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WATER QUALITY AND SEDIMENTATION MODELING IN SINGKARAK LAKE, WESTERN SUMATRA

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ABSTRACT: Numerical modeling of the spatial distribution of water quality in Singkarak Lake, Western Sumatra, Indonesia is conducted. Field measurement data are collected, including bathymetry, water level, current velocity, and water quality data. The measured parameters in the water quality survey are the total suspended sediment (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO) and phosphate (P). The finite element model is implemented using a surface-water modeling system (SMS). The model includes flow, constituent, and sedimentation models. Validation of the flow model is achieved by matching the current and the water elevation between the model and the field data. The validation shows good agreement. The model is aimed at observing yearly water quality and sedimentation change at the lake. The results from the constituent model show that the Sumpur and Sumani Rivers are having the greatest effect on the water quality of the lake in its northern and southern regions, respectively. A bed change of around 30–40 cm per year is found at the inlets of both of these rivers. Overall, the model shows that the lake water is only suitable for irrigation or fishing hatchery, and not for drinking water, according to the criteria for water quality standards in the Indonesian government's Regulation 82 of 2001.

Keywords: Numerical modeling, Water quality, Singkarak Lake

1. INTRODUCTION

Water pollution has been one of the most important issues concerning the environment. Not only in large oceans but also in rivers and lakes which are closely related to daily life. Few studies on lake-water pollution have been taken in countries such as Egypt, Iran, and the USA. The study in Egypt was carried out by Aly et al. (2018) [1]. They found that the sedimentation pattern in Lake Nasser is affected by the semi-enclosed embayment and the metal pollutions are brought by floods. Mardi et al. (2018) studied aerosol pollution in Lake Urmia, Iran [2], whereas Sherchan et al. (2017) particularly assess fecal pollution in Lake Pontchartrain, Louisiana [3].

In this study, hydrodynamic numerical modeling on Singkarak Lake, Western Sumatra, Indonesia is performed. Hydrodynamic model is used to predict the material distribution in the water [4]–[6]. Surface-water modeling system (SMS) tools such as RMA2, RMA4, and SED2D are used. Besides SMS, Deflt3D [7], MIKE [8], EFDC [9], and CE-QUAL-W2 [10] are widely used to model the ecosystems of lakes or other bodies of water.

The studied material is COD, BOD, DO, and phosphate, which highly influences the lake water quality [11]–[13]. High land use for agriculture and fish farming can lead to high phosphorus pollution. This study also includes field measurements and numerical model resulting in a spatial variations of parameters after a year. The resulted contaminant distribution will be compared with the authority regulation [14] which classify lakes into 4 classes based on the contaminants content.

1.1 Overview of Singkarak Lake Condition

The province of Western Sumatra is 42,297.3 km^2. There are five lakes in the province. They are Maninjau Lake, Singkarak Lake, Dibawah Lake, Diatas Lake, and Talang Lake, as seen in Fig. 1, and indicated by numbers 1 to 5, respectively. Singkarak Lake is the largest in Province of Western Sumatra and the second largest in Sumatra Island with an area of around 109,082 km^2 [15].

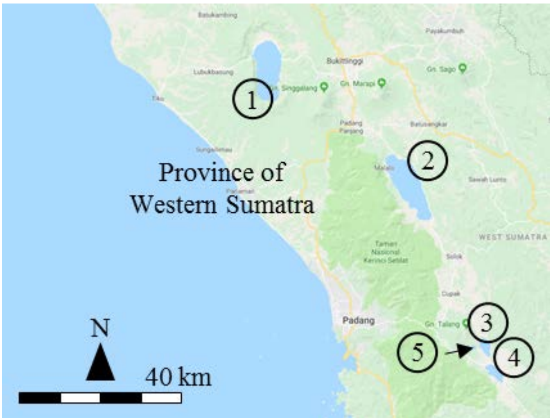

Fig. 1 Lakes in Western Sumatra, Indonesia.

Singkarak Lake has an indispensable role in West Sumatran development. Until now, Singkarak

Lake has been a water reservoir to supply the needs of daily activity, farm irrigation, and a hydropower plant. Recreational, transportation, and fish farming activities also take place in Singkarak Lake. At the same time, Singkarak Lake also becomes a basin for containing waste from sources such as housing and markets, agriculture, and from recreational and transportation activities.

