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NUMERICAL MODEL OF SEDIMENTATION AND WATER QUALITY IN KERINCI LAKE

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ABSTRACT: A study of Kerinci Lake in the Province of Jambi, Sumatera Island of Indonesia, is conducted to formulate future actions to conserve the area. The purpose of the study is to investigate the distribution of four parameters [total suspended sediment (TSS), biochemical oxygen demand (BOD), dissolved oxygen (DO), and phosphate]. The study includes field measurements and a numerical model, resulting in a time series of spatial distributions of the hydro-environmental parameters mentioned. The numerical model is driven by discharges from six rivers and generated using a Surface-water Modeling System (called SMS). SMS consists of modules RMA2 for flow modeling, RMA4 for contaminant transport modeling, and SED2D for sedimentation modeling. The result of RMA2 shows an acceptable agreement with the water level and current velocity field measurement data. The model is then developed into a sedimentation and water quality model using SED2D and RMA4, resulting in a yearly change of the investigated parameters. The results show that Tebing Tinggi River outlet has the biggest yearly bed change of around 0.3 m, caused by the high TSS value in the river. The water quality model shows that the BOD, DO, and phosphate concentrations of Merao River outlet are as expected as it has significantly bigger discharges than the other rivers. It is recommended that local authorities provide wastewater treatment facilities, particularly in Merao River, to maintain the sustainability of Kerinci Lake.

Keywords: Numerical modeling, Lake processes, Sedimentation, Water quality, Kerinci Lake.

1. INTRODUCTION

Lake areas are important ecosystems which relate directly to human activities, including not just fisheries and recreational, transportation, and irrigation activities but also daily usage. However, due to the high utilization intensity, lakes are very prone to suffering degradation in quality, such as sedimentation, algal blooms, and high chemical contents (phosphate, nitrate, sulfate, etc.).

Xie et al. (2017) showed that land use has heavily impacted the lake environment in Honghu Lake, China [1]. The study shows that lake regions close to the residential and agricultural area have the highest nitrogen and phosphate concentrations.

Similar studies have also been carried out by Wang et al. (2017) in Nansi Lake, China [2], Dissanayake et al. (1982) in Kandy Lake, Sri Lanka [3], and Vijayvergia (2018) in Udaisagar Lake, India [4].

A study by Nobori et al. (2016) of Fukami-Ike Lake, Japan, showed that the concentration of Chlorophyll-A increased by a factor of 1.6 after revetment work [5]. Another study by Nobori et al. (2016) showed that improvements to drainage facilities have a significant positive effect on the internal production of lakes [6].

In Indonesia itself, a study by Wardhani et al. (2017) on heavy metal contents in Saguling Lake showed that the risk was low to medium [7]. This was as expected since Saguling Lake connects to Citarum River whose watershed covers a large industrial and economic area.

This study was developed to investigate the water quality in Kerinci Lake spatially. The study not only determines the distribution at one time but also presents the yearly changes of the parameters driven by the river discharge. Six rivers connect to the lake, namely Merao, Kapur, Jujun, Merangin, Anak, and Tebing Tinggi rivers. Five of these rivers flow into the lake, while Merangin river is the only one that flows out of it.

The investigated parameters were the total suspended sediment (TSS), biochemical oxygen demand (BOD), dissolved oxygen (DO), and phosphate. The spatial distribution of the yearly parameters was modeled using the SMS modules RMA2, RMA4, and SED2D. RMA2 was constructed to provide the basic flow model, while RMA4 and SED2D were used to develop a sedimentation and water quality model.

Similar studies on numerical models for lake environments have also been conducted by Koue et al. (2018) [8], [9], Adawy et al. (2013) [10], and Melendez et al. (2017) [11]. Koue et al. (2018) numerically modeled thermal stratification with a three-dimensional domain in Biwa Lake, Japan [8], [9]. Adawy et al. (2013) modeled the hydrodynamics and flow pattern in El-Burullus Lake, Egypt, using Delft3D [10]. Melendez et al. (2017) carried out modeling in Olivargas Reservoir using DE-QUAL-W2 [11]. A slightly different

