The application of Two Dimension Mathematical Model for Assessing Water Quality Distribution of Jatiluhur Reservoir

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Abstract

Jatiluhur Reservoir is the most important fresh water resources for Jakarta. Simulation of water quality distribution (represented by DO concentration) of Jatiluhur Reservoir is done for two scenario of reservoir operation based on two dimensions turbulent κ -ε model. . The numerical model was developed using finite difference method where hydrodynamic equation was solved by the combination of Mc Cormack and splitting methods. Good comparison between the model result and field measurement result during the rainy period is achieved. Small incoming flow and outflow during the reservoir operation has insignificant contribution in distributing DO concentration in the reservoir. It is concluded that the improvement of model performance could contribute more significantly in determining the reservoir operation scenario for improving water quality distribution in the reservoir.

Keywords: Reservoir, Water Quality Distribution, Two Dimension Flow, Jatiluhur Reservoir, Kappa-Epsilon Model.

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1. Introduction

Reservoir is the most important resources of fresh water in Indonesia. That is why the assessment of reservoir flow due to its operation becoming one of the interesting research subject in Indonesia. Based on the criteria of Hugo B Fischer et al (1979[1]), Jatiluhur Reservoir which have short time resident is categorized as small reservoir where the governing forces of water quality dynamic could be derived from the equilibrium of inflow-outflow forces. Therefore for practical engineering problem solving, the small reservoir flow is frequently assessed by using two dimension shallow water equations where depth average velocity methods is applicable. Meanwhile, due to the complexity of its geometry, during the rainy season its reservoir flow, especially its secondary stream, is usually dominated by unstable mixing layer that could only be well predicted by this approach when the turbulent term is added as it may have very weak advection velocity but significant turbulent intensity. While measuring flow parameter for all possible inflow-outflow condition is the most accurate and cost effective way for determining the characteristic of reservoir flow, using an appropriate numerical model could significantly reduce the cost for assessing reservoir flow characteristic with an acceptable level of accuracy (Young-Oh Kim et al, 2007[12]).
Based on experimental studies, it is identified that inflowing water plunges at the upper end of the reservoir due to the density difference (Akiyama and Stefan, 1984[2]). Application standard k–ε turbulent model based on an orthogonal curvilinear grid will give a good accuracy of reservoir sediment concentration but overestimate the downstream velocity (Makato et al, 2006[5]). Two dimension depth average k–ε turbulence models are successfully applied for assessing free surface flow by Muhammad (1993[10]) and Ni. Shen et al (1995[11]). This paper attempts to discuss the results the application of k–ε turbulence model for assessing the recirculation flow in Jatiluhur Reservoir.

2. Description of Jatiluhur Reservoir

Jatiluhur Reservoir is located in the upstream part of Citarum River. It has a ± 83 km^2 inundated surface area, an average daily incoming flow of 175 m^3/s from upper Citarum River and Cirata Reservoir, a 200 m spillway width and a storage capacity of 3x10^9 m^3(see figure 1-4). The mass curve of this reservoir is shown in figure 5. The water quality of this reservoir is monitored in several measurement stations once a year (see figure 6 and Table 1). Based on this data, it is identified that the average temperature of water surface is 25˚C, surface wind velocity is 2.22 m/s and the DO concentration is 6.05 mg/l.

In the last two decade, due to decreasing water quality from Cirata reservoir and accumulated waste from fishery activity in its reservoir, the quality of reserved water in Jatiluhur Reservoir is significantly decreased. As it is believed that the recirculation flow of the reservoir has a significant role to the dynamic of water quality distribution in the reservoir, the development of tools for assessing the recirculation flow of Jatiluhur Reservoir becomes one of the priorities for the management. Regulating the reservoir flow based on the best scenario resulted from such kind of tool is one of the effort that could mitigate the reservoir water quality from being worsen.

