Analysis of the Assimilative Capacity with Various Dimensional Water Quality Models in the Tseng-Wen Reservoir (Taiwan)

Yi-Chao Lee[1], Chen-Cheng Yang[2], Chao-Shi Chen[2], Shui-Ping Chang[1], Ching-Gung Wen[3], Chih-Sheng Lee[1, *]

[1]Department of Environmental Engineering, Kun Shan University, Yung-Kang City, Tainan Hsien 71003, Taiwan,

[2]Department of Resources Engineering, [3]Department of Environmental Engineering, National Cheng Kung University, Tainan City 70101, Taiwan

Abstract: In this paper, three water quality models (WQMs) are selected to present their abilities by simulating water qualities of reservoirs. The simple zero-dimensional model and complicated two-dimensional model are used to verify the reliability of the one-dimensional model. For evaluating various dimensional WQMs, the assimilative capacity (AC) is analyzed and compared by means of water quality standards. The results of the AC analysis and pollution load find that consistence exists between the zero-, one- and two-dimensional WQMs. In addition, the BOD_5, TP and TN loads of the Tseng-Wen Reservoir have exceeded the AC of the water body. The analysis method developed in this study can be used to estimate the influences caused by the development of the watershed area of the reservoir. It also helps to choose to develop the watershed area with the maximum AC and the minimum influence to the water bodies.

keywords: Assimilative capacity; Water quality model; Tseng-Wen Reservoir.

1 Introduction

In the realm of watershed management, one of challenges is to easily and fast identify the reservoir water-quality responded from the pollution loads when they discharge to the reservoir. Most of pollution loads are produced from non-point sources (NPSs) which indicate as various land uses, such as agricultural activities (orchards, tea plantations, areca plantations and raising of livestock), urban areas (such as household wastewater), and forests in watersheds [1-5].

Since 1989, the Environmental Protection Administration (EPA) of Taiwan launched the long-term water quality monitoring project to evaluate the water quality status and their variation of ten major reservoirs and, furthermore, to build up a reservoir water quality database for effective control alternatives in their watersheds.

This study employs water quality models to link the relationship of pollution loads and reservoir water quality, a one-dimensional water-quality model (WQM) is selected to predict the response of water quality in a reservoir. In addition, a simple zero-dimensional model and two-dimensional model are used to verify the reliability of the one-dimensional model. For evaluating various dimensional WQMs, the assimilative capacity analyzed and compared by means of water quality standards.

2 Reservoir Water-Quality Models

There have been many water-quality models developed and applied in the last three decades [2,6,7]. In this study, several developed WQMs, including simple well-mixed model and more complicated longitudinal and vertical models are selected and applied. A typical shape of reservoir system and its water quality model formulation are given in Figure 1.

2.1 Zero-dimensional water-quality models

The zero-dimensional (O-D) WQM takes the entire water body as a homogenous or well-mixed one, and formulates as the mass balance equation. Merits of 0-D model consists of : (1) fast estimating water quality with simple calculations involved; (2) easily implementing errors and uncertainty analysis; and (3) taking as a basis on developing complicated models [6,7]. The general equation of 0-D model is presented as

$$V\frac{dC}{dt} = W_{in} - Q_{out}C - KVC - V_s A_s C \qquad (1)$$

where W_{in}: total annual input loadings, including surface loading, sub-surface loading, and internal loading (settlement release) (M/T) ; Q_{out}: outflow from the reservoir (L^3/T) ; V: volume of the reservoir (L^3); C: concentration of the substance in the reservoir (M/L^3); K: decay coefficient of the substance in the reservoir (1/T); Vs: apparent settling velocity of TP (L/T); A_s : surface area of reservoir (L^2); and t: time interval (T).