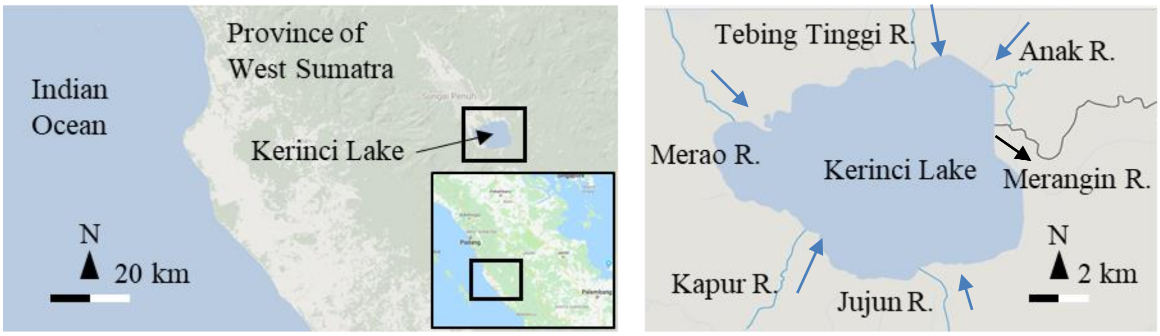

Fig.1 The location of the study area: Kerinci Lake with its surrounding river. The blue and black lines in the right figure show the rivers flowing into and out of the lake, respectively. The arrows depict the direction of river flow.

model was generated by Li et al. (2017) using Hydrus-2D [12]. Hydrus-2D simulated the soil flume phenomena and was used to determine the effect of wind waves on the groundwater level and head pressure change.

2. DATA AND FIELD MEASUREMENTS

To obtain the data needed for numerical modeling, four field measurements were carried out, namely bathymetric, water level, current velocity, and water quality field measurements. River discharges were calculated. The river discharges became the boundary input. The locations of Kerinci Lake and the rivers around it are given in Fig. 1.

2.1 Bathymetric and Topographic Data Measurements

A bathymetric survey was performed using a single beam echosounder. The topographical survey was also conducted using a total station and a water pass. The bathymetric and topographical data were then processed and compiled to create a base map which would become the base map for modeling. The base map datum was referenced to the datum of the National Geodetic Reference. The lowest water level of the lake was obtained from the secondary data recorded by the Sumatera VI Watershed Management Agency, Ministry of Public Works and Housing. The data were recorded for 10 years in the upstream of Merangin River. The total area covered by the field measurement was approximately 4,600 hectares. Figure 2 shows the base map of Kerinci Lake.

2.2 Water Level and Current Velocity Field Measurements

The water level was measured by tide gage for 15 days at the location marked by the green circle in Fig. 3. The hourly current velocity measurements were conducted using a current a meter at a depth of 3 to 10 m for 1 day. The current velocity survey was conducted at four points, indicated by red circles in Fig. 3. These data were used for model validation.

2.3 Water Quality Field Measurements

The water quality survey was conducted at 10 points using a water sampler, indicated by black circles in Fig. 3. The sample water was brought to the laboratory to find the values of the TSS, BOD,

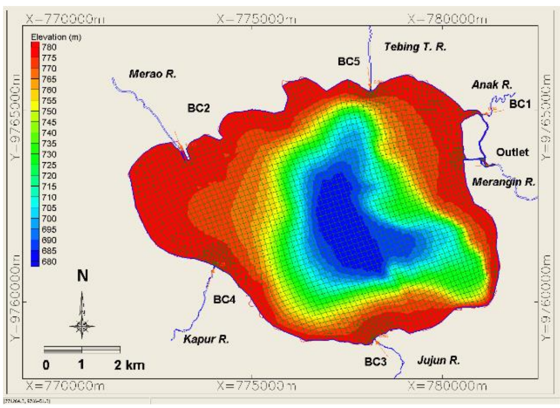

Fig. 2. Base map of Kerinci Lake

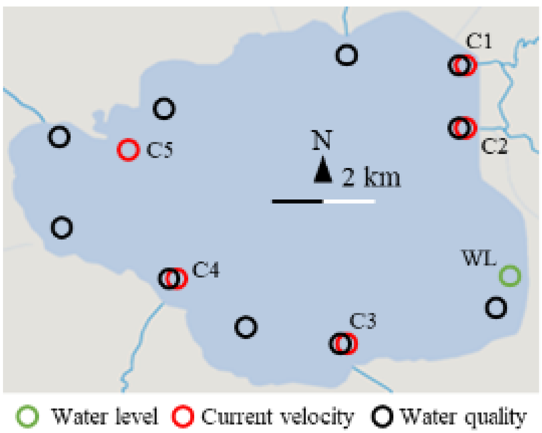

Fig. 3 The locations of field measurements.

