Development of Total Maximum Daily Load Using Water Quality Modelling as an Approach for Watershed Management in Malaysia

S. A. Che Osmi, W. M. F. Wan Ishak, H. Kim, M. A. Azman, M. A. Ramli

Abstract**—**River is one of important water sources for many activities including industrial and domestic usage such as daily usage, transportation, power supply and recreational activities. However, increasing activities in a river has grown the sources of pollutant enters the water bodies, and degraded the water quality of the river. It becomes a challenge to develop an effective river management to ensure the water sources of the river are well managed and regulated. In Malaysia, several approaches for river management have been implemented such as Integrated River Basin Management (IRBM) program for coordinating the management of resources in a natural environment based on river basin to ensure their sustainability lead by Department of Drainage and Irrigation (DID), Malaysia. Nowadays, Total Maximum Daily Load (TMDL) is one of the best approaches for river management in Malaysia. TMDL implementation is regulated and implemented in the United States. A study on the development of TMDL in Malacca River has been carried out by doing water quality monitoring, the development of water quality model by using Environmental Fluid Dynamic Codes (EFDC), and TMDL implementation plan. The implementation of TMDL will help the stakeholders and regulators to control and improve the water quality of the river. It is one of the good approaches for river management in Malaysia.

Keywords**—**EFDC, river management, TMDL, water quality modelling.

I. Introduction

ENVIRONMENTAL issues involving river pollution has become one of the serious problems around the world nowadays. Since the river is one of the primary sources of water supply, facing with these problems can interrupt the routines of daily activities. The main contributor of river pollutions comes from point sources and nonpoint sources [3]. The point sources can be described as single, identifiable source of pollution such as a pipe or a drain; and the nonpoint sources (NPS) can be defined as the various sources of pollution and widely distributed such as pollution from agricultural runoff, precipitation and atmospheric deposition [13], [26]. The discharge of the pollutant from industrial areas, urban areas and runoff from agricultural activities causes the deterioration of river. Rapid development or urbanization of watershed areas has a high impact on the natural environment, thus potentially leading to the significant increase of sediment and pollution into the river. The control strategies, such as TMDL implementation, have been developed by Environmental Protection Agency (EPA) with implemented in United State, to overcome these issues [2], [19]. TMDL programs have been designed to restore water quality in streams, as well as reduce the pollution load from the point and nonpoint sources. Besides that, other countries such as Korea [1], [20], China [27], Taiwan [2] and Thailand [16] have developed TMDL implementation plan.

TMDL can be determined as the total maximum amount of daily pollutant that can enter the water body, without violating the water quality standard [1], [3], [25]. According to the Clean Water Act (CWA), there is a standard procedure in developing TMDL, by assessing the water quality of the river and the impaired water bodies which listed in section 303(d) CWA [22], [24]. After that, the cause of water quality degradation is identified, and the amount of pollutant within the allowable load is allocated to the water bodies. If the water quality of the river has improved, then the water bodies are not listed as impaired river and removed from the 303(d) list [12].

The development of TMDL usually used water quality modelling as the water quality planning tools during the development process. It is one of the best methods to simulate the changes in water bodies including physical, chemical and biological changes, and reflecting the response between load reduction and water quality relationship, besides it creates the scenarios analysis for decision-making process by using mathematical technique [4], [15], [23]. The results obtained from modelling process, and simulation can support the decision-making process that can used by government agencies in the development process [23]. The development of water quality modelling has played significant roles in TMDL development in order the achieved the specific water quality target and assists in decision making process.