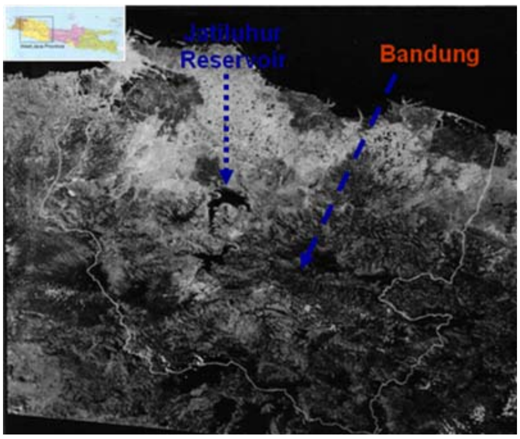

Figure 1. Location of Jatiluhur Reservoir, West Java, Indonesia

Figure 2. Jatiluhur serving area

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Figure 3. Jatiluhur inundated area

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Figure 4. Aqua Culture in Jatiluhur.

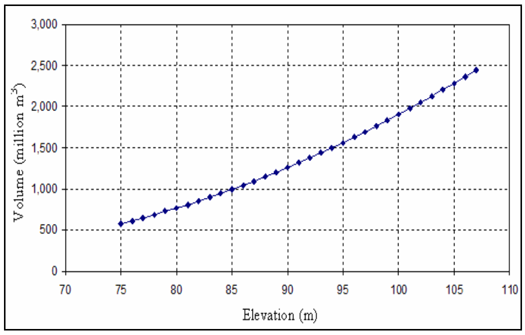


Figure 5. Reservoir mass curve

3. Model Description

The model is developed as a tool to simulate several possible scenarios that could be used to operate the reservoir for certain condition during rainy season. For this purpose, a two dimension κ-ε turbulent model is developed based on finite different method as it will discussed in the following paragraph.

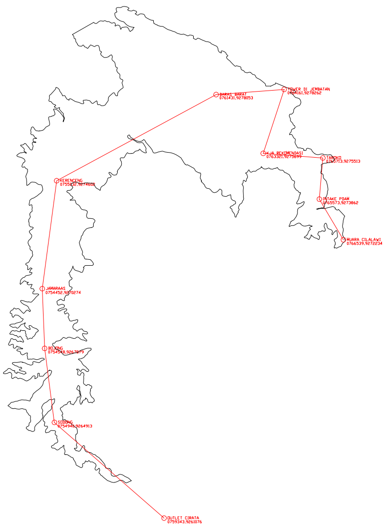


Figure 6 Measurement Station of Jatiluhur Reservoir

3.1. Governing Equation and Numerical Solution

The model was developed using finite difference method where hydrodynamic equation was solved by the combination of Mc Cormack and splitting methods. The detail description of the model could be seen in M. Syahril B.K et al (2004[6], 2006[7,8] & 2007[9]). The κ -ε equation is solved using quickest scheme in convection term, central scheme in diffusion term and Euler scheme in reaction term. Water quality equation is solved using quickest scheme. This developed model had been satisfactorily applied to assess flow pattern in several cases of open channel turbulent flow such as bending channel, expansion-contraction channel, non prismatic channel and fish pond (M. Syahril B.K et al, 2004[6], 2006[7,8] & 2007[9]). The governing equation of the model in depth average velocity form is as follow:

Table 1. DO Concentration based on field measurement

Station	Distance (Km)	DO Concentration (mg/L)
Parungkalong		4.00
Sodong	5.10	2.45
Bojong		2.13
Jamaras	33.8	8.43
Kerenceng	54.1	5.15
Keramba	59.48	7.30
Cilalawi		6.24
PDAM	50.58	7.46
Taroko		7.37
Baras Barat	71.39	7.59
Dam		8.45

- Continuity Equation

$$\frac{\partial H}{\partial t}+\frac{\partial}{\partial x}(UH)+\frac{\partial}{\partial y}(VH)=0 \quad \ldots\ldots\ldots\ldots\ldots(1)$$

- Momentum equation for x direction

$$\frac{\partial}{\partial t}HU+\frac{\partial}{\partial x}U^2H+\frac{\partial}{\partial y}UVH=$$

$$\frac{\partial}{\partial x}\left[2\hat{v}_t\left(\frac{\partial HU}{\partial x}-\frac{2}{3}H\hat{k}\right)\right]+\frac{\partial}{\partial y}\left[\hat{v}_t\left(\frac{\partial HU}{\partial y}+\frac{\partial HV}{\partial x}\right)\right]+\left[gHS_{ox}-\frac{gU\sqrt{U^2+V^2}}{C^2}+\frac{\rho_a C^* W_x W}{\rho}\right] \quad (2)$$