DO, and phosphate contents. The results of the water quality survey were then used to set the values of TSS, BOD, DO, and phosphate at the boundaries between the rivers and lake.

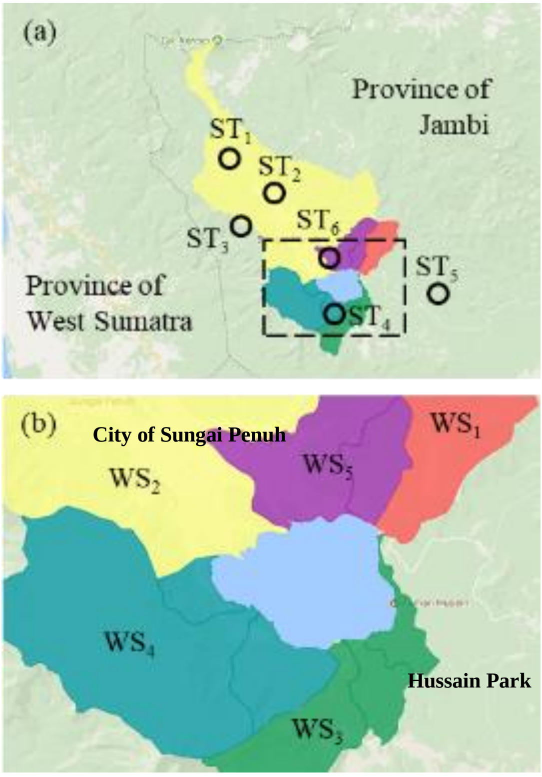

Fig.4 (a) Locations of Rainfall Data Stations and Climatological Station. (b) Watershed area

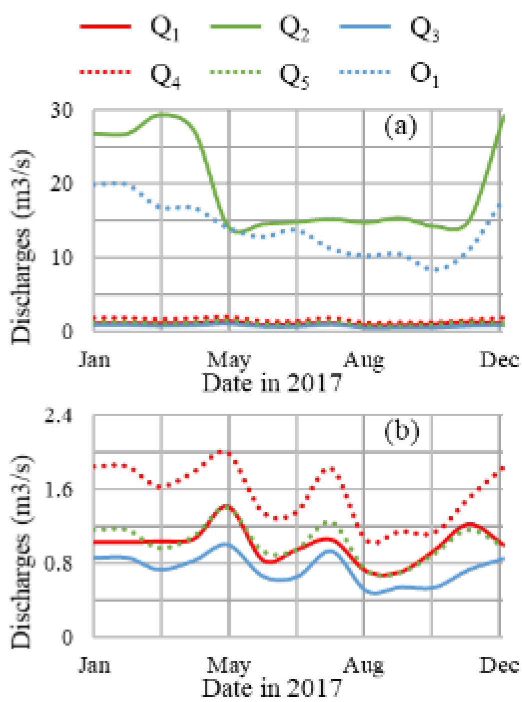

Fig.5 Monthly river discharges for RMA2 model, (a) all rivers discharges (b) Q1, Q3, Q4, Q5 river discharges

2.4 River Discharge Analysis

River discharge analysis was carried out using Mock analysis to find the monthly river discharge by processing the data of the watershed area and climatological data such as rainfall, solar radiation, pressure, wind velocity, and humidity. The watershed area was obtained from the document "Indonesia Movement on Saving the Lake of Kerinci (in Indonesian: *Gerakan Penyelamatan Danau (Germadan)*" [13].

Germadan was arranged by the Indonesian Ministry of Environment and Forest in 2014. The watershed coverage is given in Fig. 4. The areas are named WS1 to WS5, respectively, and the corresponding river discharges are named Q1 to Q5, respectively. WS1 to WS5 denote the watershed areas for the Anak, Merao, Jujun, Kapur, and Tebing Tinggi rivers, respectively. These are the rivers that flow into the lake. The monthly river discharge of Merangin River is denoted by O_1, which corresponds to the river flowing out of the lake.

The climatological and rainfall data were obtained from five rainfall observation stations and one climatological station. The rainfall stations were Siulak Deras, Semurup, Koto Limau Sering, Pulau Tengah, and Tamiai, labeled as ST1 to ST5, respectively, in Fig. 4. The climatological station at Depati Parbo Station is labeled ST6 in Fig. 4. The results of the Mock analysis using the watershed and rainfall data are given in Fig. 5 as river monthly discharges. The monthly discharges for the six rivers are given in Fig. 5a. Figure 5b shows the discharges for the river with values below 2.5 m^3/s.

