73.0 (II)	60.4	III
21	72.0 (II)	36.4 (IV)	73.5 (II)	60.7	III
22	72.1 (II)	37.0 (IV)	73.9 (II)	61.1	III
23	72.1 (II)	37.5 (IV)	74.2 (II)	61.4	III
24	72.2 (II)	38.0 (IV)	74.5 (II)	61.7	III
25	71.6 (II)	38.0 (IV)	75.9 (II)	61.9	III
26	69.8 (III)	37.5 (IV)	75.3 (II)	61.0	III
27	70.4 (II)	37.7 (IV)	76.4 (II)	61.6	III
28	69.0 (III)	37.3 (IV)	75.6 (II)	60.7	III
29	71.5 (II)	40.3 (IV)	78.2 (II)	63.4	III
30	70.5 (II)	39.9 (IV)	78.1 (II)	62.9	III
31	69.7 (III)	39.5 (IV)	77.9 (II)	62.4	III

Firstly, the upper reaches of the main stream had a "Good" water quality because the simulated water quality from element 1 to element 6 was graded as "Class II". The simulated water quality of remaining river reaches was graded as "Class III" which means a "Medium" quality.

Secondly, the element 6 had the best water quality (79.4, Class II) among all river elements. Oppositely, the element 10 had the worst water quality (54.5, Class III).

In general, the overall water quality of the main stream may be considered acceptable because there is no any element had a QWQI lower than 50.0. However, the T-N of the main stream should be improved because the T-Ns of most elements were graded as "Class IV", which means a "bad" quality.

The QWQI indexing result can provide a description of the simulated water quality by QUAL2E. It can be used to judge whether or not an element should be improved. By the judgment, some appropriate improvement plans can be made.

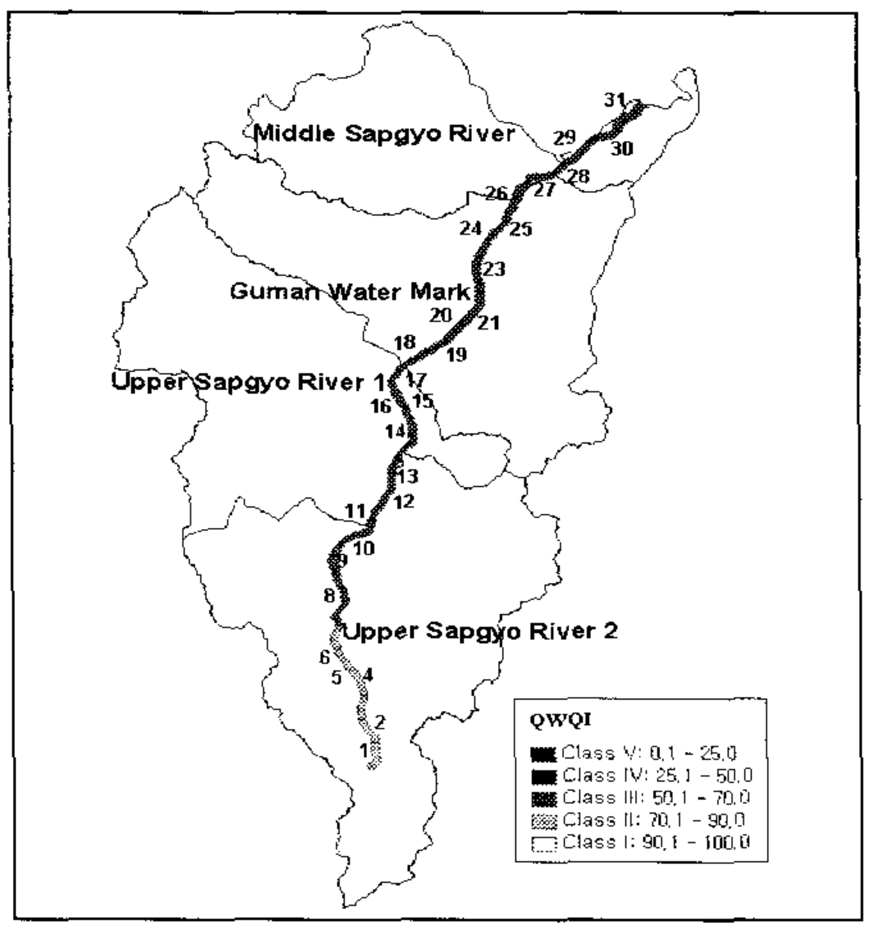

Figure 2. QWQIs of Sapgyo River (2004) within a GIS.

5. CONCLUSION

Decision analysis of water quality is one important branch of multi-criteria decision problems. It has been also addressed in GIS applications. In this study, a water quality index called the QWQI was developed specially for the simulated water quality by QUAL2E. The development procedure includes variable selection, sub-index development, weight assignment and sub-index aggregation. An experiment of applying the QWQI to make decisions on the QUAL2E modelling results of the Sapgyo River in Korea was implemented. The QWQI can classify the simulated water quality by QUAL2E based on water quality standards and provide the basis of decision support. Furthermore, interfacing with a GIS, the management and decision analysis of water quality can be performed within a spatial environment. However, more study needs to be made in the future including detailed design of improvement actions.

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