- Momentum equation for y direction

$$\frac{\partial}{\partial t}HV+\frac{\partial}{\partial x}UVH+\frac{\partial}{\partial y}V^2H=$$

$$\frac{\partial}{\partial x}\left[\hat{v}_t\left(\frac{\partial HU}{\partial y}+\frac{\partial HV}{\partial x}\right)\right]+\frac{\partial}{\partial x}\left[2\hat{v}_t\left(\frac{\partial HV}{\partial y}-\frac{2}{3}H\hat{k}\right)\right]+\left[gHS_{oy}-\frac{gV\sqrt{U^2+V^2}}{C^2}+\frac{\rho_a C^* W_y W}{\rho}\right] \quad (3)$$

- κ equation (Chapman & Kuo)

$$\frac{\partial(h\hat{\kappa})}{\partial t}+\frac{\partial(hU\hat{\kappa})}{\partial x}+\frac{\partial(hV\hat{\kappa})}{\partial y}=\frac{\partial}{\partial x}\left[\frac{\hat{v}_t}{\sigma_k}\frac{\partial(h\hat{\kappa})}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{\hat{v}_t}{\sigma_k}\frac{\partial(h\hat{\kappa})}{\partial y}\right]+p_h+p_k-\hat{\varepsilon}h \quad (4)$$

- ε equation (Chapman & Kuo)

$$\frac{\partial(h\hat{\varepsilon})}{\partial t}+\frac{\partial(hU\hat{\varepsilon})}{\partial x}+\frac{\partial(hV\hat{\varepsilon})}{\partial y}=\frac{\partial}{\partial x}\left[\frac{\hat{v}_t}{\sigma_k}\frac{\partial(h\hat{\varepsilon})}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{\hat{v}_t}{\sigma_k}\frac{\partial(h\hat{\varepsilon})}{\partial y}\right]+\frac{\hat{\varepsilon}}{\hat{\kappa}}(C_1 p_h-C_2\hat{\varepsilon}h)+p_\varepsilon \quad (5)$$

- Water Quality Equation

$$\frac{\partial(\Phi H)}{\partial t}+\frac{\partial(U\Phi H)}{\partial x}+\frac{\partial(V\Phi H)}{\partial y}=\frac{\partial}{\partial x}\left(D_x\frac{\partial(\Phi H)}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial(\Phi H)}{\partial y}\right) \quad (6)$$

Where

$$P_h=\frac{\hat{v}_t}{h}\left\{2\left[\frac{\partial(hU)}{\partial x}\right]^2+2\left[\frac{\partial(hV)}{\partial y}\right]^2+\left[\frac{\partial(hU)}{\partial y}+\frac{\partial(hV)}{\partial x}\right]^2\right\} \quad (7)$$

$$P_k=\frac{g}{C^2}q^3,\ P_\varepsilon=\frac{C_2 C_\mu^{1/2} g^{5/4} q^4}{hD^{1/2}C^{5/2}},\ q=\sqrt{U^2+V^2} \quad (8) \ldots.$$

$$\hat{v}_t=C_\mu\frac{\hat{k}^2}{\hat{\varepsilon}}= \text{Depth averaged turbulent viscosity}$$

(Prandtl–Kolmogorov-Relationship)

g = gravitation (m/sec^2)
$\hat{\varepsilon}$ = epsilon or dissipation rate
$\hat{\kappa}$ = kappa or turbulence kinetic energy
C_μ =empirical constant=0.09
C_1 = 1.44, C_2 = 1.92, C_μ= 0.09, σ_k = 1.0,
σ_ε = 1.3 and D = 0.075
U = Depth Average Velocity in x Direction
V = Depth Average Velocity in y Direction
H = Mean flow depth
ρ_a = Air density (kg/m^3)
C* = Ekman Coeficient = 0.026