3. HYDRODYNAMIC MODEL

The hydrodynamic model was developed to simulate the lake processes in Kerinci Lake.

3.1 Governing Equations

RMA2 of SMS uses the two-dimensional finite element method to present the flow condition of the water area forced by tidal or source discharge. The tool was coded by the US Army Corps of Engineering Waterways Experiment Station (USACE-WES).

The three governing equations of RMA2 are presented below; these are the continuity equation and the x and y momentum equations [see Eqs. (1), (2), and (3), respectively] [14].

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \quad (1)$$

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left[E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right]$$
$$+gh\left[\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right]+\frac{gun^2}{\left(1.486h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2}$$
$$-\zeta V_a^{\,2}\cos\psi-2hv\omega\sin\Phi=0 \quad (2)$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left[E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right]$$
$$+gh\left[\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right]+\frac{gvn^2}{\left(1.486h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2}$$
$$-\zeta V_a^{\,2}\sin\psi+2hu\omega\sin\Phi=0 \quad (3)$$

where h is the water depth, x are y the Cartesian coordinates, t is time, u and v are the velocities in Cartesian coordinates, ρ is the fluid density, E is the eddy viscosity coefficient, g is the acceleration due to gravity, a is the elevation of the bottom, n is the Manning's roughness n-value, 1.486 provides the conversion from SI to non-SI units, ζ is the empirical wind shear coefficient, V_a is the wind speed, ψ is the wind direction, ω is the rate of angular rotation of the Earth, and Φ is the local latitude.

3.2 Model Setup

Previously, hydrodynamic modeling using SMS was performed by Ajiwibowo and Pratama in a study about North Jakarta reclamation [15], [16]. The modeling took place in North Jakarta Bay, which connects the North Jakarta coastal area and the Java Sea. The model was forced by tidal and river discharge. The simulation results were in good agreement with the field survey data.

However, since this study took place in a closed water area, specifically at Kerinci Lake, the model is only forced by the river discharges. The fluctuation of the lake water level is only a function of river discharge.

Five main rivers were considered to significantly affect the water flow in Kerinci Lake, namely the Anak, Merangi, Jujun, Kapur, Merao, and Tebing Tinggi rivers. Their river discharge values are given in Fig. 5. The discharges varied monthly as shown by the hydrological analysis. Later, the resulting water elevation and current velocity from the model were validated with the field measurement data.

After the validation, the flow model constructed by RMA2 was developed into a sediment and water quality model by SED2D and RMA4. To develop the sediment model using SED2D, the TSS was added to the river boundary inputs. The TSS values of the rivers and the lake's initial condition are given in Table 1.

For the water quality modeling using the RMA4 module, three parameters were investigated, namely BOD, DO, and phosphate. The parameter values of river inputs and the initial condition at the lake are given in Table 1.

Table 1 Values of the water quality parameters for rivers input (denoted by Q1 to Q5) and the lake initial condition (denoted by "initial at the lake").

	TSS	BOD	DO (mg/l)	Phosphate
Q1	26	0.63	6.53	0.026
Q2	27	1.33	6.90	0.028
Q3	18	0.63	6.53	0.032
Q4	17	0.77	5.18	0.030
Q5	29	0.58	5.76	0.032
Initial at lake	24	0.50	5.00	0.025

3.3 Model Validation

To determine the accuracy of the hydrodynamic model, the resulting water elevation and current velocity data from the model simulation were compared with field measurement data. The results of the water elevation validation are given in Fig. 6. The validation location for water level is given in Fig. 3 as WL, denoted by the green circle. The solid red line and dotted black lines are the model and field data, respectively. Figure 6 shows a good agreement between the model and field measurement data.

The current velocity validation is given in Fig. 7. There were five locations for current validation, which are shown by the red circles labeled as C1 to C5 in Fig. 3. The solid red line and black dots are the model and field data. The validations with the field data show good agreement. The model results for C4 and C5 show better validation with the field data (see Figs. 7d and 7e).