2.2 One-dimensional water-quality models

Water quality in the reservoir is affected by the factors of season, temperature, sunlight intensity, aeration, sedimentation, photosynthesis, etc., resulting in turnover and stratification in the reservoir. Therefore, the vertical change is more significant than the horizontal one in a natural water body. Besides, the horizontal transfer in the reservoir is less significant than in the river. The 1-D model of each layer is expressed as

$$V\frac{\partial C}{\partial t} = E_Z A_Z \frac{\partial^2 C}{\partial^2 Z}\triangle Z - A_Z V_z \frac{\partial C}{\partial Z}\triangle Z + Q_i C_i - Q_0 C \pm W \qquad (2)$$

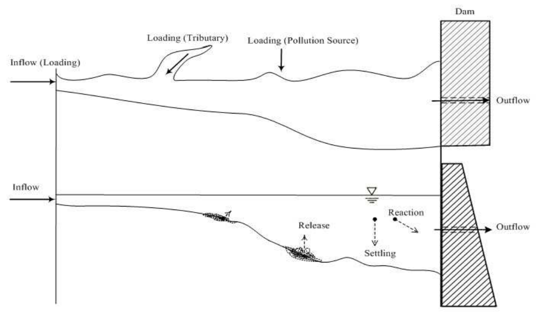
where A_Z: section area of the Z (depth) direction (L^2) ; E_Z: dispersion coefficient of the Z (depth) direction (L^2/T); and V_Z: velocity of the Z (depth) direction (L/T).

However, a vertical 1-D model is able to simulate the stratification of a reservoir, and to predict whether the dissolved oxygen is enough at the hypolimnion of the water body, so as to prevent anaerobic actions and odor and pollution from the settlement.

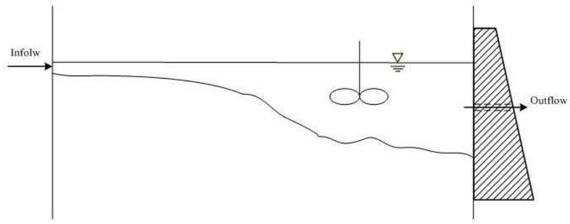
But for a narrow and shallow river-typed reservoir, horizontal changes shall be significant, the 1-D longitudinal WQM can be expressed as

$$V\frac{\partial C}{\partial t} = E_X A_X \frac{\partial^2 C}{\partial^2 X}\triangle X - A_X V_X \frac{\partial C}{\partial X}\triangle X + Q_i C_i - Q_0 C \pm W \qquad (3)$$

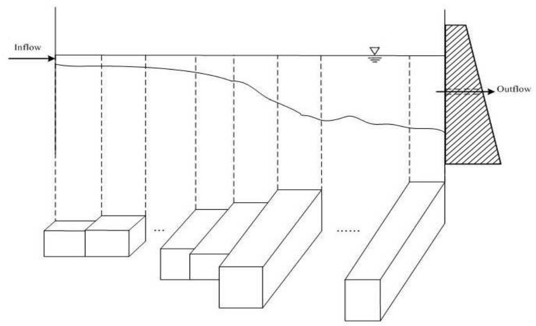
Thomann and Mueller [2] perhaps first established the Finite Segment Approach (FSA) by using this model on water quality simulation of the outlet of the Delaware Estuary. FSA, also called Finite Difference Approximation or Control-Volume Approach [1], usually divides the water body into several segments along the direction of the flow, assuming no gradient for every segament. Figure 1 (c) is a typical expression of Finite Segment Approach.



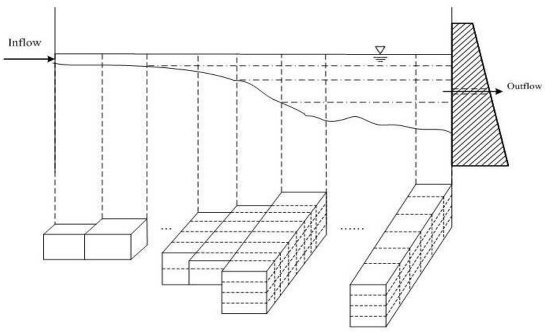
(a) A typical reservoir system.



(b) Zero-dimensional water quality model



(c) One-dimensional water quality model



(d) Two-dimensional water quality model

Figure 1. A typical reservoir system and its water quality models.