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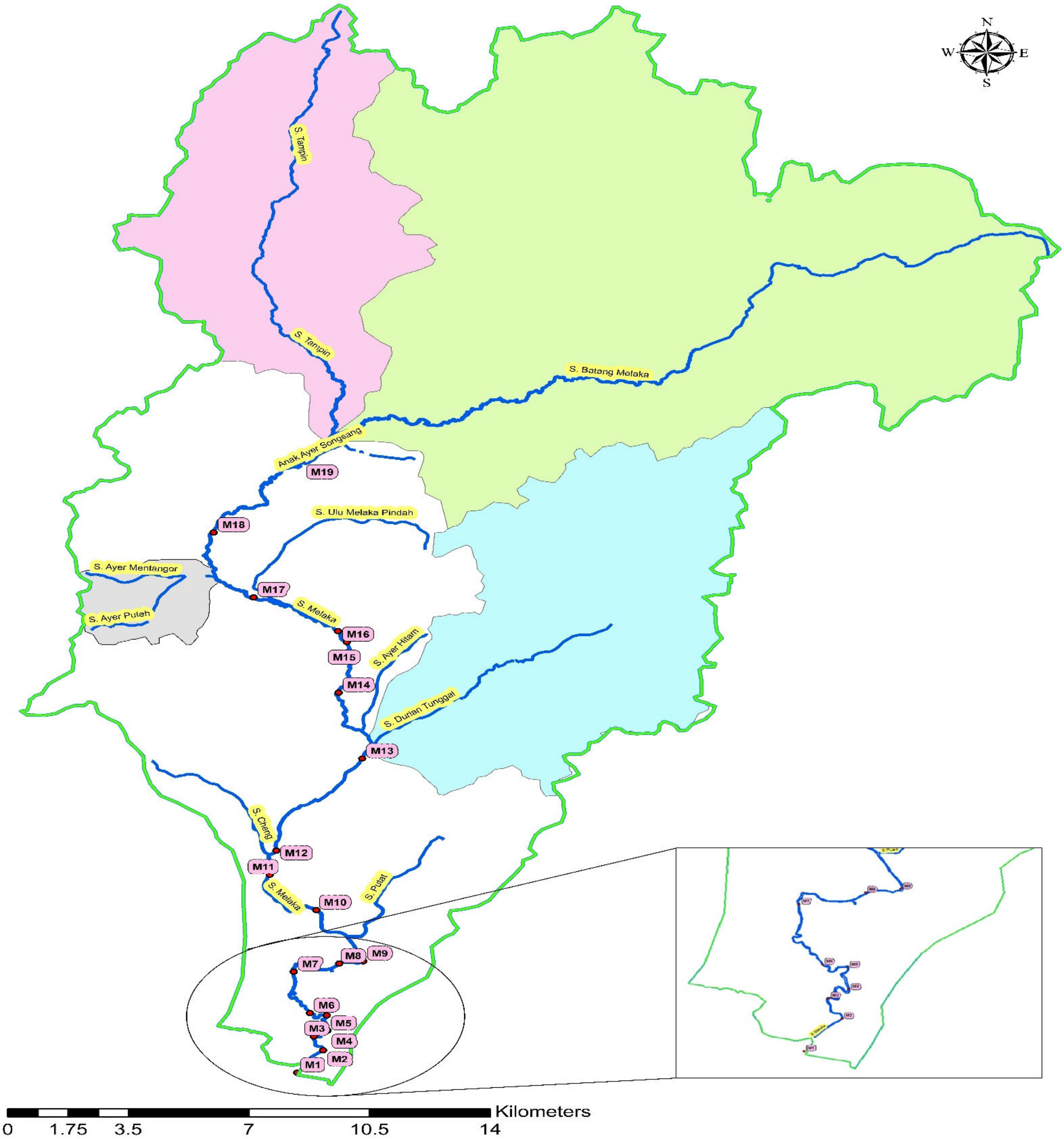

Fig. 1 Malacca River and its tributaries

In Malaysia, there are about 3000 river basins, and the main river basin is more than 80 km^2. There are several approaches implemented for river management to control the river pollution such as Integrated River Basin Management (IRBM) program lead by Department of Drainage and Irrigation (DID), Malaysia. The IRBM coordinates the management of resources in the natural environment based on land and water to ensure their sustainability, by providing the clean and sufficient water, reduce the flood risks and enhance the environmental conservation, to maximize the economic and social benefits. The development of TMDL can be collaborated with IRBM, to develop an effective watershed management.

This study develops a TMDL implementation plan for watershed management to achieve sustainable development using water quality modelling technique. The good water quality standards are set up, and COD are chosen as target water quality parameter to reduce at 25 mg/l, Class II in water quality index (WQI). The target area of the study is Malacca River, in the west Malaysia, by using EFDC as water quality planning tools. Fig. 1 shows the sampling location at Malacca River and the tributaries within Malacca watershed. The scenarios for load reduction analysis are created based on the water quality model generated. The TMDL implementation are choose based on model scenarios created. It further demonstrates a pioneering plan to develop an approach for watershed management in Malaysia.

II. Modelling Framework

A. Study Area

Malacca River is over 40.0 km starting from the mouth of the Straits of Malacca to the Kg. Gadek. The watershed consists of hundreds of tributaries and there are five major tributaries which are Batang Malacca River, Tampin River, Durian Tunggal River, Putat River and Cheng River. Malacca River basin area is 615 km^2 and the land use consists of oil palm, rubber, urbanization, forest, garden mix, open areas, lakes or ponds and others. Malacca River has selected for TMDL development, due to environmental issues such as fish kills accident, smelly river, low dissolved oxygen, and sewage pollution [7].

The study area is divided into four main catchment areas of Malacca River, Durian Tunggal River, Cheng River and Putat River. Site visits were conducted to identify suitable locations to carry out the data collection. There were several key features can describe the Malacca River, where the downstream area is rapidly developing and a focal point for tourism, industrial and residential areas. While the upstream of Malacca River is dominated by farming activities and village areas, which stems from and Tampin River and Batang Malacca River.

B. Data Collection

There are 23 samplings location are selected from Malacca River (20 sampling points; M1-M20), Durian Tunggal River (DT1), Cheng River (C1), and Putat River (P1). The DT1, C1, and P1 are considered as tributaries for Malacca River as shown in Fig. 1. The water quality survey was conducted between Augusts 2014 until November 2014, which based on monthly basis. In-situ parameters such as water temperature, salinity, pH, dissolved oxygen (DO) and conductivity, were analysed using EUTECH Instrument PCD650 (calibrated prior sampling). The latitude and longitude of sampling location are located by using Global Positioning System (GPS). The water samples are collected by using water sampler, and preserved in acid washed plastic bottles.

Samples were analysed based on standard method analysis APHA, 1995. Biochemical Oxygen Demand (BOD), Ammoniacal Nitrogen (NH_3^+), Chemical Oxygen Demand (COD), Total Nitrogen (TN), Total Phosphorus (TP), and phosphate (PO_4^{3-}).