The wastes converging in Singkarak Lake are identified as the main cause of lake quality degradation. In the Bali Agreement of 2009, Singkarak Lake is one among 14 lakes in Indonesia to be prioritized under an integrated management [15], as well as Maninjau Lake.

1.2 Study Location

The study takes place in Singkarak Lake located in Province of Western Sumatra (see Fig. 1). There are nine rivers flowing into Singkarak Lake: Sumani, Sumpur, Anak Cangking, Ambius, Paninggahan, Sibaladi, Batu Panjang, Pingai, and Malalo Rivers. They are denoted by R1 to R9 (see Fig. 2), respectively. There is one river flowing out from Singkarak River denoted by O1, namely Ombilin River.

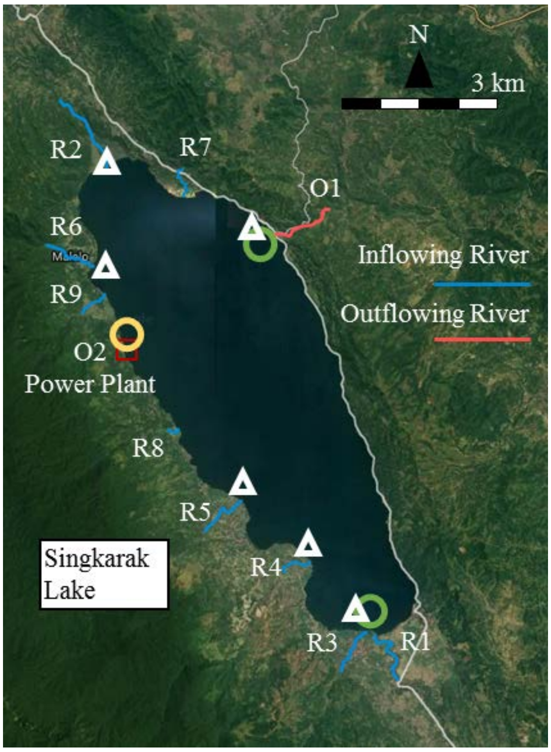

Fig. 2 The overview of Singkarak Lake including locations of rivers, power plant, and survey points)

Jeanse (2015) in his thesis shows the detail of the most significant rivers around Singkarak watershed. Among the 10 rivers in Fig. 2, the Sumani, Sumpur, and Ombilin Rivers are found to have a great sub-basin area. The Sumani and Sumpur Rivers flowing into Singkarak Lake have sub-basin areas of 482.5 and 164.1 km^2 with major river lengths of 52.6 and 4.16 km, respectively [16].

The lake water also supplies water to the Singkarak hydropower plant since 1998 [17]. The power plant uses around 35 m^3/s of water from the lake in a given month and the amount remains constant for the year. The Singkarak power plant is shown in Fig. 3 and the location is given in Fig. 2 as a red box placed between Malalo (R9) and Pingai River (R8).

Fig. 3 Singkarak Hydro-based Power Plant.

2. METHODOLOGY

Field data measurements includes bathymetric, water level, current velocity, and water quality measurements.

2.1 Bathymetric Field Data

The bathymetric data are needed for the model domain base map. The lake-bed depth data are measured using a single-beam echo-sounder. Fig. 4 shows the documentation of the lake-bed depth field data acquisition. The covered survey area is around 10,800 hectares. The lake-bed elevation data are taken along lines parallel with the lake width in every 200 meters.

Fig. 4 Documentation of bathymetric field data acquisition.

2.2 Water Level Field Data

One of the model validation methods is using water level field data at the lake. The hourly water level data are manually taken for two weeks by installing a staff gauge in the lake nearshore. The location of water level data acquisition is given in Fig. 2 as the yellow circle. The survey result as the black line are given in Fig. 9 in the figure of water level validation result. The water elevation field data do not show much fluctuation. The lake water elevation is dominantly affected by the volume of rivers discharge.