2.3 Two-dimensional water-quality models

A two-dimensional (2-D) longitudinal and vertical WQM is normally used to simulate in the vertical and horizontal directions. This model is suitable for simulating deep and narrow reservoirs. 2-D WQM is expressed as follows

$$V\frac{\partial C}{\partial t}=E_X A_X\frac{\partial^2 C}{\partial X^2}\triangle X-E_Z A_Z\frac{\partial^2 C}{\partial^2 Z}\triangle Z-A_X V_X\frac{\partial C}{\partial X}\triangle X-A_Z V_Z\frac{\partial C}{\partial Z}\triangle Z+Q_i\,C_i-Q_0\,C\pm W \quad (4)$$

3 Case Study

3.1 Tseng-Wen Reservoir Watershed

The Tseng-Wen Reservoir, located in Southern Taiwan, is an artificial reservoir by intercepting the upstream of Tseng-Wen River. The geographical location of the reservoir is shown in Figure 2. The reservoir is a narrow and steep reservoir which intakes from more than ten tributaries with a watershed area of about 481 square kilometers. The designd capacity of the reservoir was 708 million cubic meters (with effective capacity of 650 million cubic meters in 2000) with a surface area of 17 square kilometers. The annual average precipitation is 2500 mm with annual inflow of 1.6 billion cubic meters.

3.2 Water Quality Status

Annual average water quality is listed in Table 1, in which the 1.3 mg/L BOD_5 exceeds the limit of Taiwan Class A standard, and the 0.028 and 0.5 mg/L of TP and TN are also out of the critical limit of eutrophication. The results showed that the reservoir is influenced by human pollution such as sewer, animal wastewater, and improper application of pesticides. A detailed analysis of water-quality status could be referred in Chang et al. [8].

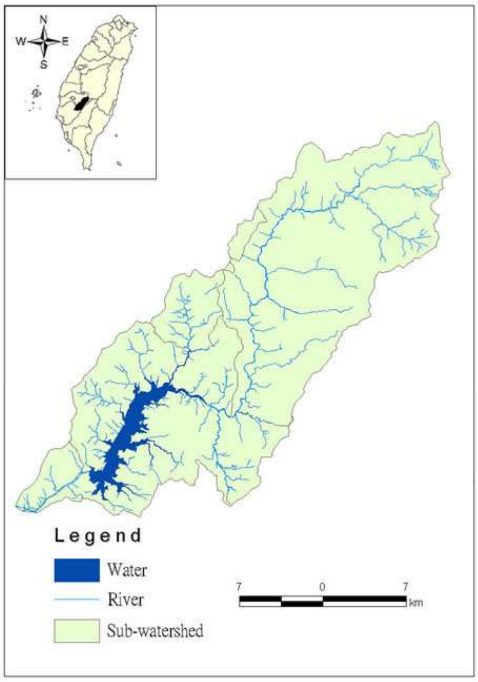


Figure 2. The geographical location of the Tseng-Wen Reservoir Watershed.

Table 1. Water quality status of the Tseng-Wen Reservoir.

Water quality	Average	Standard deviation
BOD_5 (mg/L)	1.3	0.3
TN (mg/L)	0.5	0.1
TP (mg/L)	0.028	0.002
Secchi disc (m)	1.8	0.2
Chl-a (μg/L)	10.6	1.2
DO (mg/L)	8.3	0.2
Temperature (℃)	25.4	0.5

4 Results and Discussion

4.1 Estimation of Pollution Load

Table 2 gives WQMs used in this study for the pollution loads and AC of BOD_5, TP and TN in the Tseng-Wen Reservoir. Accompanied with hydrological and water quality parameters given in Table 3 (for 0-D model) and Table 4 (for 1-D and 2-D models), the pollution loads of BOD_5, TP and TN are shown in Table 5. The analysis of AC is similar to pollution load estimation, excepting the concentrations are substituted by water quality standard or critical eutrohpic criteria, the ACs are also shown in Table 5. The table indicates that BOD_5 in the Tseng-Wen Reservoir is beyond the allowed limit of the pollution load for Taiwan Class A, but still within the Class B water body limits. As for TP and TN, the loads all exceeded critical ACs a lot.

4.2 One-Dimensional Water Quality Model

Table 4 shows the system parameters of each segment at normal water levels of 225 meters. In the table, calculations of the BOD_5 decomposing coefficient and TP and TN vanishing coefficients are assumed to be first-order reaction. As shown in Figure 3, the slope will be presented as the decomposing coefficient or vanishing coefficient. In this figure, about 70 days of traveling time, the discharge of sewage from Chiayi Farm and the pollution load of point source and NPS from the recreational facilities near the dam caused the water concentration increasingly.