C. EFDC Model Development

The Environmental Fluid Dynamics Code (EFDC) is utilized for water quality modelling in this study. The EFDC is a general-purpose surface water modelling package for simulating 3D flow circulation, mass transport, sediment and biogeochemical processes rivers, lakes, reservoirs, estuaries, and coastal systems [8], [11], [14], [17]. It is an orthogonal, curvilinear grid, hydrodynamic model [21]. The EFDC was originally developed by the Virginia Institute of Marine Science to perform estuarine and coastal studies [9], [10]. Over the past decades, the United States Environmental Protection Agency (USEPA) has continued to support the model development, and the EFDC is now one of the public domain surface water models recommended by USEPA. The governing equation in for EFDC is [27]:

$$\frac{\partial(m_x m_y HC)}{\partial t} + \frac{\partial}{\partial x}(myHuC) + \frac{\partial}{\partial y}(m_x HvC) + \frac{\partial}{\partial z}(m_x m_y wC) = \frac{\partial}{\partial x}\left(\frac{m_y H A_X \partial C}{m_x \partial x}\right) + \frac{\partial}{\partial y}\left(\frac{m_y H A_y}{m_y}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(m_x m_y \frac{A_z}{H}\frac{\partial C}{\partial z}\right) + m_x m_y H S_C \quad (1)$$

where C is the concentration of a water quality state variable; u, v, w, are velocity components in curvilinear, sigma x-, y-, and z- are directions, respectively; A_x, A_y, A_z are the turbulent diffusivities in x-, y-, and z- directions, respectively; S_c is the internal and external sources and sink per unit volume; H is the water column depth; m_x, m_y are the horizontal curvilinear coordinate scale factors. Water temperatures needed for computation of the water quality state variables, and they are provided by the internally coupled hydrodynamic model [27].

D. Grid Generation

The model was setup for the Malacca River. The entire model domain was 38 km long covering M1 to M20. The model domain consists of 1,158 horizontal cells, and the horizontal surface is 65.5 m × 10.9 m (Fig. 2). The model also included of 2 vertical layers. The main boundary for the river imposed at the upstream (M20). Three main tributaries (DT1, C1, and P1) appended to the main river. A total of thirteen proposed outlets (MO1-MO13) added to the main river.

E. Model Calibration

To develop TMDL implementation plan by using water quality model as the analytical framework, it is essential to calibrate the model during the development of water quality modelling [15]. The calibration process determines the relative validity and reliability of model development based on the predicted data against the observed data. The model is considered well calibrated if the prediction fits the estimated adequately [18]. This process was conducted to enable the model reproduce the observed water quality patterns in the river, which the simulated water quality was compared with observed data and key kinetic parameters were adjusted until a reasonable match between model results and data was achieved [27].

The simulation periods started from August 2014 until October 2014. The water quality data collected from upstream boundary (M20) to the downstream (M1), three tributaries (C1, P1, and D1), and thirteen outlets (MO1-MO13) are used for the model calibration in the study. The model calibration is performed for three water quality parameters; COD, TN, and TP. Also, a total of eleven small watersheds were included for the model calibration as shown in Fig. 3. The water quality of small watersheds is assumed to be a measure of the neighborhood. However, due to the lack of data, model validation was not conducted in this study. Therefore, a more comprehensive survey could be performed to better calibrate and validate the model in the future.

III. Result

A. Hydrodynamic Simulation and Calibration

Fig. 4 shows the simulation results for TN, TP, and COD with the observed data. The simulated results matched the observed trend very well, indicating that the water balance in the hydrodynamic model is well maintained except for TP calibration model. The purpose of the water quality calibration was to customize the EFDC water quality model to the local river conditions by evaluating model parameters and to accurately reflect the water quality response to pollutants entering the river. The well-calibrated model can be used for the TMDL calculation which considered as relatively reliable and accurate.

IV. Scenario Analysis on Responses to Load Reduction

After the model had been developed and calibrated, the model was used to analysis several series of water quality load reduction that comply with the required water quality standard. Based on water quality analysis, COD has been selected as the target water quality parameter for TMDL development at Malacca River. According to Department of Environmental Water Quality Index (DOE-WQI) in Malaysia [26], to achieve the Class II standard of water quality, the COD value must be 25 mg/L as shown in Table I.

