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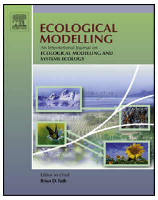

Modeling approach to evaluation of environmental impacts on river water quality: A case study with Galing River, Kuantan, Pahang, Malaysia

Ingyu Lee[a], Hyundong Hwang[b], Jungwoo Lee[c], Nayoung Yu[b], Jinhuck Yun[b], Hyunook Kim[a,*]

[a] Department of Energy and Environmental System Engineering, University of Seoul, Seoul, Republic of Korea
[b] Human Planet Ltd., Daejeon, Republic of Korea
[c] Environmental Engineering Research Division, Korea Institute of Civil Engineering and Building Technology, Gyunggi-do, Republic of Korea

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ABSTRACT

One of the major issues in Kuantan, Pahang, Malaysia is the water quality of Galing River which is flowing through the area. Currently, overall water quality of the river is very poor, i.e., Class IV (based on the Malaysian water quality standards), mainly due to wastewater discharged from residential area and industries without being properly treated. Due to severe pollution, aquatic ecosystem has not been properly developed. Thus, it is being considered to construct a new wastewater treatment plant (WWTP) to prevent discharge of pollutants and to improve the river water quality. Therefore, this study was conducted to identify the pollution sources along the river and assess their impacts on the water quality. In addition, a numerical model was formulated with the Environmental Fluid Dynamic Code (EFDC) to find a best plan to improve the water quality. Through the model simulation, it was found that wastewater from all the U-drains and culverts along the river should be collected by sewer, transported to a WWTP for treatment, and then pumped to the upstream of the river for discharge. It was also found that if the WWTP would reduce pollution load by 80%, the current water quality of the river would improve by 80% to achieve Class II.

1. Introduction

Urban development without a proper plan often results in environmental issues, for example, deterioration of water quality of rivers, lakes, and reservoirs. In other words, the urban development causes human population and activities to increase and surrounding environment to be polluted. Therefore, the modern cities in western countries have been established through a comprehensive development plan including sewage collection and treatment. However, most cities in the south-eastern Asian countries have been developed without such a plan; wastewater generated from the cities often pollutes a receiving water body since it is discharged without a proper treatment (OECD, 2012). Due to uncontrolled flowing-in of pollutants, i.e., organics, nitrogen, phosphorus, receiving water bodies often experience algal blooming, fish death/floating, and deterioration of biodiversity, eventually negatively-affecting human life (Wang et al., 2014). Thus, many city governments in the countries, e.g., Malaysia, China, Thailand, etc. are building new wastewater treatment plants (WWTPs) to prevent water pollution (Rashidi et al., 2015). When construction of a WWTP is planned, a number of factors should be considered; they include the design capacity, characteristics of the influent, location of the WWTP, and the ecological and beneficial impacts of sewage collection and treatment on the water environment (Ji et al., 2013). Construction of a WWTP including a sewer system involves a huge capital investment and operation and management costs, which are also important factors considered in an urban development plan (Massoud et al., 2009). In order to make a reliable plan for environmentally sound urban development, various scenarios for the plan, each of which considers both economic and environmental consequences, should be made and evaluated. Then, the best one should be chosen (Hernández-Sancho et al., 2015).

Over the past decades, computer models have been applied to assess environmental impacts of a development plan (Wang et al., 2013). Using computer models is more advantageous than doing traditional empirical and experimental models in assessing

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[*] Corresponding author.
E-mail address: h_kim@uos.ac.kr (H. Kim).