Table 2. Water quality models applied in this study.

	BOD_5	TP	TN
0-D	$\frac{W_{in}}{Q_{out}+KV}$	$\frac{W_{in}/A}{11.6+1.2q_s}$	$\frac{W_{in}}{Q_{out}}$
1-D	Finite Difference Approach		
2-D	-	2D Hydraulic and Water Quality Model	

Table 3. Some parameters for Zero-dimensional Model in Tseng-Wen Reservoir.

Inflow[1] (m^3/yr)	Surface Area[2] (m^2)	Surface Loading (m/yr)	Volume[2] (m^3)	BOD_5 degradation Coefficient[3] (l/d)
1600×10^6	17×10^6	94	65×10^7	8.2×10^{-3}

1: data calculated from July, 1990 ~ June, 1991; 2: at the average water level 225 m ; 3: See Figure 3

Table 4. System parameters for One-dimensional model in Tseng-Wen Reservoir.

Segament	Length (m)	Volume ($\times10^7$ m^3)	Section Area ($\times10^3$ m^2)	Flowrate ($\times10^9$ m^3/yr)	Dispersion Coefficient[1] (m^2/s)	BOD_5 Degradation Coefficient[3] (l/d)	TP Degradation Coefficient[3] (l/d)	TN Degradation Coefficient[3] (l/d)
0	-	-	-	1.49	-	-	-	-
1	2,400	8.66	38	1.50	1	0.0082	0.0018	0
2	2,400	17.18	44	1.55	1	0.0082	0.0018	0
3	2,100	13.15	54	1.56	1	0.0082	0.0018	0
4	1,700	17.36	58	1.59	1	0.0082	0.0018	0
5	-	8.53	-	1.61	-	0.0082	0.0018	0

1: Calibrated from Two-dimensional Water quality model. Note: at the average Water level 225 m。

Table 5. Loadings and assimilative capacity estimated by water quality models.

Water Quality Model	BOD_5 ($\times10^6$ kg/yr)			TP ($\times10^3$ kg/yr)			TN ($\times10^3$ kg/yr)		
	Loading	Assimilative Capacity		Loading	Assimilative Capacity		Loading	Assimilative Capacity	
		Class A	Class B		Class A	Class B		Class A	Class B
0-D	4.6	3.6	7.1	58.2	10.6	21.2	800	160	320
1-D	4.3	3.5	7.2	59.4	10.1	20.0	826	162	324
2-D	-	-	-	57.2	9.3	19.2	860	162	325

Table 6. The water quality of each segment in the Tseng-Wen Reservoir.

Segment	BOD (mg/L)		TP (mg/L)		TN (mg/L)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
1	1.6	0.5	0.030	0.006	0.480	0.320
2	1.3	0.6	0.027	0.008	0.440	0.270
3	1.0	0.5	0.027	0.009	0.490	0.310
4	1.1	0.3	0.027	0.009	0.460	0.310
5	1.2	0.6	0.031	0.007	0.510	0.410

Table 7. Loads and Assimilative capacity of each segament in the Tseng-Wen Reservoir.

Loads and Assimilative Capacity($\times 10^3$kg/yr)	Segment	TP		TN	
		Class A	Class B	Class A	Class B
Allowable loads	1	7.5	15.2	150	301
	2	0.4	0.9	0	0
	3	0.6	1.3	4	8
	4	0.4	0.9	4	8
	5	0.4	0.9	4	8
Assimilative capacity		9.3	19.2	162	325
Loads		57.2		860	