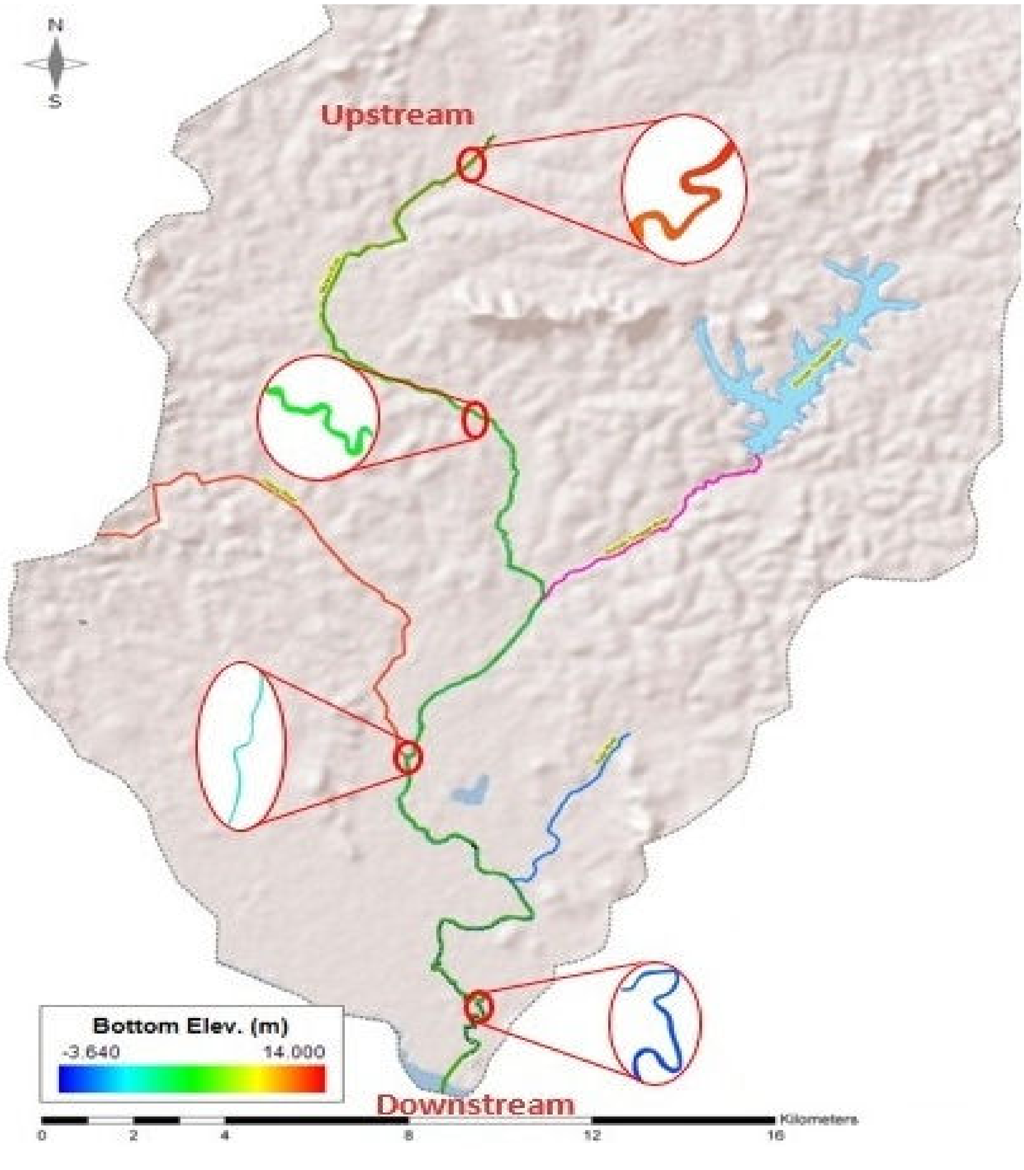

Fig. 2 Segmentation of Malacca River

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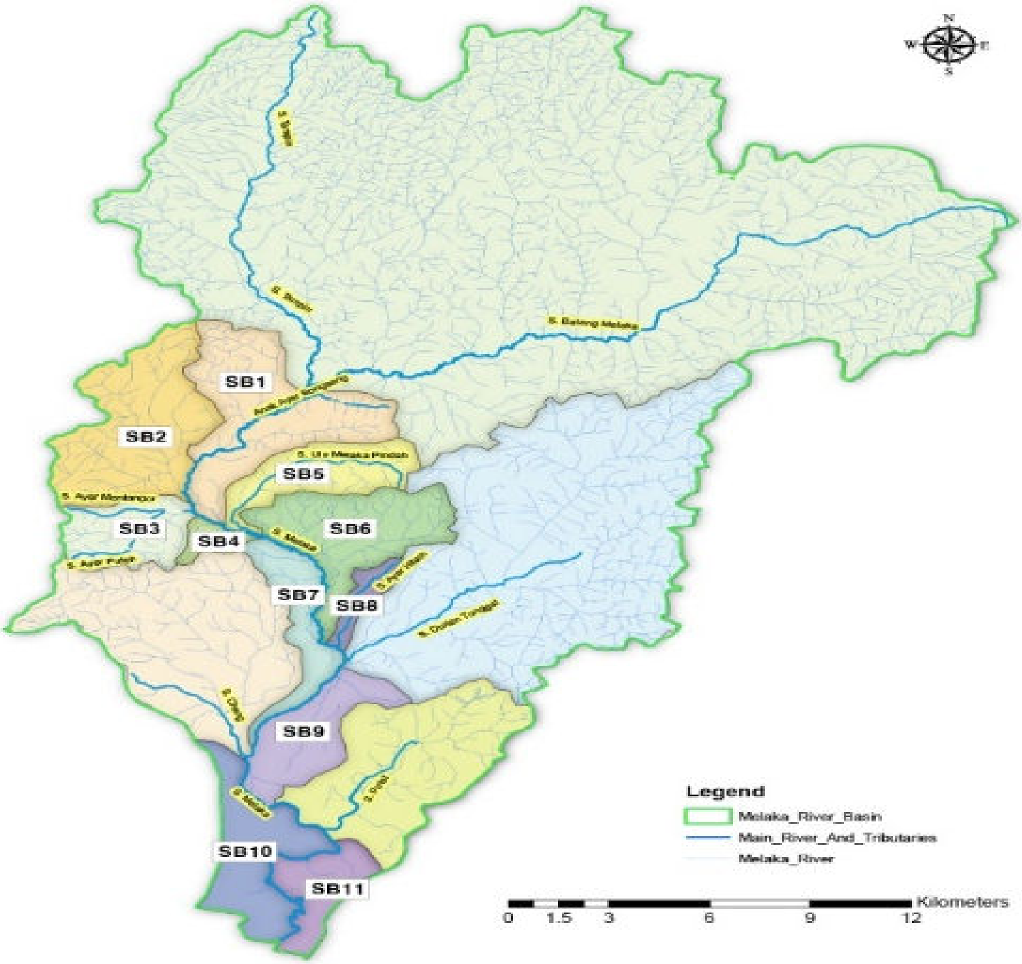