2.3 Current Velocity Field Data

The flow velocity resulted from the model is also validated using field current velocity. The survey uses current meter which record the current magnitude in a specify time. There are two current data acquisition points as indicated by green circles in Fig. 2. The points are located at the river-mouth of the Sumani and Ombilin Rivers. The velocity data are taken four times in one day throughout the day. They are at 7 am, 11 am, 14 pm and 18 pm. Fig. 5 shows the documentation of the data acquisition. The white buoy floating in the lake show the current meter deployment point.

Fig. 5 Documentation of current velocity survey.

2.4 Water Quality Field Data

The water quality data acquisition is required to determine the boundary conditions of the model. The field data acquisition is conducted by taking water samples stored in a sample bottle, as documented in Fig. 6. The water samples are tested in the government-certified water laboratory to obtain the values of total suspended sediment (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO), and phosphate. These parameter values recorded by the lab test will become the boundary conditions and initial conditions of the water quality model.

The water samplings are carried out at five points (see white triangles in Fig. 2). They are located at the mouth of the Sumpur, Malalo, Paninggahan, Sumani, and Ombilin Rivers.

Fig. 6 Documentation of water quality field data acquisition.

2.5 River Discharge Analysis

Besides the values of TSS, COD, BOD, DO, and phosphate, the boundary conditions of inflowing and outflowing river discharges are also calculated. The river discharge is analyzed using a mock analysis method by considering the watershed area of each river and using the rainfall data from Sialaing Bawah, Saniang Baka, Sumani, and Linta Buo rainfall stations. The monthly river discharges are given in Fig. 7.

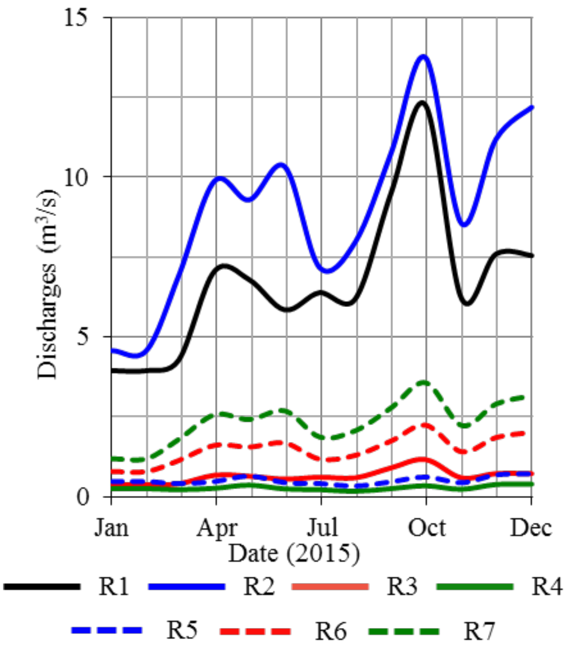

Fig. 7 Monthly river discharges.

From the graph in Fig. 7, the Sumani (R1, black line) and Sumpur (R2, blue line) Rivers have the highest discharge. The peak discharges are around

12 and 14 m^3/s for Sumani and Sumpur Rivers, respectively, which occurs in September. For the outflowing water, the Ombilin River and Singkarak Power Plant discharges are set to be constant at 11.5 and 35 m^3/s, respectively.

3. HYDRODYNAMIC MODEL

3.1 Governing Equations

The basic flow model is constructed using RMA2 of the Surface-water Modeling System version 8.1 (SMS). It is developed by the US Army Corps of Engineering Waterways Experiment Station or USACE-WES. The model uses a two-dimensional finite element method to simulate the flow condition forced by the tide or sources/sinks. The governing equations are given below. Equation 1 is the continuity equation. Equations 2 and 3 are the x-direction, and y-direction momentum equations, respectively [18].

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

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

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

where h is the water depth, x and y are the Cartesian coordinates, t is the 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. Beside RMA2 for basic flow model, the RMA4 and SED2D modules are used for the water quality and sedimentation model.

3.2 Model Construction

The lake water flow model grid is generated. The model domain and mesh are given in Fig. 8. The locations of the mentioned river inlets are presented as R1 to R7 and O1. The power plant is indicated by the red box. Tidal effects in the model are assumed to be small and the only applied forcing is from the discharges and intakes of the rivers and power plant. The parameters used for the modeling are given in Table 1.