4. RESULTS AND ANALYSIS

After the model validation, the model was then developed into sedimentation and water quality models to find the sedimentation pattern and the

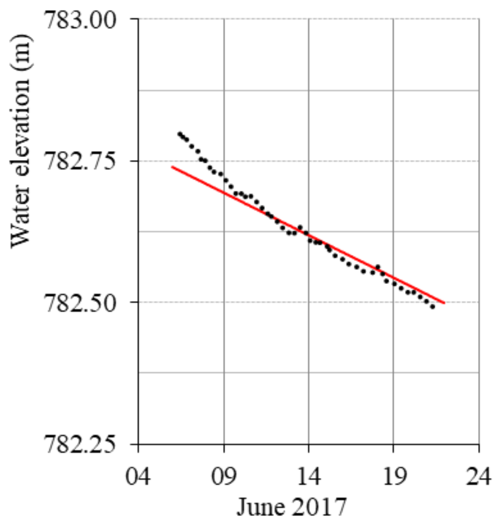

Fig. 6 Result of water level validation at WL.

distribution of BOD, DO, and phosphate at Kerinci Lake. The analysis presented in this chapter will show the yearly sedimentation pattern particularly at locations/sections with the most significant bed changes. The yearly change of water quality parameters (BOD, DO, and phosphate) in spatial distributions are also discussed.

4.1 Sedimentation

The result of the sediment model for one year is given in Fig. 8. The figure shows that the bed change is mostly significant around the river-mouth while in the middle of the lake the change it is insignificant.

A clearer view of the yearly bed change is given in Fig. 9a. The surroundings of the mouth of Tebing Tinggi River show the highest rate of bed change. Figure 9b shows two cross-sections, A and B, presenting the details of the bed change. It shows that the bed change ranges from 0.08 to 0.3 m in a year. The highest bed change is obtained at the river mouth. Conservation action in the form of depth-maintenance dredging using methods such

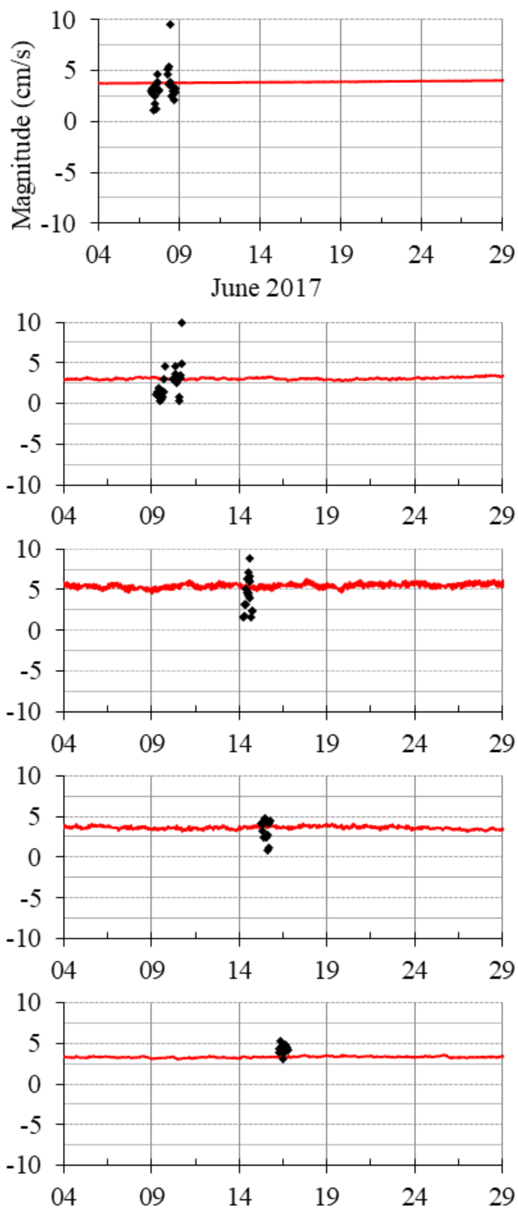

Fig. 7 Result of current velocity validation at C1 to C5, respectively, from top to bottom.