W_x = Wind Velocity in x direction
W_y = Wind Velocity in y direction

$$W = \sqrt{W_x + W_y}$$

Φ = Flux, water quality concentration
h = flow depth
ρ = Fluid Density
μ = Dynamic Viscosity
υ = Kinematic viscosity
D_{xx} = Diffusion Coef in x direction
D_{yy} = Diffusion Coef in y direction

C =Chezy Coeficient = $\dfrac{R^{1/6}}{n}$

The description of Mac Cormack Scheme, splitting technique and quickest scheme are written in the following form.

a). Mc Cormack Scheme:

$$\frac{\partial W}{\partial t} + \frac{\partial F(W)}{\partial x} + T(W) = 0$$

Predictor:

$$\tilde{W}_i = W_i^n - \frac{\Delta t}{\Delta x}\left[F(w)_{i+1}^n - F(w)_i^n\right] - \Delta t T(w)^n$$

Corrector:

$$\tilde{\tilde{W}}_i = W_i^n - \frac{\Delta t}{\Delta x}\left[\tilde{F}(w)_i - \tilde{F}(w)_{i-1}\right] - \Delta t \tilde{T}(w)$$

$$W_i^{n+1} = \frac{\tilde{W}_i + \tilde{\tilde{W}}_i}{2}$$

b). Quickest Scheme:

$$\phi_i^{n+1} = \phi_i^n + \underbrace{\lambda\left[\hat{F}(\phi)_{i+\frac{1}{2}} - \hat{F}(\phi)_{i-\frac{1}{2}}\right]}_{\text{Convection}} + \underbrace{\left[\overline{D}\hat{F}(\phi)_{i+\frac{1}{2}} - \overline{D}\hat{F}(\phi)_{i-\frac{1}{2}}\right]}_{\text{Diffusion}} - \underbrace{\varphi\phi\Delta t}_{\text{Reaction}} + \underbrace{q_s C_s \Delta t}_{\text{Source}}$$

c). Splitting Scheme:

$$F^{n+2} = \left[\left(L_x L_y L_{xx} L_{yy} L_s\right) \bullet \left(L_s L_{yy} L_{xx} L_y L_x\right)\right] F^n$$

Where:

- Lx = solution of first order differential equation in x direction
- Ly = solution of first order differential equation in y direction
- Lxx = solution of second order differential equation in x direction
- Lyy = solution of second order differential equation in y direction
- Ls = solution of reaction equation

3.2. Discretization

A simplified geometry of Jatiluhur Reservoir is developed as the model domain which is discretized using 91 x 63 of 200 m orthogonal grids of Δx & Δy so that a straight boundary line of the reservoir geometry is determined. This simplification could avoid numerical instability and error generated by the complexity of reservoir geometry (see figure 3 and table 2). The model is run during as long as 120 hours with time interval Δt of 0,5 second .

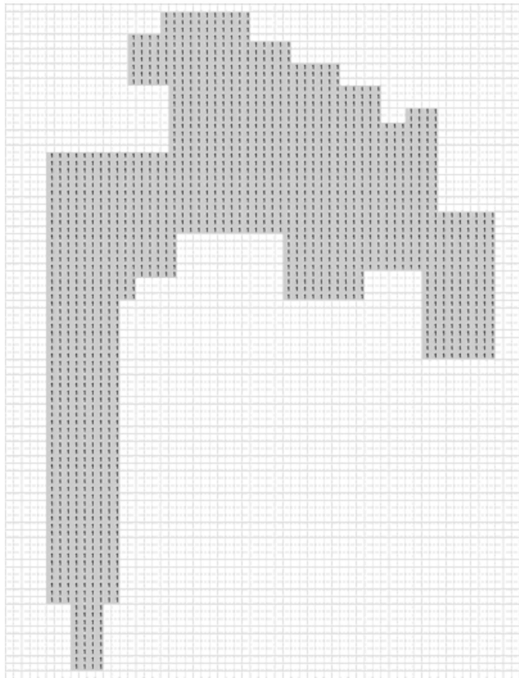


Figure 7 The grid system of the model

3.3. Model Application

The outflow is set up at the spillway of the reservoir which has 200 m width. The reservoir water quality is represented by the concentration of Dissolve Oxygen (DO). In this case, the model considers only water flow and wind blow velocity as the generator parameter of water aeration. As an example, the following simulations were discussed in this paper.