Table 1 The parameter properties used for numerical modeling.

A. RMA2 Parameter Properties	
Turbulence parameter	Isotropic values Peclet number method Exx ratio 1.0 Peclet number 20.0 Min velocity 0.5 m/s
Roughness	0.02
Fluid temperature	28°C
Fluid density	1000 kg/m^3
Initial water surface	362.5 m
Simulation type	Dynamic
Iterations	4
Time step	1.0 hour
Number of time step	8760
B. RMA4 Parameter Properties	
Diffusion coefficient	-1.0
C. SED2D Parameter Properties	
Bed type	Sand
Diffusion coefficient	100.0
Settling velocity	0.01 m/sec
Gravitation	9.806650 m^2/s
Hydraulic bed shear stress	Manning equation
Specific gravity	2.65
Layer thickness	1.0 m
Grain size	0.81 mm

The locations of water level and current velocity survey points are given as yellow and green circles in Fig. 2, respectively. The model is run in the same time frame as the field data collection; thus the model results can be compared with the field data. For the flow model, the main results are the water level and current velocity parameters. The comparison will show the level of validity of the model.

After the flow model is validated, the hydrodynamic model is then expanded to incorporate the water quality and sedimentation models. For the water quality model, the concentration of the investigated parameters must be included in the model. The input for TSS, COD, BOD, DO, and phosphate values are given in Table 2.

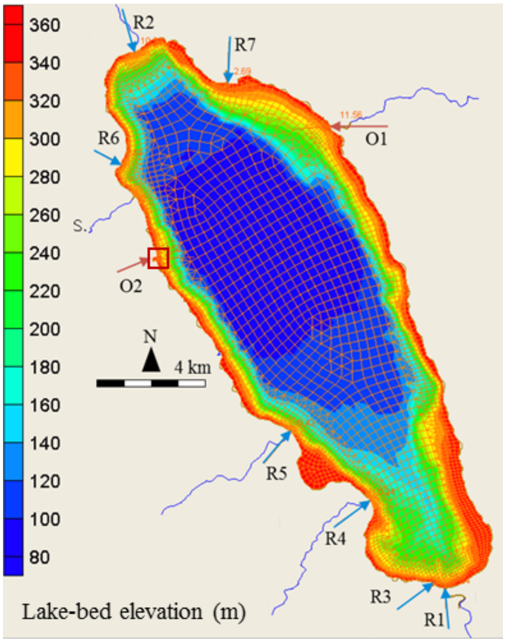

Fig. 8 The domain and mesh of numerical model.

Table 2 The parameter concentrations in (mg/l) at the initial and rivers boundary conditions.

	TSS	COD	BOD	DO	Phosphate
Initial	33	15.59	3.305	5.62	0.202
R1	51	21.33	5.460	5.16	0.280
R2	260	13.33	2.190	6.25	0.275
R3	51	21.33	5.460	5.16	0.280
R4	35	5.53	1.070	5.95	0.056
R5	42	21.33	4.460	6.01	0.268
R6	20	16.00	3.450	5.10	0.048
R7	25	16.00	3.200	5.25	0.286

3.3 Model Validation

The water levels and current velocities resulting from the model are validated using field data. Fig. 9 shows the water level validation. The black and dotted green lines are the field and model data, respectively. Both lines show similar trends in amplitude and phase. Fig. 10 shows the current velocities validation. The x- and y-axes present the current velocity of field data and model data, respectively. The current data are in good agreement with the model results with errors around 0–2 cm/s.

4. RESULTS AND DISCUSSION

4.1 Sedimentation

The final TSS value after one-year simulation is given in Fig. 11a. The highest final value is situated at Sumani River (R1) with an increase of 30 mg/L. The spatial bed change for lake area is given in Fig. 11b. It is found that rivers with large river discharge

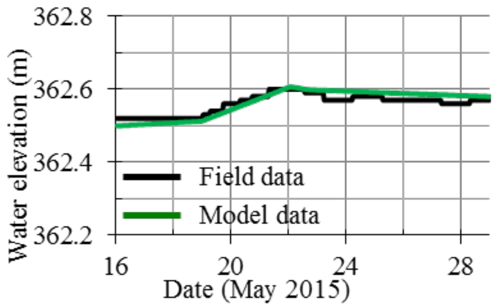

Fig. 9 Water elevation validation.