Fig. 3 The other small watershed along Malacca River (SB1-SB11)

TABLE I
WATER QUALITY TARGET BASED ON CLASS-II COD

Parameters	Unit	Classes					
		I	IIA	IIB	III	IV	V
COD	$mg \cdot L^{-1}$	10	25	25	50	100	>100

Class-IIA/IIB represents water bodies of good quality. Most existing source waters of Malaysia come under this category. In practice, no body contact with water of this class is allowed for preventing probable infection with human pathogens.

To identify an action plans to improve the water quality of Malacca River, the four main group of simulation analysis is created and divided into Simulation A, B, C, and D. The Simulation A describes the COD-load reduction at two major point sources (M9 and M12) and consists of three scenarios which is Scenario 1, Scenario 2 and Scenario 3. The Simulation B consists of two scenarios analysis, which is Scenario 4 and Scenario 5, where the COD-load reduction has been done at tributaries only. While Simulation C is created to simulate the load reduction at several point sources (M9-M12), Simulation D represents the combination of load reduction at point sources (M9-M12) and tributaries. The Scenario 6, Scenario 7 and Scenario 8 represent the Simulation C, while Scenario 9, Scenario 10 and Scenario 11 represent Simulation D. The summaries and details of each scenario are described in Table II. For each scenario of COD-load reduction, the model was run to predict how much the river could be improved based on pollution reduction analysis.

In this study, the upstream of the Malacca River becomes higher priority for the improvement of water quality management. The pollution reduction along the upstream of river will give significant improvement in river water quality especially at the cruise area which is located in SB10, a sub-watershed of the Malacca watershed.

TABLE II
LIST OF REDUCTION CONFIGURATION

Simulation	Scenario	Description
A	Scenario 1	M9 and M12 50% Reduction of COD Loading
	Scenario 2	M9 and M12 70% Reduction of COD Loading
	Scenario 3	M9 and M12 80% Reduction of COD Loading
B	Scenario 4	C1 and P1 50% Reduction of COD Loading
	Scenario 5	DT1 30% Reduction of COD Loading
C	Scenario 6	M9-M12 50% Reduction of COD Loading
	Scenario 7	M9-M12 70% Reduction of COD Loading
	Scenario 8	M9-M12 80% Reduction of COD Loading
D	Scenario 9	Scenario 6 + C1, P1 30% Reduction of COD Loading
	Scenario 10	Scenario 7 +C1, P1 30% Reduction of COD Loading
	Scenario 11	Scenario 8 +C1, P1 30% Reduction of COD Loading

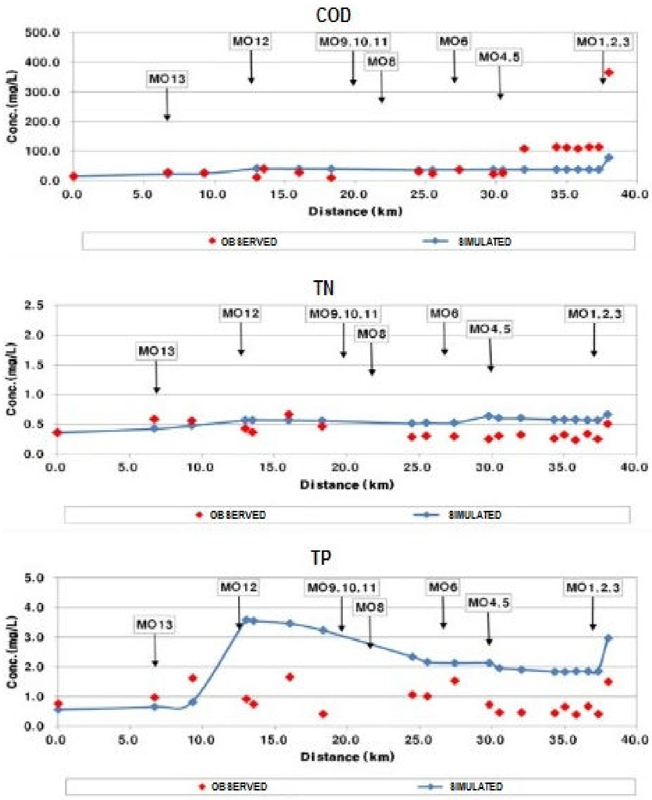


Fig. 4 Model Calibration Simulated vs. Observed water quality concentration (COD, TN, TP)