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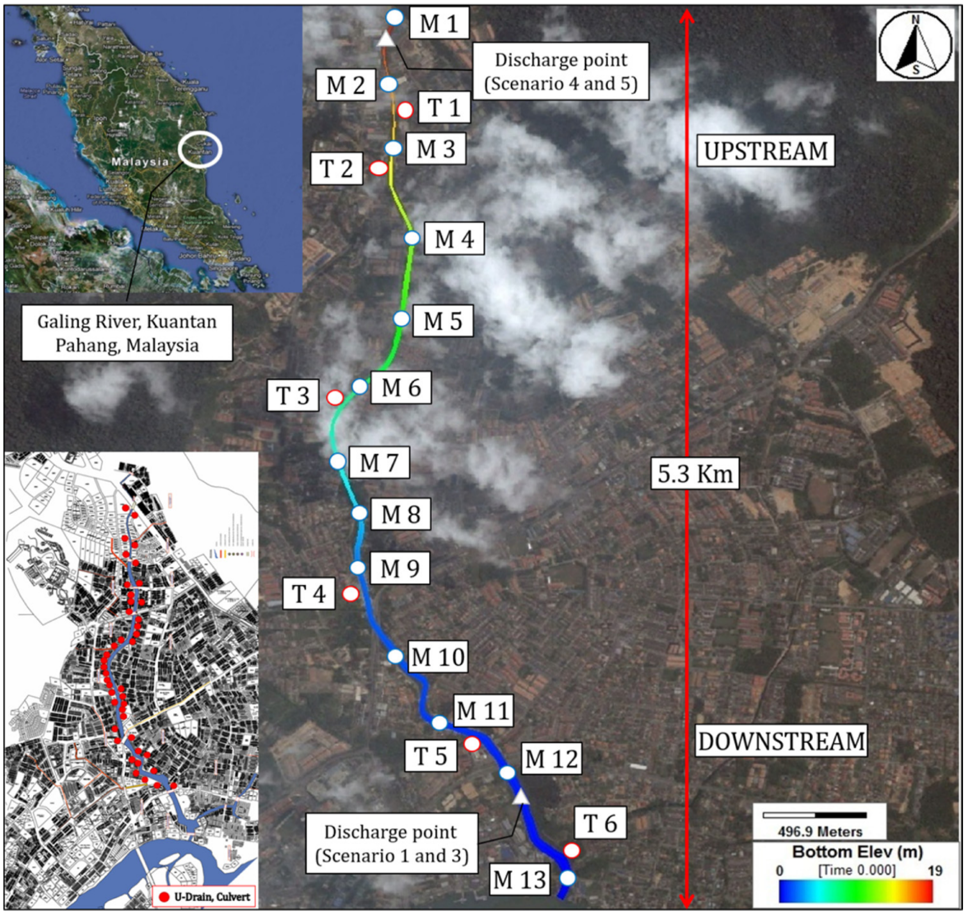

Fig. 1. Sampling locations along Galing River.

environmental impacts of a development and management plan (Beck, 2013; Chen et al., 2014; Liangliang and Daoliang, 2015).

Numerical models have been widely used to evaluate water quality issues in both fresh water and sea water (Park et al., 2005; Seo and Kim, 2011; Shi et al., 2011). As the fresh water environment is concerned, Water quality Analysis Simulation Program (WASP) developed by the United States Environmental Protection Agency (US EPA) in 1983 (Ambrose et al., 1988) has been widely used; for example, WASP was applied for the estimation of regional risk assessment for point source pollution in Taipu River, China (Yao et al., 2015). It also used to simulate water quality of Daliao River and calculate the waste loads for the water environmental capacity of the water body (Lei et al., 2015). Recently, it has been applied to simulate water quality and hydrodynamics of a water body, being linked with the Environmental Fluid Dynamics Code (EFDC) (Luo and Li, 2009; Jeong et al., 2010; Wu and Xu, 2011; Wang et al., 2015); EFDC was also developed by the US EPA (Shoemaker, 1997) and has been applied for simulating three-dimensional flow circulation, mass transport, and biogeochemical processes in rivers, lakes, wetland, and reservoirs (Su et al., 2014; Wang et al., 2014; Yang et al., 2016). In fact, EFDC has been extensively tested and is now considered as a standard model for river and estuary studies (Ji, 2008). For example, Seo et al. (2012) applied EFDC for prediction of *Chlorophyll-a* change of a river before and after construction of weirs. In order to improve water quality of the surface water in terms of dissolved oxygen (DO), *Chlorophyll-a*, COD (chemical oxygen demand), TN (total nitrogen), and TP (total phosphorus), scenario analyses using an EFDC model were also performed (Kang and Jang, 2015). EFDC has been used for calculating allowable pollution loads for streams in an environmental capacity management system (Liang et al., 2015). Seo and Song (2015) applied it for modeling three-dimensional hydrodynamics and water quality of Youngsan River, Korea. Recently, EFDC has been applied in Total Maximum Daily Load (TMDL) programs in which water quality of a watershed is estimated, a few scenarios are set-up and analyzed, and pollution loads are allocated (Kang and Jang, 2015; Wang et al., 2015).