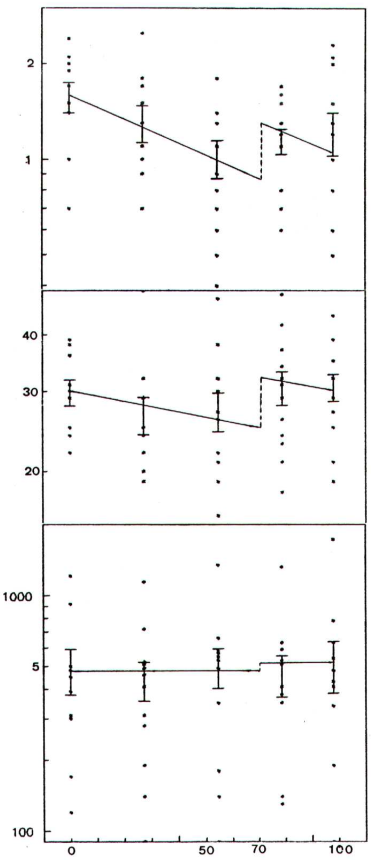


Figure 3. Calibration of the degradation coefficients of the BOD_5, TP, and TN.

The water qualities of each segment is shown in Table 6, flowrates of the tributaries are allocated according to the watershed areas by hydrological balance equation to keep that the annual intake of Tseng-Wen Reservoir is almost equal to the output. Annual average BOD_5, TP and TN pollution loads are calculated and presented in Table 7 ant the ACs for TP and TN are also shown in Table 7.

In view of each segment, segment #1 takes the intakes of the mainstream and main tributary as well as the majority of the point source and NPS pollution loads in the watershed from Dapo Township, therefore its pollution load is the highest of all the segments. Pollution loads of TN in segment #3 and TP in segment #4 are all greater than the AC, this shall be connected with the cultivation of dry fields and orchard farms which caused NPS pollution in those areas. Segment #5 is subject to point source and NPS pollution loads from Chiayi Farm and tourist facilities near the dam, as well as its position in the downstream of the reservoir which sustains the pollution loads transported from the upstream, the BOD_5 and TN pollution loads are therefore large.

4.3 Discussion for Various Dimensional Water Quality Models

Tables 5 and 7 show that the AC estimations of BOD_5, TP and TN are very close, which means the suitability for Tseng-Wen Reservoir as well as the common applicability for other cases. The pollution loads are mainly NPS pollutions which took more than 90 %, and came mainly from heavy rain wash-down of the forest area, farm area, community and tourist facilities so that the soil, carrying great amounts of nutritious salts, entered the water column. This is verified by the water quality inspection results of Tseng-Wen Reservoir, the TP and TN were high in the rainy season (July-August). For the water qualities, BOD_5 load is slightly higher than AC of Taiwan Class A, meaning that further control of the BOD_5 pollution load, say 20% cut, the Class A standard can then be met. For TP and TN, the pollution loads are both higher than the critical eutrophication and AC of Japan Classes A and B, meaning that Tseng-Wen Reservoir is already eutrophic, but the eutrophication is still mild. Reduction of pollution amount shall be conducted step by step, i.e. in short terms, cutting 30% TP and 20% TN to upgrade the water body into medium-eutrophic. For the mid-term objective, to achieve a low-eutrophic water body, 60% of pollution shall be reduced. For the long-term objective as Japan Class A, a 80% cut is required.

In addition, Tseng-Wen Reservoir is a long and narrow one, a 2-D hydrological water quality model is suitable for the simulation, but the climatic, hydrological and water quality data is large and must be complete in order to yield an accurate simulation result. If time is not sufficient or the data is not complete, the 1-D water quality model with finite segment approach is recommended for a more accurate AC estimation, because if AC is expressed for each water column, it shall be able to show the locality of the pollution in the reservoir, and therefore help identify the location of the pollution source, so that proper remedial measures can be taken accordingly and the improvement of the reservoir water quality can become more easy.

5 Conclusions

From the results of the AC analysis and pollution load, we find that consistence exists between the zero-, one- and two-dimensional WQMs. If any other reservoir in Taiwan is completed with actually measured data necessary for the water quality model and the model is calculated and verified, its AC can then be analyzed accordingly.

BOD_5 pollution load of the Tseng-Wen Reservoir exceeded the AC of Taiwan Class A; TP and TN are also over the critical eutrophic criteria (TP 0.02 mg/L, TN 0.5 mg/L), showing that the pollution load has exceeded permissible AC of the water body. The AC analysis method developed in this study can be used to estimate the influences caused by the development of the watershed area of the reservoir. It also helps to choose to develop the watershed area with the maximum AC and the minimum influence to the water bodies**.**

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