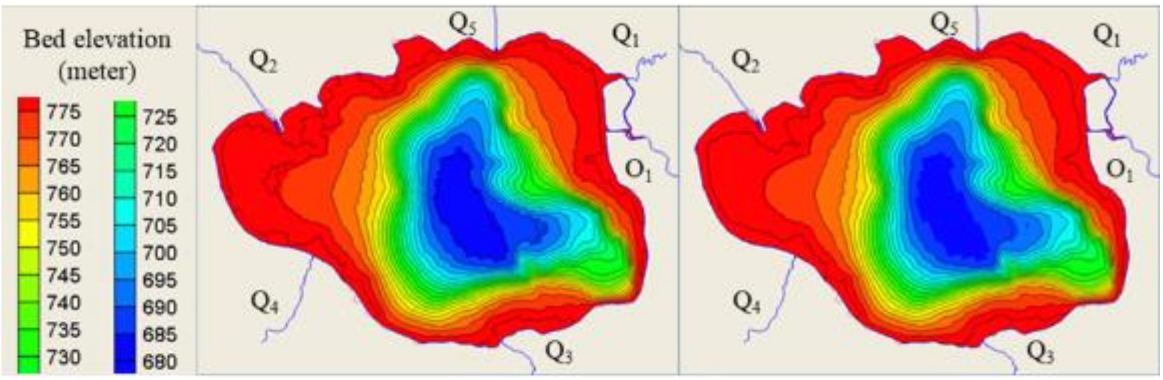

Fig. 8 Comparison of lake bed elevations before (left) and after (right) one year.

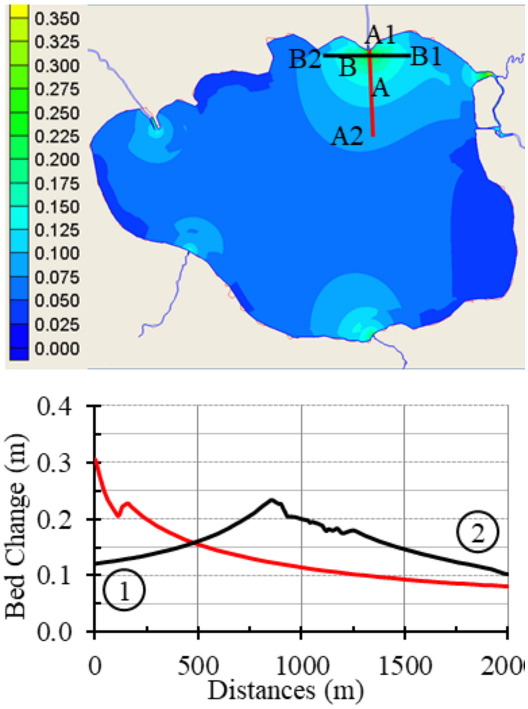

Fig. 9 (a) Detailed view of bed change near Tebing Tinggi River inlet. (b) The red and black lines are the bed changes for sections A and B, respectively.

as clamp-shell dredger, excavator dredger, or cutter suction dredger is needed to preserve the depth of Kerinci Lake.

4.2 Water Quality

Three parameters were investigated in this study: BOD, DO, and phosphate. The changes in the parameters after one year are given in Fig. 10. In this study, seven points were observed as shown in Fig. 10. Six points were located at each river mouth (Merao, Tebing Tinggi, Anak, Merangin, Jujun, and Kapur) and one point was at the center of the lake; these points are denoted by P1 to P7, respectively. The points were placed to show the change after one year at the particular points given in Table 2. The maximum, minimum, and average values within one year were noted.