The Malaysian government has initiated a nationwide stream restoration plan to make national waters clean. Kuantan which is the capital city of Pahang, the largest state in Malaysia has also initiated a restoration project for Galing River, the most important branch of Kuantan River flowing through the city. Since there is no WWTP along the river, all the wastewater from nearby residences and industries flows into Galing River. At present, the river is so polluted that almost no aquatic life can be found (Kozaki et al., 2016). Therefore, the city plans to build a WWTP at the downstream of Galing River. In addition, the city, if necessary, intends to pump the treated wastewater to the upstream of the river. Lastly, treatment of all the water from small tributaries (a total of 6 tributaries along Galing River) is also considered; in this case, a treatment facility can be installed at the junction of each tributary and the river. Therefore, this study was conducted to assess the effects of installing a new WWTP for treating wastewater from residential area and polluted tributary water on overall water quality of Galing River. A numerical model was formulated with EFDC and a scenario analysis was performed. A total of five scenarios were set up depending on the discharge point of the WWTP and installation of facilities treating polluted water from six tributaries.

Table 1
Scenarios made in this study.

Scenario	Description
1	Water from U-drains and culverts will be collected, transported, treated[a] and discharged at the downstream (M12 in Fig. 1).
2	Water from U-drains and culverts will be collected, transported, treated[a], pumping and discharged at the upstream (M1 in Fig. 1).
3	Water from tributaries (T1–T6 in Fig. 1) will be treated[a] and discharged at the same locations. Total of 6 treatments facilities
4	Combination of Scenario 1 and 3. Total of 7 treatment facilities
5	Combination of Scenario 2 and 3. Total of 7 treatment facilities

[a] Based on treatment efficiency of 80% for TOC, TN, and TP.

Table 2
Water quality data for model calibration.

Site / Para.	M1	M2	T1	M3	T2	M4	M5	M6	T3	M7	M8	M9	T4	M10	M11	T5	M12	T6	M13
pH	6.8	6.5	6.7	6.9	7.0	6.9	6.9	7.0	6.9	6.5	7.2	7.0	6.9	6.8	7.2	6.8	6.9	7.0	7.0
Temp.	20	26	31	30	30	32	29	30	31	30	31	30	30	30	31	30	30	30	30
DO	4.1	3.5	3.7	4.5	3.3	3.9	4.1	5.2	5.1	4	4.2	4.5	3.1	2.7	2.1	2.5	3.1	2.6	2.1
COD	19	20	12	23	20	13	17	36	55	16	13	34	13	16	28	12	18	10	20
TN	8.0	3.4	2.1	9.4	0.8	5.6	2.9	2.8	4.2	4.9	2.1	6.1	6.4	4.9	4.7	6.7	6.1	2.8	4.6
$NH_3—N$	3.0	2.4	1.0	2.5	0.5	2.2	1.4	1.3	1.3	1.4	1.6	1.2	1.7	1.9	1.4	2.5	1.5	1.4	1.4
$NO_3—N$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TP	1.7	0.7	0.3	1.1	0.2	1.2	2.0	1.5	0.7	0.7	0.4	0.7	1.4	1.0	0.8	1.5	1.0	0.9	0.7
PO_4-P	0.9	0.6	0.2	0.4	0.2	0.7	0.4	0.6	0.5	0.3	0.2	0.4	0.5	0.7	0.6	1.2	0.6	0.6	0.6
TOC	8.2	8.1	9.9	5.9	7.7	5.9	5.8	6.5	8.2	6.9	9.2	7.3	6.6	7.0	6.2	5.8	6.8	7.0	8.8
TSS	13	8	23	26	16	21	1	9	11	11	14	3	8	7	5	23	8	3	4

Units: pH (No Unit), Temp. (°C), Water quality ($mg\,L^{-1}$).

2. Methods

2.1. River basin under study and sampling locations

Kuantan is the capital city of Pahang Province, Malaysia. The population of the city is about 427,000 (Kozaki et al., 2016). As shown in Fig. 1, Galing River starts at the Semamb Industry area and joins the Kuantan River at the location of 7.7 km upstream from the opening of the South China Sea (Datusahlan et al., 2013). The mouth of the river is directly affected by tide which travels several kilometers to the upstream of the river. The water quality of Galing River has been deteriorated for the past decades by rapid urban development in the river basin area. The water quality of this river is classified as IV (see Table S1 for the Malaysian Water Quality Standards) (Amirul Juwaidy, 2010).