A. Simulation A: Reduction of Pollution Loading at Two Major Point Sources (M9 and M12)

Based on Simulation A, the load reduction of COD loading are reduced by 50%, 70% and 80% of the loading from the two major point sources which is M9 and M12, for the Scenario 1, Scenario 2, and Scenario 3, respectively. The simulation of COD reduction for Simulation A are shown in Fig. 5, where the reduction of pollution loading from the tributaries was excluded. The significant reduction of COD loading has been done at M12, in Scenario 2 and Scenario 3, the water quality of the Malacca River is expected to improve significantly. However, the targeted COD concentration goal is predicted not to be achieved at the downstream of the river in Scenario 1 and 2.

B. Simulation B: Reduction of Pollution Loading at Tributaries (C1, P1 and D1)

The Simulation B analysis indicates the COD-loads reduction from tributaries which is C1, P1 and D1 as shown in Scenario 4 and Scenario 5. The C1 represents Cheng River, P1 represents Putat River, and D1 represents Durian Tunggal River. The Scenario 4 describes 30% of COD-loads reduction from C1 and P1, while Scenario 5 indicates the 50% of COD-loads reduction from D1. However, pollution loading from point sources are not considered in this simulation. Based on simulation results as shown in Fig. 6, the water quality of the river is expected not to be improved if action plans are made according to Scenarios 4 and 5. The result shows that there is no significant impact on water quality improvement from the reduction of COD loading at tributaries only. Therefore, these two scenarios are not listed as a candidate target for the TMDL program of the Malacca River.

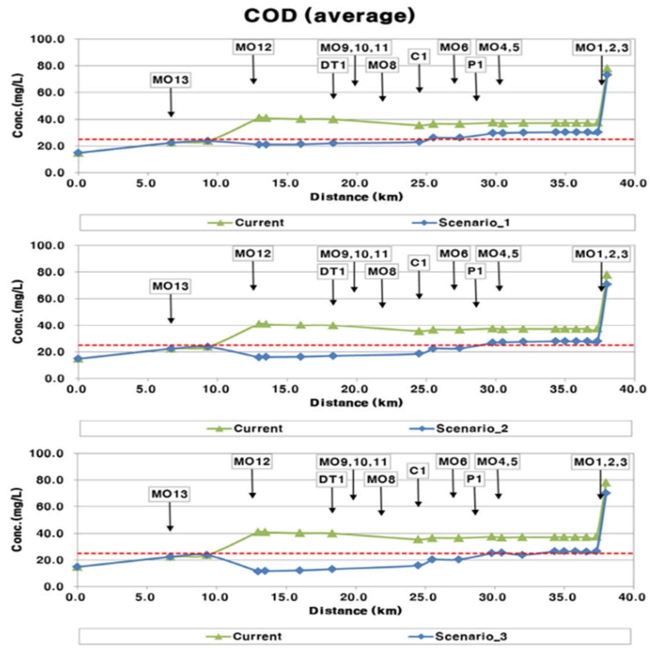


Fig. 5 Comparison of Predicted and Measured Spatial COD Concentrations for Scenarios 1-3

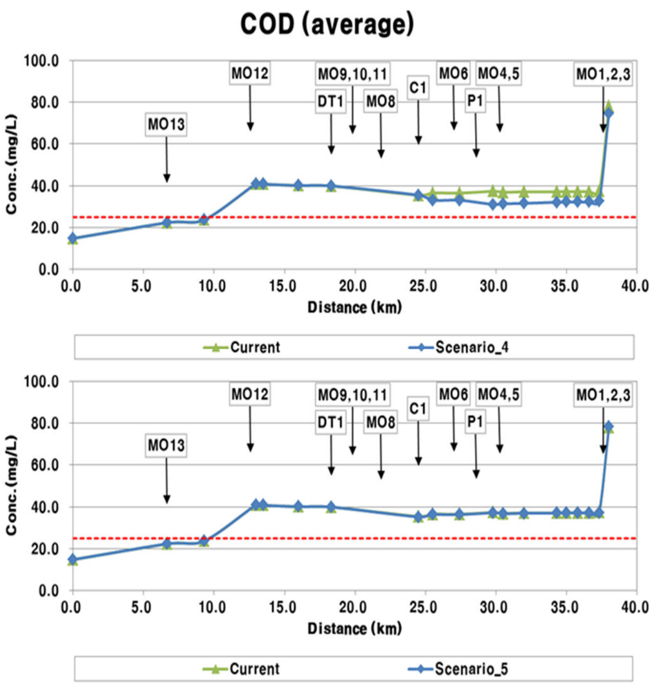


Fig. 6 Comparison of Predicted and Measured Spatial COD Concentrations for Scenario 4 and 5

C. Simulation C: Reduction of Pollution Loading at Several Point Sources (M9-M12)

Simulation C as shown in Fig. 7 describes the Scenario 6, Scenario 7 and Scenario 8, where the COD loading from all the major point sources (M9-M12) reduced by 50%, 70%, and 80%, respectively, while pollution loads from tributaries were excluded. Based on the significant reduction of COD, loading from each point source has done, the water quality of the Malacca River is expected to be improve accordingly. However, the target COD concentration goal is predicted not to be achieved at the downstream of the river in Scenario 6. Nonetheless, two scenarios which are Scenario 7 and 8 can be listed as a candidate target for the TMDL program of the Malacca River.