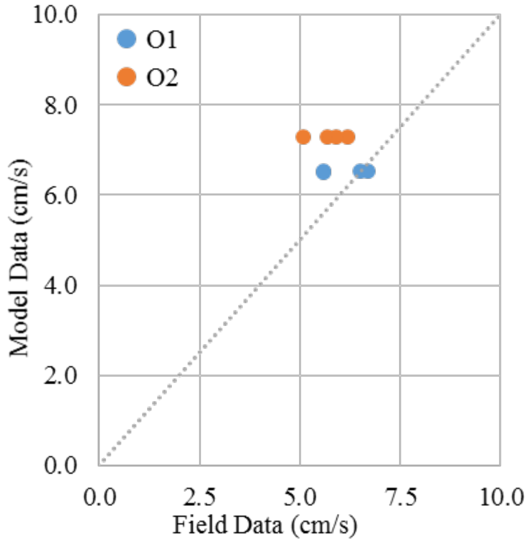

Fig. 10 Current velocity validation.

result in a high bed change, as seen with the Sumani (R1) and Sumpur (R2) Rivers. The change after a year is around 40 cm for both locations.

4.2 Water Quality

The resulting spatial concentrations after one year of simulation time are given. The COD, BOD, DO, and phosphate concentrations are given in Figs. 12a to 12d, respectively. The final concentration of the investigated parameters after one year of simulation is summarized in Table 3.

Table 3 The resultant concentrations (mg/l) in the inlet of rivers for a simulation of one year.

	COD	BOD	DO	Phosphate
Initial	15.59	3.31	5.620	0.202
R1	16.00	3.50	5.600	0.210
R2	15.50	3.25	5.650	0.210
R3	15.80	3.42	5.600	0.205
R4	15.70	3.37	5.615	0.204
R5	15.65	3.35	5.615	0.204
R6	15.65	3.35	5.600	0.200
R7	15.65	3.35	5.600	0.210
O1	15.65	3.35	5.615	0.204

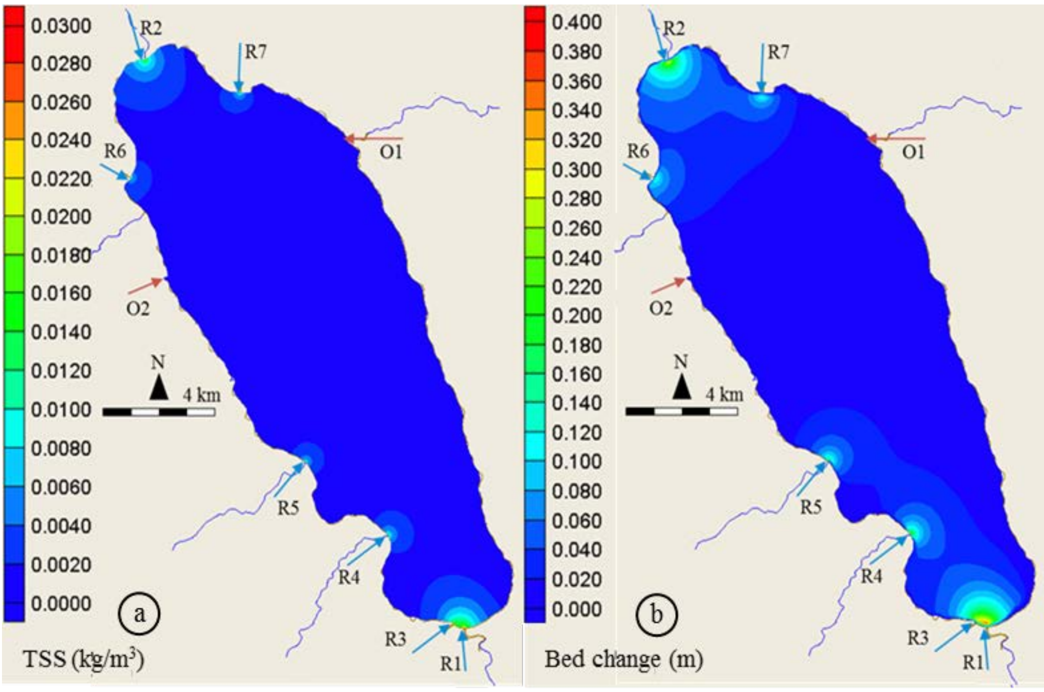

Fig. 11 The spatial distributions of TSS and bed change resulted from the numerical model.