2.2. Sample collection for water quality evaluation

To better understand the current water quality status of Galing River and model calibration, a total of four sampling events were conducted between September and November 2012. At each sampling event, water samples were collected at 19 sites (13 sites on the main stream and 6 sites on mouths of the river tributaries (Fig. 1)) and water quantity and quality were assessed for each sampling location. In addition, the flow rates of wastewater discharged from 43 U-drains and culvert were measured; the averaged flow rate was 0.005 $m^3\,s^{-1}$. A total of eleven water quality parameters were analyzed.

2.3. Development of scenarios for water quality prediction

A total of five river management scenarios for improving the water quality of Galing River were made (Table 1). The scenarios are as follows: (1) water from all the U-drains and culverts is collected, transported by gravity via sewer, treated and discharged to the downstream of Galing River (M12 in Fig. 1) without treatment of water from tributaries; (2) water from U-drains and culverts is collected, transported by gravity via sewer, treated, and pumped to the upstream of the river for discharge (M1 in Fig. 1) and to augment the river flow without treatment of water from tributaries; (3) water from each tributary is treated and discharged at same locations (T1–T6 in Fig. 1) without treatment of wastewater from U-drains and culverts; (4) Scenarios 1 and 3 are combined, and (5) Scenarios 2 and 3 are combined. In all Scenarios 1–5, the removal efficiencies of all the WWTP and tributary water treatment facilities for TOC (total organic carbon), TN, and TP were assumed approximately 80%, respectively.

2.4. Model setup and calibration

In this study, the EFDC was utilized for simulating water quality change along Galing River. The total model domain from upstream (M1 in Fig. 1) to downstream (M13 in Fig. 1) of the river was 5.3 km long. A total of six tributaries (T1–T6 in Fig. 1) were appended to the model domain of Galing River. M1 and M12 indicate potential locations which are located discharge from the treated wastewater (triangles in Fig. 1) for Scenarios 1, 2, 4, and 5, respectively. The water surface elevations measured at Kuantan were used for the tidal boundary at M13. The meteorological data of Kuantan including air temperature, humidity, radiations, cloud coverage, evaporation, and wind direction and speed were obtained from the Malaysia Meteorological Department.

The model domain consists of 1995 horizontal cells in a vertical layer. Water quality data collected at the upstream and downstream boundaries and junctions of six tributaries to Galing River were used for the model calibration (Table 2). In addition, water quality data for wastewater discharged from a total of 43 U-drains and culverts (Fig. 1) and water collected at T1–T6 were included in the model calibration. The averaged discharge rate of the U-drains and culverts was used for the entire model simulation, assuming that there was no significant variation. The model was manually fitted by changing model parameters (Table S2) to three water quality variables, i.e., TOC, TN, and TP.