D.Simulation D: Reduction of Pollution Loading at Point Sources and Tributaries

The Simulation D describes the Scenario 9, Scenario 10 and Scenario 11, where the combination of reduction COD loading from point sources and tributaries are made simultaneously (Fig. 8). The Scenario 9 shows the 50% of COD-loads reduction at M9-M12 and 30% reduction at C1 and P1 (tributaries). While in Scenario 10 shows the reduction of 70% COD loading at M9-M12 and 30% reduction of COD loading at C1 and P1, and Scenario 11 is based on 80% of COD-loads reduction at M9-M12 and 30% of COD-loads reduction at C1 and P1. Since a significant reduction of COD loads from both point and non-point sources is made, the water quality of the Malacca River is expected to improve significantly. In all the scenarios, the target COD concentration goal is predicted to be achieved at the downstream locations of the river. Based on significant improvement are observed from the simulation, the Scenario 9, Scenario 10 and Scenario 11 can be considered as a candidate target for the TMDL program for the Malacca River.

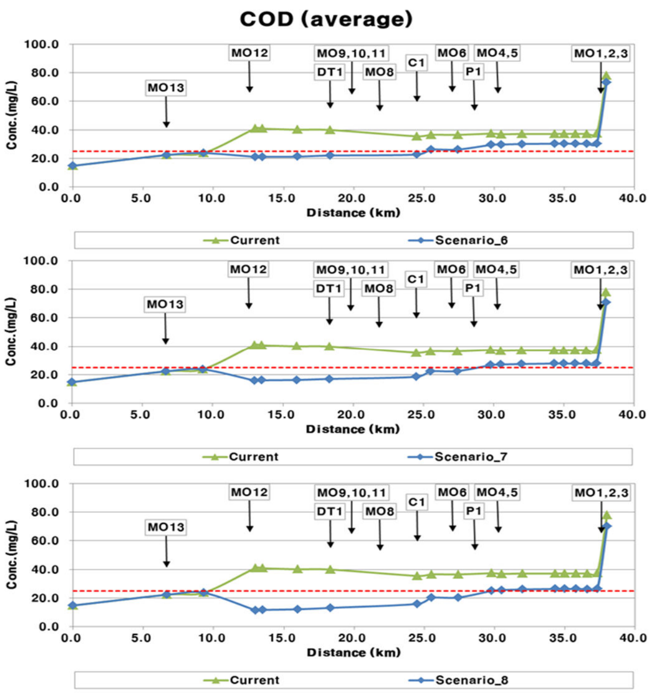


Fig. 7 Comparison of Predicted and Measured Spatial COD Concentrations for Scenarios 6-8

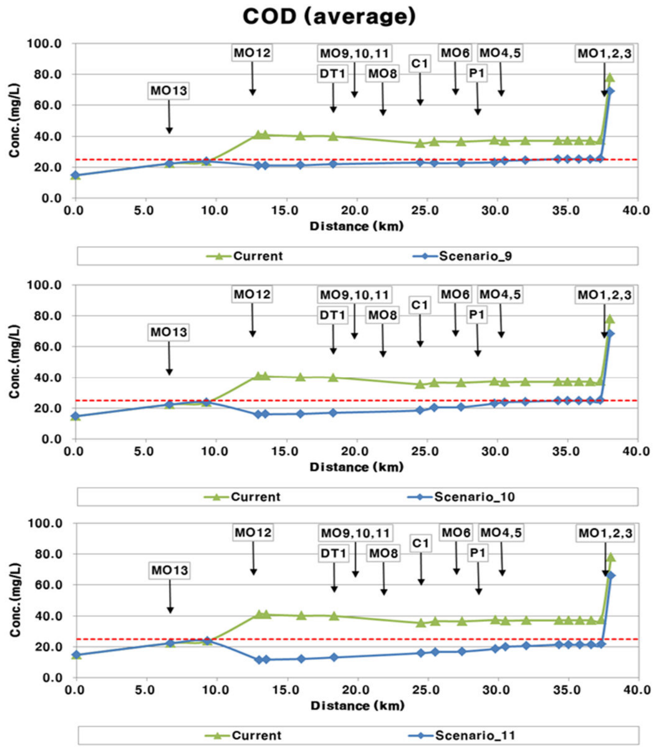


Fig. 8 Comparison of Predicted and Measured Spatial COD Concentrations for Scenarios 9, 10 and 11