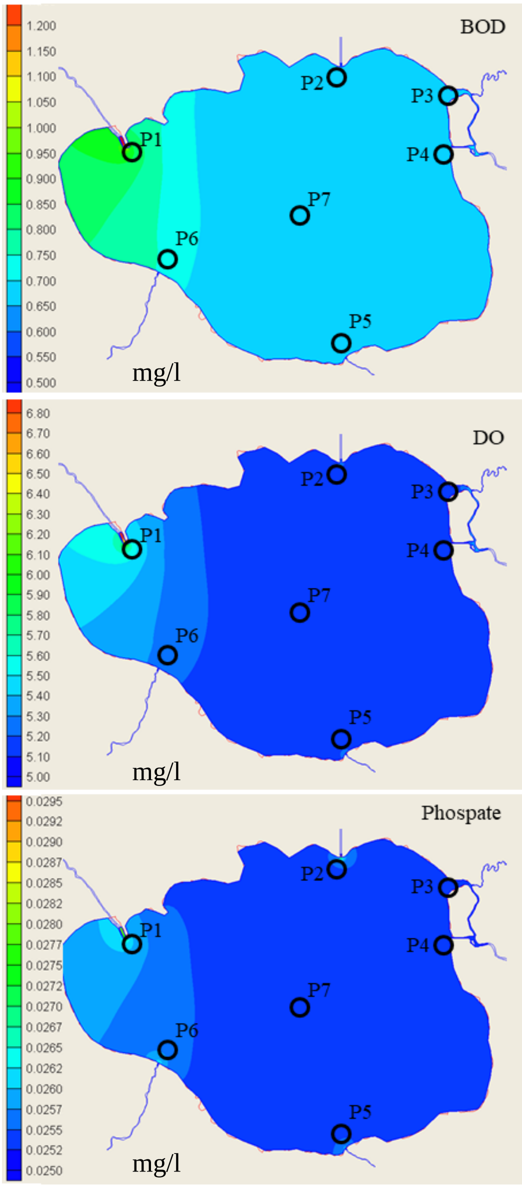

Fig. 10 The spatial distribution of BOD, DO, and phosphate (top to bottom) after one year.

Figure 10a shows that P1 (located at the mouth of Merao River) exhibited a greater change than other locations. The maximum changes in BOD, DO, and phosphate at P1 were 1.246, 5.881, and 0.027 mg/l respectively.

Table 2 Values of parameters at the investigated points

No	Points	BOD (mg/l)			DO (mg/l)			Phosphate (mg/l)		
		Max	Aver	Min	Max	Aver	Min	Max	Aver	Min
1	P1	1.246	0.999	0.644	5.881	5.608	5.276	0.027	0.026	0.025
2	P2	1.18	0.884	0.503	5.604	5.343	5.004	0.027	0.026	0.025
3	P3	1.197	0.902	0.527	5.608	5.353	5.012	0.027	0.026	0.025
4	P4	1.192	0.893	0.515	5.6	5.338	5.002	0.027	0.026	0.025
5	P5	1.187	0.89	0.507	5.608	5.345	5.005	0.027	0.026	0.025
6	P6	1.206	0.922	0.519	5.663	5.397	5.009	0.027	0.026	0.025
7	P7	1.183	0.885	0.501	5.605	5.342	5	0.027	0.026	0.025

The BOD value around Merao River (Q2) was highest after one year's simulation since the existing BOD value at the mouth of Merao River was the highest. The DO value at the mouth of Merao River showed the same trend. This trend shows that Merao River can be considered to provide the main governing conditions of Kerinci Lake. This is as expected because the discharge of Merao River is bigger than those of the other rivers.

4.3 Assessing the Condition of Kerinci Lake

Referring to the Indonesian Government Regulation number 82, the year 2001 (PP 82, the year 2001) for Water Quality Management and Water Pollution Control [17], the quality standards of a water area are divided into classes I to IV based on its physical, chemical, and biological contents. Table 3 shows the water quality standard values according to PP 82, 2001, of the four parameters investigated in this study. Class I is the standard for raw water for drinking. Classes II, III, and IV comprise water for irrigation, fisheries, and so on.

Table 3 Water quality standards of the four investigated parameters based on PP 82, 2001.

Parameters (mg/l)	Class			
	I	II	III	IV
TSS (max)	50	50	400	400
BOD (max)	2	3	6	12
DO (min)	6	4	3	0
Phosphate (max)	0.2	0.2	1	5

Compared to the values in the table above, the maximum BOD value obtained from the field survey and numerical model is 1.33 mg/l, which is still good for all classes. The minimum value of DO is 5 mg/l, which is in the range of Classes II to IV. The maximum phosphate content is 0.027 mg/l, which is good for all classes. For the TSS survey, the maximum content is 29 mg/l (from field measurement). The TSS value is still under the maximum value given by the standard, and thus the lake is good in terms of TSS for all classes.

As an overall assessment considering these four parameters only, Kerinci Lake should aim to provide water only for freshwater fish farming, farms, and irrigation. If the water is needed as raw material for drinking water, it should be treated first.

5. CONCLUSION

The numerical model of Kerinci Lake using RMA2 of SMS showed a good validation result against water level and current velocity measurement data. It was then further developed to create sedimentation and water quality models to investigate the sedimentation distribution pattern and the BOD, DO, and phosphate distribution.

The model shows that the inlet of Tebing Tinggi River is the location with the greatest bed change. Overall, the lake bed suffers sediment deposition, which may lead to a decrease in the lake capacity.

A similar conclusion is also found in the BOD model analysis. Merao River has the highest value of BOD and hence causes the biggest BOD change across the lake at the river inlet. However, the model of DO and phosphate content also shows that Merao River inlet results in the biggest change, even though the boundary condition values of DO and phosphate of this river are smaller than those of the other rivers.