Table 2 Total Grid over the model domain

Parameters	Unit	Physical Condition	Numerical Model
Surface Area	M^2	83 10^6	83.1 10^6
Grid in water surface	Grid	2075	2077
Grid in land surface	Grid	3658	3656
Grid inside reservoir	Grid	5733	5733

1. Scenario 1 :

The scenario one is reached when the reservoir water elevation is +107 m above sea level and out flow Is 177 m^3/s. In this state as the initial condition, the DO concentration of the control point at Jamaras, Sodong, Baras, KJA, Kereceng and Intake PDAM are set respectively 3.56 mg/l, 3.28 mg/l, 4.03 mg/l, 5.52 mg/l, 5.86 mg/l and 5.45 mg/l, and its flow velocity at 0.02 m/sec. The boundary condition is set up by inflowing the incoming flow with discharge as large as 155 m^3/sec and controlling the water level above the spillway by $Q=CLH_e^{3/2}$ (C=Discharge Coefficient, L=Width of the weir and H_e is energy head above the weir).

2. Scenario 2 :

The scenario one is reached when the reservoir water elevation is +107 m above sea level and out flow is 0 m^3/s. In this state, DO concentration of the control point at Jamaras, Sodong, Baras, KJA, Kereceng and Intake PDAM are set respectively 3.56 mg/l, 3.28 mg/l, 4.03 mg/l, 5.52 mg/l, 5.86 mg/l and 5.45 mg/l, and its flow velocity at 0.02 m/sec are set as the initial condition. The boundary condition is set up by inflowing the incoming flow with discharge as large as 175 m^3/sec and controlling the water level above the spillway by $Q=CLH_e^{3/2}$ (C=Discharge Coefficient, L=Width of the weir and H_e is energy head above the weir).

4. Results and discussion

Good comparison between water elevation, current and DO distribution of the model with those of field measurement is achieved at control point of PDAM, Keramba and Baras Barat. The gap resulted from the model, especially at Sodong, might be generated by the following matter.

- The average DO distribution measurement is conducted during the day where solid and liquid waste inflow of the reservoir.
- As the electricity peak load occured during the night, the incoming flow to Jatiluhur Reservoir from releasing water of Cirata Reservoir during the night is higher than that of the day. This cause the model will generate much higher and more distributed DO concentration than that of field measurement.
- More densed grid dis require to develop better model domain.