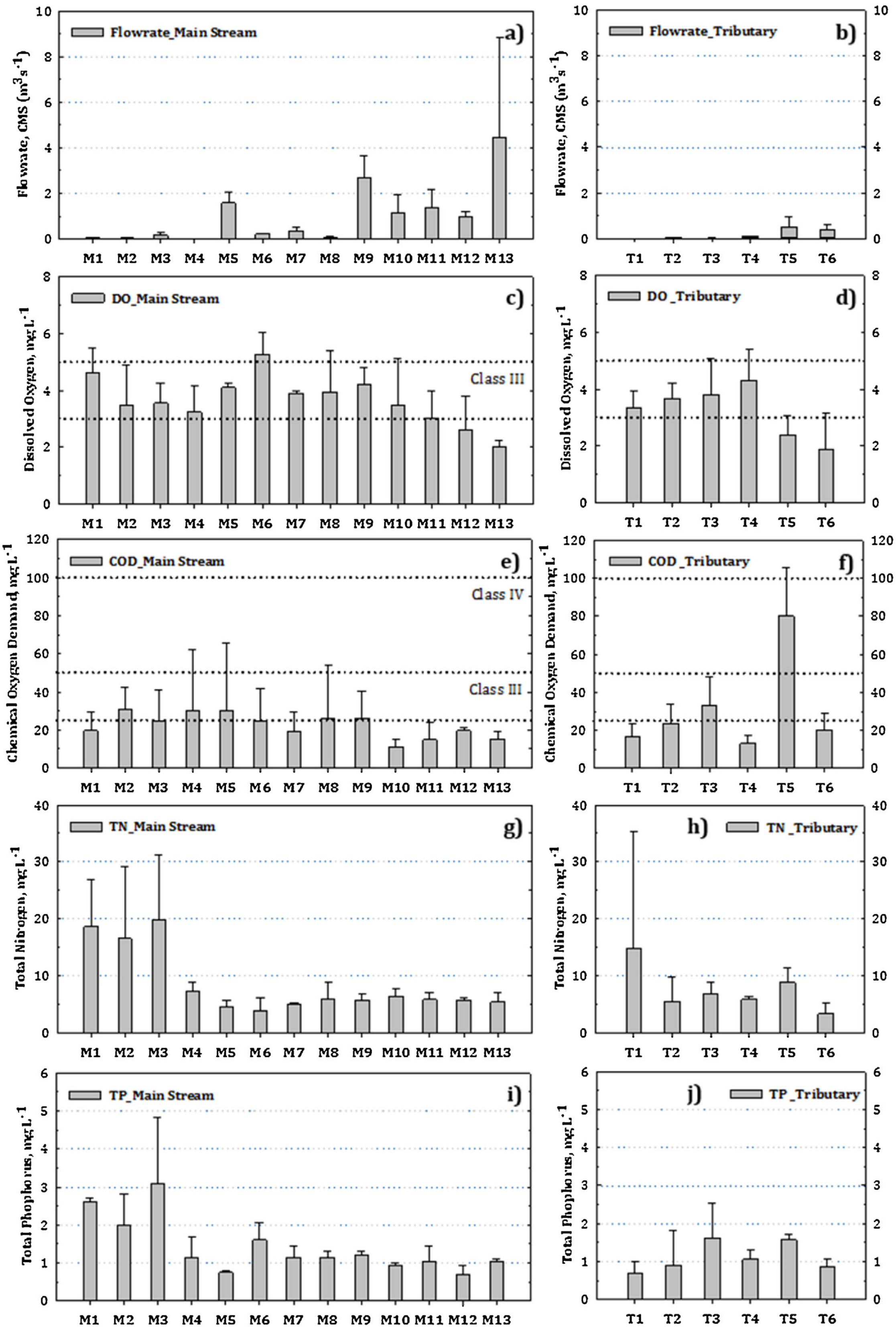

Fig. 2. Flow rate and water quality measured along Galing River; a), c), e), g), and i) for main stream (M1–13) and b), d), f), h), and j) for junctions of tributaries to the river (T1–6) ($n = 4$).