The dominant contribution of Merao River to the BOD, DO, and phosphate to Kerinci Lake is caused by the large river discharge. As Merao River plays an important role in governing the environment of Kerinci Lake, it is recommended that local authorities provide wastewater treatment facilities to maintain lake sustainability.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Xie Y, Li K, Wang L, Li Z, Wang X, Fang Q, "Exploring the spatial-seasonal dynamics of water quality, submerged aquatic plants and their influencing factors in different areas of a lake", Water, Vol. 9, 2017, p. 707.

[2] Wang L, Xia J, Yu J, Yang L, Zhan C, Qiao Y, Lu H, "Spatial variation, pollution assessment and source identification of major nutrients in surface sediments of Nansi Lake, China", Water, Vol. 9, 2017, p. 444.

[3] Dissanayake CB, Senaratne A, Weerasooriya SVR, De Silva SHG, "The environmental pollution of Kandy Lake: A case study from Sri Lanka", Environmental International, Vol. 7, 1982, pp. 343–351.

[4] Vijayvergia RP, "Eutrophication: A case study of highly eutrophicated Lake Udaisagar, Udaipur (Raj.), India with regards to its nutrient enrichment and emerging consequences", in Proc. Taal 2007: The 12th

World Lake Conf., 2007, pp. 1557–1560.

[5] Nobori M, Suda H, Oyagi M, Yokoyama A, Yagi A, "Changes of chlorophyll-A, bacteriochlorophyll-C and DOC before and after revetment work in Lake Fukami-Ike, Japan", International Journal of Geomate, Vol. 11(25), 2016, pp. 2416–2421.

[6] Nobori M, Suda H, Oyagi M, Yokoyama A, Yagi A, "Changes in depth and the sediment rate before and after the lakeshore development in Lake Fukami-Ike, Japan", International Journal of Geomate, Vol. 11(26), 2016, pp. 2547–2552.

[7] Wardhani E, Notodarmojo S, Roosmini D, "Heavy metal speciation in sediments in Saguling Lake West Java Indonesia", International Journal of Geomate, Vol. 12(34), 2017, pp. 146–151.

[8] Kuoe J, Shimadera H, Matsuo T, Kondo A, "Evaluation of thermal stratification and flow field reproduced by a three-dimensional hydrodynamic model in Lake Biwa, Japan", Water, Vol. 10, 2018, p. 47.

[9] Kuoe J, Shimadera H, Matsuo T, Kondo A, "Numerical assessment of the impact of strong wind on thermal stratification in Lake Biwa, Japan", International Journal of Geomate, Vol. 14(45), 2018, pp. 35–40.

[10] El-Adawy A, Negm AM, Elzeir MA, Saavedra OC, El-Shinnawy IA, Nadaoka K, "Modeling the hydrodynamics and salinity of El-Burullus Lake (Nile Delta, Northern Egypt)", Journal of Clean Energy Technologies, Vol. 1(2), 2013, pp. 157–163.

[11] Jofre-Melendez R, Torres E, Ramos-Arroyo YR, Galvan L, Ruiz-Canovas C, Ayora C, "Reconstruction of an acid water spill in a mountain reservoir", Water, Vol. 9, 2017, pp. 613.

[12] Li Y, Simunek J, Wang S, Zhang W, Yuang J, "Simulating the effects of lake wind waves on water and solute exchange across the lakeshore using Hydrus-2D", Water, Vol. 9, 2017, pp. 566.

[13] Idris A, Asropi, Manurung H, Harahap TN, Retnowati, Nasution SR, Rustadi WC, "Gerakan Penyelamatan Danau, Danau Kerinci", Indonesian Ministry of Environment, 2014.

[14] User Guide to RMA2 WES Version 4.5. USA: US Army, Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulic Laboratory, 2005, ch. 2, pp. 4–6.

[15] Ajiwibowo H, Pratama MB, "The influence of the Jakarta Bay reclamation on the surrounding tidal elevation and tidal current", International Journal of Geomate, in the press, corrected proof, 2017.

[16] Ajiwibowo H, Pratama MB, "The effect of gate existence at L Island on the seabed profile due to the reclamation of Jakarta Bay", International Journal of Engineering and Technology, Vol. 9, 2017, pp. 3763–3774.

[17] Indonesian Government, "Peraturan Pemerintah nomor 82 Tahun 2001 tentang Pengelolaan kualitas air dan pengendalian pencemaran air", Indonesian Government, 2001.