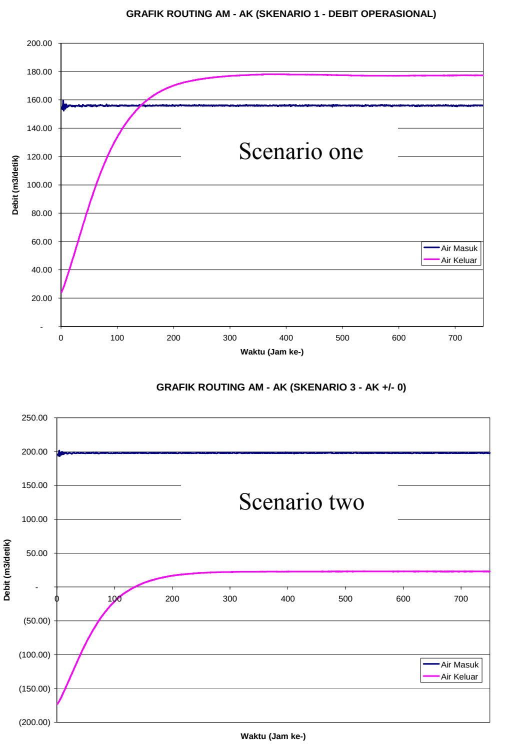


Figure 4. Inflow and outflow discharge

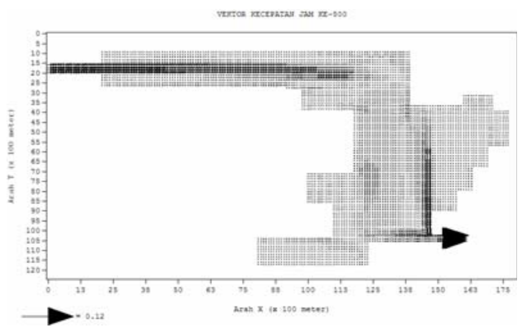


Figure 5 Velocity pattern in scenario 1

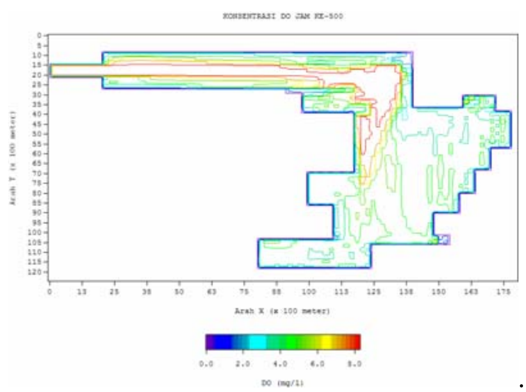
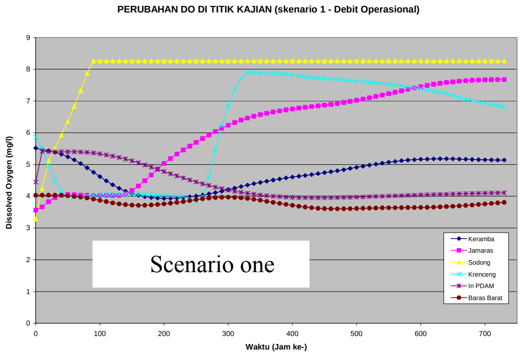


Figure 6. DO distribution after 500 hour for scenario 1.



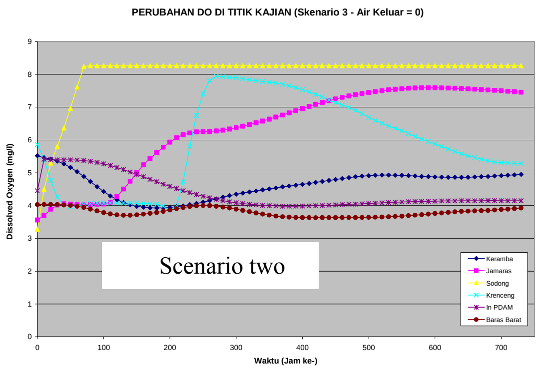


Figure 5 DO Concentration for

Tabel 1 Calculated and measured ***DO***

Lokasi	Kondisi Awal Pengukuran	Perhitungan			Kondisi Akhir Pengukuran
	Jam ke- 0	250	500	750	750
Keramba	5.52	4.01	4.91	5.14	6.15
Jamaras	3.56	5.70	7.02	7.67	4.14
Sodong	3.28	8.26	8.26	8.26	0.92
Baras Barat	4.03	3.89	3.61	3.83	5.32
Kerenceng	5.86	3.82	7.62	6.72	4.34
Intake PDAM	4.45	4.45	3.97	4.12	4.39

DO distribution resulted by model has the following pattern :

- The DO concentration of the control point in the surrounding area of aqua culture is the less reactive part of the reservoir to both inflow and out flow compared to the other part of thereservoir.
- The DO concentration of control point in the upperpart of the reservoir is more reactive to the inflow than that of the down stream part of the reservoir. Meanwhile the control point in the upperpart of the reservoir is less reactive to the outflow than that of the down stream part of the reservoir.

5. Conclusion

Simulation of water quality distribution (represented by DO concentration) of Jatiluhur Reservoir is done for two scenario of reservoir operation. Small incoming flow and outflow during the reservoir operation has insignificant contribution in distributing DO concentration in the reservoir. The model could give good comparative result with field measurement. The improvement of model performance could contribute more significantly in determining the reservoir operation scenario for improving water quality distribution in the reservoir.

Acknowledgement

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