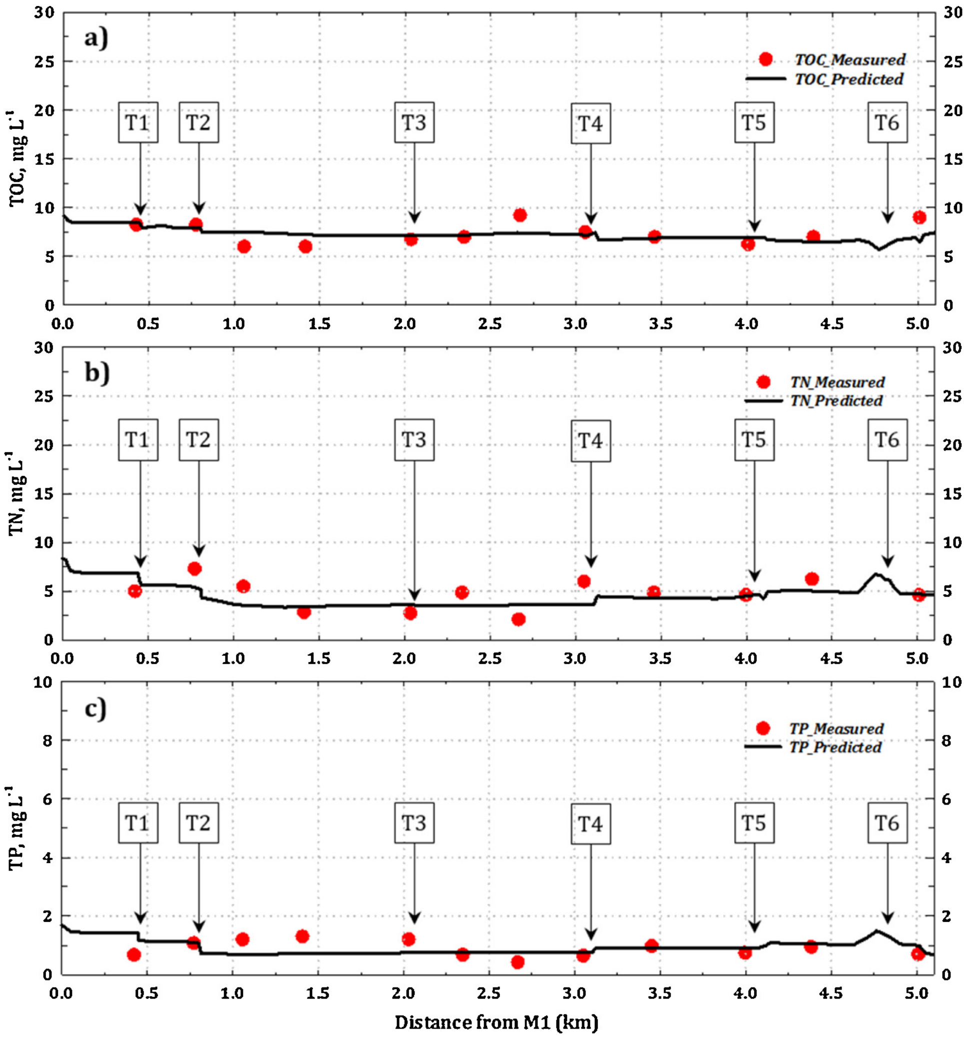

Fig. 3. a) TOC, b) TN, and c) TP measured along Galing River and predicted by the model.

Table 3
Summary of simulation results for Scenarios 1–5.

Parameter	Distance from M1	Current	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
TOC ($mg\,L^{-1}$)	1 km	9.3	10.2 (−9.8)	4.3 (53.4)	2.0 (78.0)	2.8 (69.5)	1.7 (82.1)
	2 km	8.8	10.2 (−16.8)	5.8 (33.4)	2.0 (76.6)	3.0 (65.9)	1.7 (80.9)
	3 km	8.5	10.2 (−19.7)	6.4 (24.7)	2.0 (76.0)	3.2 (62.8)	1.7 (80.3)
	4 km	8.4	8.5 (−1.6)	5.2 (37.5)	1.7 (79.6)	4.1 (51.2)	1.7 (79.9)
	5 km	7.3	6.6 (8.6)	5.0 (31.6)	3.0 (58.2)	5.8 (19.4)	2.9 (59.7)
TN ($mg\,L^{-1}$)	1 km	9.7	11.7 (−19.9)	4.2 (56.7)	2.3 (76.0)	3.0 (69.3)	1.6 (83.7)
	2 km	8.7	11.7 (−35.3)	5.4 (37.3)	2.3 (72.9)	3.1 (64.4)	1.6 (81.7)
	3 km	8.2	11.4 (−39.4)	5.9 (27.6)	2.3 (72.1)	3.2 (60.7)	1.6 (80.6)
	4 km	7.7	7.9 (−2.8)	4.8 (37.8)	1.6 (79.4)	3.8 (50.2)	1.5 (80.0)
	5 km	7.0	5.7 (18.6)	4.7 (32.3)	2.9 (57.9)	5.6 (19.6)	3.0 (57.7)
TP ($mg\,L^{-1}$)	1 km	1.1	1.2 (−5.2)	0.6 (50.3)	0.2 (78.9)	0.4 (66.7)	0.2 (80.1)
	2 km	1.1	1.2 (−7.7)	0.8 (30.1)	0.2 (78.4)	0.4 (65.6)	0.2 (79.9)
	3 km	1.1	1.2 (−10.8)	0.9 (22.5)	0.2 (77.8)	0.4 (63.9)	0.2 (80.1)
	4 km	1.1	1.3 (−13.2)	0.7 (39.0)	0.3 (77.3)	0.6 (51.1)	0.2 (80.3)
	5 km	1.1	0.9 (16.7)	0.7 (34.2)	0.4 (58.9)	0.9 (19.8)	0.4 (59.6)

Note: Numbers in brackets denote % increase/deterioration (negative value) or decrease/improvement (positive value) comparing to the present.