The initial condition of COD for the lake is 15.587 mg/L. As presented in Fig. 12a, high concentrations are found at the Sumani, Cangking, and Ambius Rivers. (R1, R3, and R4) which exceeded 15.7 mg/L. The only concentration below 15.5 mg/L is obtained at Sumpur River, R2. For BOD parameters, the dispersal is given in Fig. 12b. The trend is quite similar with COD dispersal where the highest and lowest concentrations are located at Sumani and Sumpur River with values of 3.50 and 3.25 mg/L, respectively. The initial value is 3.31 mg/L.

The Sumani and Sumpur Rivers are also dominant in the analysis of phosphate and DO models. The Sumani and Sumpur Rivers contain high phosphate concentrations. The Sumpur River has the highest DO concentration, while the Sumani River has a low concentration that is shared by three other rivers. The Ombilin River consistently has parameter concentrations at a medium value.

4.3 Lake Status

The government document on the preservation of Singkarak lakes (*Germadan*) includes field surveys conducted in 2012. The comparison of *Germadan* data, field data, and model results are given in Table 4. The nitrate content from the *Germadan* Survey had doubled in 2015. However, a nitrate model is not provided in this study.

For the phosphate content, the concentration value in the *Germadan* Survey covers the total value of phosphorus. Based on work by Haryadi et al. (1991), the total phosphorus consists of polyphosphate, phosphate, and orthophosphate [19]. In the field survey and resultant model data, the investigated content is only the phosphate. However, the phosphate content in the Ombilin River is still greater than the total phosphate in the *Germadan* Survey. It indicates that there is an increase of phosphate content inside the lake.

According to regulations for water quality management and water pollution control in Indonesia, written as Government Regulation No. 82/2001, the lake class can be divided into four classes based on parameter values given in Table 5 [14]. Class I is the standard for raw water for drinking. Classes II, III, and IV are water for irrigation, fisheries, and etc.

Table 4 The comparison of *Germadan*, field, and model data.

Concentrations in mg/L	2012, *Germadan* Survey			2015, Field Data			2016, Model Results		
	Sumani River	Center of the Lake	Ombilin River	Sumani River	Center of the Lake	Ombilin River	Sumani River	Center of the Lake	Ombilin River
Phosphate	0.479	0.172	0.276	0.280	-	0.286	0.2100	0.2035	0.2035
Nitrate	0.806	0.513	0.487	1.740	-	1.960	-	-	-