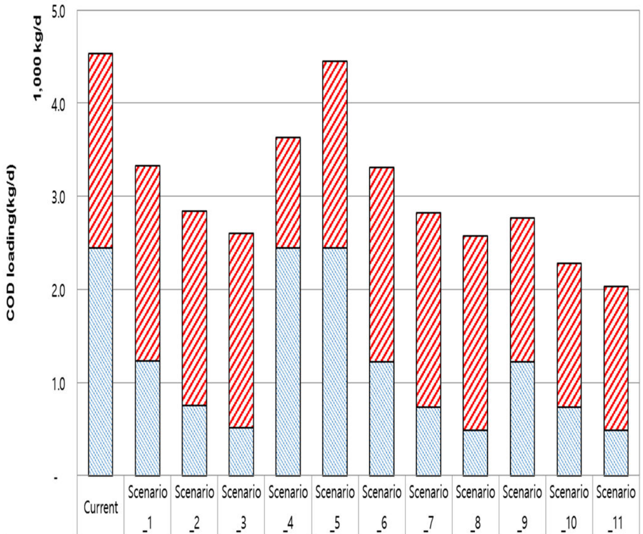
E. Summary of Scenario Analysis

The potential COD-loads reduction estimated for each scenario is summarized in Fig. 9. Based on the simulation created, the most suitable scenarios are chosen as the candidate for TMDL program at Malacca River. Based on the scenario created, Scenario 10 was selected as the best candidate for TMDL programmed at Malacca River, by 70% of COD-loads reduction from all the major point sources (M9-12) and 30% COD-loads reduction from the tributaries (C1 and P1).

It is estimated that COD loads from point sources and tributaries could be reduced, when Scenario 10 is implemented for the watershed. Also, COD concentrations of the effluent from point sources and tributaries waters are presented. Based on the scenario, the effluent of COD concentration from the largest wastewater plant (M12) should be lowered to 15 mg L^{-1}, which requires a more advanced treatment process. It is suggested to maintain the water quality of downstream at Class II. The value was obtained from the model simulation for Scenario 10 (Fig. 8). The effluent of COD concentration from the small factories (M9-11) should be lowered to 20 mg L^{-1}, which may require one of conventional wastewater treatment processes. The COD concentrations of water flowing through the two tributaries are expected to be 20 mg L^{-1} which is also obtained from the model simulation in Scenario 10. To achieve the COD-loads reduction outlined in the selected scenario (Scenario 10), the proper control strategies are required to apply for the wastewater discharged from the point sources and river water from the tributaries.

Regarding point sources, a treatment plant or facility should be built to treat the wastewater [5], [6], [16]. The treatment plants planned for this purpose can consist of physical and biological processes which are responsible in removing the organic and inorganic materials for target parameter of load reduction [4], by applying the following processes such as a using the membrane bioreactor (MBR), a sequencing batch reactor (SBR), an A_2O, and micro-bubble floatation. By considering all the factors regarding the treatment efficiency, the required capital investment, and difficulty in management and operation, the SBR system is the most suitable option to choose as the process to be implemented for the major point sources along the Malacca River.

For non-point sources or tributaries, a constructed wetland along with riparian zones can be presented as a control strategy. Wetlands and riparian areas serve as a significant non-point source abatement system by preventing pollutants from flowing into water bodies; reducing the flow rate of runoff to allow for deposition of the pollutant or infiltration of runoff; and remediating or intercepting the pollutant through chemical or biological transformation.



	Current	Scenario _1	Scenario _2	Scenario _3	Scenario _4	Scenario _5	Scenario _6	Scenario _7	Scenario _8	Scenario _9	Scenario _10	Scenario _11
Tributary	2,089.0	2,089.0	2,089.0	2,089.0	1,184.9	2,004.8	2,089.0	2,089.0	2,089.0	1,546.6	1,546.6	1,546.6
Point Source	2,445.7	1,236.5	752.8	510.9	2,445.7	2,445.7	1,222.8	733.7	489.1	1,222.8	733.7	489.1

Fig. 9 Overall Scenario Configuration of COD Reduction

V. Conclusion

(1) This study developed a hydrodynamic and water quality model for Malacca River, Malaysia by using EFDC water quality modelling. The modelling framework is developed to simulate the load reduction for COD as the pollutant controlled at the selected area. The water quality parameter, COD, is chosen as target water quality parameter, to improve the water quality of Malacca River at Class II based on DOE-WQI requirement. The model is well calibrated using COD, TN, and TP water quality parameter. The model results reproduced the receiving data reasonably well. However, the model was not validated due to limited data availability. The 11 scenarios analysis were created for pollution reduction analysis.

(2) The modelling results show that there was no significant improvement to achieve the Class II of DOE-WQI river water quality requirement, when the COD-loads reduction has only done at tributaries (C1, P1 and D1). The combination of COD load reduction at major point sources and tributaries has shown significant improvement on river water quality at downstream to achieve Class II water quality. The Scenario 10 is selected as the best candidate for TMDL program in Malacca River, by doing 70% of load reduction at major point sources (M9-M12) and 30% reduction at tributaries (C1 and P1).

(3) The study also suggested the installation of wastewater treatment plan as one of best methods to reduce the pollution loading of COD at major point sources areas. The best management practices should be applied for nonpoint sources, to ensure the COD load reduction can be achieved. Therefore, more comprehensive survey is suggested for future study. The continuous monitoring for selected point at study area with post audit of modelling would be useful in tracking the successfulness of TMDL programmed in future.

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