3. Results and discussion

3.1. Water quality of Galing River

The averaged water quality data and quantity ones for each site during all the four sampling events (Tables S3–S6) are presented in Fig. 2. The results reveal that Galing River is extremely polluted in terms of all the water quality parameters. For example, the average COD and DO ranged from 15 to 30 $mg\,L^{-1}$ (Class IIB-III based on Malaysian Water Quality Standards (see Table S1)) and 1.9–5.3 $mg\,L^{-1}$ (Class III–V), respectively. The water quality of the river at the upstream, which has low inflows from small tributaries,

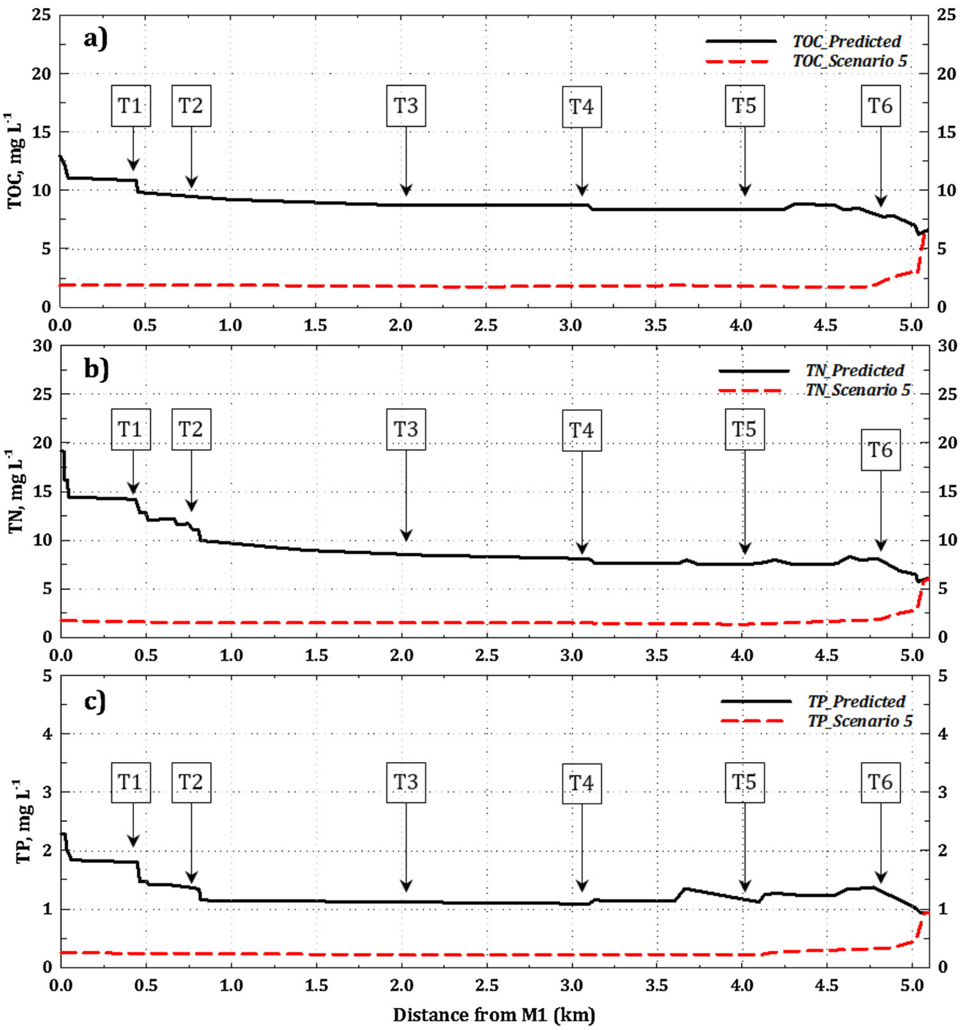

Fig. 4. Comparison of water quality along Galing River when no action is taken (black line) and when Scenario 5 (red line) is applied: a) TOC, b) TN, and c) TP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was worse than that at downstream, which is close to the open ocean and therefore directly affected by tide. For a better understanding of the water quality variation along Galing River, a more comprehensive and long term survey should be carried out.