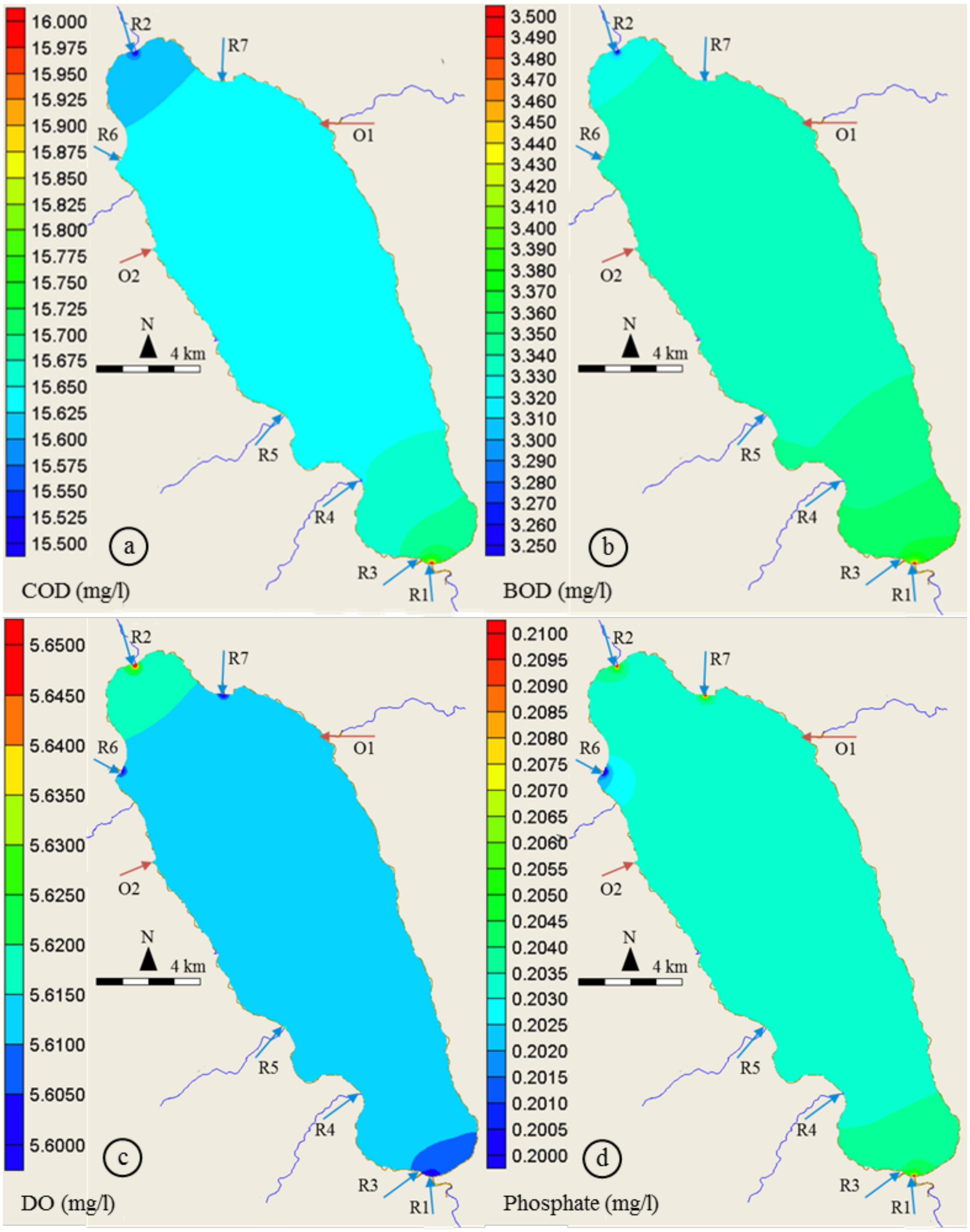

Fig. 12 The spatial variations of water quality model resulted from numerical model.

Table 5 The standard parameters based on lake classification.

Parameters (mg/L)	Class I	Class II	Class III	Class IV
TSS (max)	50	50	400	400
COD (max)	10	25	50	100
BOD (max)	2	3	6	12
DO (min)	6	4	3	0
Total Phosphorus (max)	0.2	0.2	1	5

The TSS value for Singkarak Lake is in the first class with the maximum value below 50 mg/L, which is 30 mg/L. The COD and DO values are in the second class with values of 16 and 5.6 mg/L, respectively. The BOD and phosphate values are in the third class. With this class distribution, the Singkarak Lake is suitable for the third class, appropriate only for fish farming and farm irrigation.

5. CONCLUSION

The COD, BOD, and phosphate in Sumani and Sumpur Rivers are consistently high. The bed change is also relatively high, the maximum values are between 30–40 cm a year. The Sumani and Sumpur Rivers play important roles in the condition of Singkarak Lake.

One suggested mitigation action is a collaboration between local residents and authorities to maintain lake sustainability by controlling wastes, such as detergent waste, and waste from agriculture and fish farming. These wastes mainly originate from these two rivers. It is also shown that the lake is only appropriate for irrigation or fishing hatcheries, not for drinking water according to criteria for water quality standards set by the Indonesian government. Another mitigation regarding sedimentation is maintenance of rivermouth of each river coming into the Singkarak Lake by conducting dredging every two years when the bed change already reaches around 1 meter.

6. ACKNOWLEDGMENTS

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