3.2. Model calibration

Water quality data for samples collected at a sampling event were used to calibrate the model by comparing the model prediction and real data; kinetics and stoichiometric parameters were adjusted to obtain the calibrated model (Table S2). Both water quality and quantity data of each sampling location (i.e., M1–M13 and T1–T6) collected at all the four sampling events were averaged and supplied as input data for the program. The result of the calibrated model for TOC, TN, and TP concentrations at M2-M13 is shown in Fig. 3. The coefficient of determination (R^2) indicating the goodness of fit of the model was calculated 0.70, 0.71, and 0.69 for TOC, TN, and TP, respectively. As shown in Fig. 3, the model relatively well follows the measured TOC, TN, and TP. Therefore, the calibrated model was applied for evaluating different water quality management scenarios. To support a decision making process, the water quality of the river at a pseudo steady-state was predicted.

3.3. Scenario analysis using the calibrated model

The potential water quality improvement was assessed for each management scenario described in Table 1. Since they are commonly adopted as water quality standards by many countries, TOC, TN, and TP were chosen as performance indicators in evaluating the impact of each management scenario. The river was divided into five segments, each of which was about 1 km long. Then, the monthly-averaged concentration for each water quality parameter was predicted for each segment, and each scenario result was compared with the case where no action is taken. Water quality data predicted for Segment 4 (4 km distance from M1) were used to assess the impact of each scenario on Galing River.

When the first scenario was applied, it was predicted that water quality only at the last segment would be improved, in which all the wastewater from U-drains and culverts was assumed to be treated and discharged there. However, water qualities at Segments 1–4 were predicted to be worse than those for the case of no action. This negative result was predicted to change positively if the discharge location is moved to the upstream of Galing River (Scenario 2). When the treated wastewater would be pumped to the upstream for discharge, water quality at the upstream segment was predicted to improve significantly; the averaged water quality of the river for TOC, TN, and TP was estimated to improve by about 37%. If water from tributaries (T1–T6 in Fig. 1) is treated and discharged at the same location (Scenario 3), the overall water quality of TOC, TN, and TP was predicted to improve by about 77%. If both Scenarios 1 and 3 are implemented (Scenario 4) at the same time, overall water quality was expected to improve (up to 50%), compared with the result from Scenario 3. However, it was predicted that the most significant water quality of TOC, TN, and TP improvement (up to 80%) would be possible when Scenario 5 is applied, which is the combination of Scenarios 2 and 3 (Fig. 4 and Table 3).

Based on Scenario 5, seven treatment plants (six treatment facilities for water from tributaries and one WWTP for wastewater from U-drains and culverts) should be constructed. Since wastewater (flow rate: 19,000 $m^3 d^{-1}$) from U-drains and culverts contains high organic and nutrient contents, a large-scaled biological nutrient removal (BNR) system, such as the Anaerobic-Anoxic-Oxic system and the Sequencing batch reactor should be considered. The capital costs for a BNR system is estimated 5–25 million USD (US EPA, 2015). For six treatment facilities for treating water from tributaries, however, a simple physical-chemistry process can be applied. Therefore, the dissolved air floatation (DAF) might be a suitable process for the treatment of water from 6 tributaries. DAF can easily remove suspended solids and phosphorus by more than 80%. Flow rates of the water from the tributaries range 600–43,000 $m^3 d^{-1}$, so the construction cost for each facility is estimated about 0.22–1.6 million USD (Hernández-Sancho et al., 2015).

4. Conclusion

In this study, a total of five water quality management plans for improving water quality of Galing River were evaluated using EFDC. The model results showed that water quality the river would improve most significantly when wastewater from all the U-drains and culverts are collected, transported, and treated by a WWTP with water from six tributaries treated and when the treated wastewater is pumped to the upstream for discharge (Scenario 5). When the treatment efficiency of the WWTP is assumed 80% for TOC, TN, and TP, the water quality of Galing River was expected to improve by about 80%; the river water can be classified in Class II of the Malaysian Water Quality Standards.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2017.01.021.

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