Development Study of Turbulent κ-ε Model for Recirculation Flow III: Two Dimension Recirculation Flow in a Reservoir

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Abstract. An assessment of recirculation flow in Jatiluhur reservoir is conducted 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. The κ-ε equation is solved using quickest scheme in convection term, central scheme in diffusion term and Euler scheme in reaction term. The simulations were done for maximum incoming flow during the rainy season and the dry season. Model results are compared to field measurement from which it is found that rainy season scenario has shown better agreement. Maximum incoming flow released in the rainy season could generate a boundary layer greater average velocity and more recirculation flow than that in the dry season. Further development is required to get more accurate results for the case with less average velocity.

Keywords: *reservoir; two dimension recirculation flow; turbulent kappa-epsilon model.*

1 Introduction

Reservoir is the most important resources of fresh water in Indonesia where water quality is the main issue of its feasibility.Many previous study have shown that DO (Dissolved Oxygen) is one of the important indicator of reservoir water quality. Water mass which has a good aeration will have a good level of DO. Water aeration process in reservoir depend on its mixing process. Based on the level of mixing process, H.B Fischer, et al. [1] distinguis reservoir water mass into three layer: epilimnion, hypolimnion and thermocline. Epilimnion layer is surface mixed layer where mixing process is generated by wind and convective flow. Thermocline is a sharp temperature transition layer separating the hypolimnion in the deeper mass waters from epilimnion layer. Hypolimnion, which is protected by thermocline layer from disturbance generated by flow dynamic in eplimnion, is anaerobic layer where vertical mixing process depend on density gradient. Wind breeze directly generate water aeration process through its radiation stress on surface water in eplimnion layer. Meanwhile flow dynamic, especially its recirculation flow, generate mixing process between water mass with higher DO with water mass with less DO.

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This mixing process could occure between epilimnion and hypolimnion layer or between aerated water mass with unaerated watermass in epilimnion layer. The dynamic of reservoir flow depend on the regulation of inflow and outflow of that reservoir. That is why the development of the model which is capable for assessing the dynamic of reservoir flow due to its operation becoming one of the interesting subject on numerical model research in Indonesia.

The dynamic of reservoir flow is governed not only by the advection term but also by the mixing term. The significant forces governing the dynamic of reservoir flow could be effectively determined by using the mean residence time of the reservoir ([1]) which is defined as the volume of the reservoir divided by the mean inflow rate. Based on this criterion, 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.

Most of the reservoir flow is three dimension flow where its flow regime depends on not only to the flow velocity but also to the reservoir geometry. The generation of recirculation zones due to the complex geometry of channel flow is discussed by Driver and Seegmiller [2], Hunt [3] and Hussain [4]. The complexity of reservoir geometry is usually developed by a sudden change of reservoir geometry such as canal expansion, canal contraction, canal bed step etc. Therefore, a precise and efficient simulation requires a grid system expressing this line of flow. Mesh refinement study to express the geography is one of practical options for this problem. For practical engineering problem solving, a small reservoir flow is frequently assessed using two dimension flow equation for shallow water condition where vertical velocity distribution is approached with the depth average velocity methods. The main stream of a reservoir flow along its thalweg, which is dominated by advection term, could be well enough predicted by this approach. Its secondary stream, which is generated during the rainy season by the influence of the complexity of its geometry and usually dominated by unstable mixing layer, 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. Experimental studies have been conducted on the movement and deposition of fine sediment in different sections of the reservoir, and it has been determined that inflowing water plunges at the upper end of the reservoir due to the density difference [5], forming an underflow on the bed slope [6]. Although numerous laboratory experiments have been conducted, data obtained from field experiments are limited. The rapid progress in computer technology improve the accurate of numerical model ([7]-[9]) that could be used to fill the lack of field measurement for assessing the reservoir flow.

Younus has developed a depth-averaged κ-ε Turbulence Model for assessing free-surface flow. Based on field measurements at the Shichikashuku Reservoir, Japan and standard κ-ε turbulent model, Umeda, Makoto, et al. [10] have studied the water quality and sediment distribution in stratified reservoir. By adopting an orthogonal curvilinear grid to discretize the reservoir geometry, the model achieves good accuracy and resolution of sediment concentration in the reservoir, but over estimates the downstream velocity due to inaccurate of its grid system to cope the complexity of the reservoir geometry. Farrell and Stefan [11] constructed a vertical two-dimensional (2D) flow simulation model based on a κ-ε turbulence model in cylindrical coordinates and discussed the plunge depth of the density current. Younus, Muhammad [12] and Ni, H.Q., Shen [13] has successfully developed a two dimension κ-ε turbulence model by applying a depth average velocity for free surface flow. Choi and Garcia [14] simulated the density underflow and examined the repeatability of vertical structures of velocity and concentration in comparison with experimental data. Chung and Gu [15] applied a 2D model to analysis of the Shasta Reservoir during periods of thermal stratification through the simulated diffusion of a chemical (not suspended sediment) carried by the penetrating density current, and the model was shown to successfully reproduce the plunge flow and interflow of the density current. Measuring the flow pattern for all possible inflow-outflow condition is the most accurate and cost effective way for determining the characteristic of reservoir flow [16]. While using an appropriate numerical model could significantly reduce the cost for assessing reservoir flow characteristic with an acceptable level of accuracy.This paper attempts to discuss the results the application of κ-ε turbulence model for assessing the recirculation flow in Jatiluhur Reservoir.

2 Description of Jatiluhur Reservoir

Jatiluhur Reservoir is located in the Citarum River Catchment Area where there are also located Cirata Reservoir and Saguling Reservoir. It has a geometry as it is shown in Figure 1. It has a surface area of about ± 83 km^2, an average daily incoming flow of 175 m^3/s, a spillway width of 200 m, a storage capacity of 3x10^9 m^3 and a flood discharge capacity of 3,000 m^3/s. The mass curve of this reservoir is shown in figure 2. The water quality of this reservoir is monitored in several measurement station once a year. Table 1 has shown the result of DO measurement in several measurement station. Based on the data measurement of 2005 monitoring work, the mean temperature of water surface is 25˚C, the wind velocity over the reservoir surface is 2.22 m/s and the mean concentration of DO is 6.05 mg/l. As the most downstream of that three cascade reservoir, Jatiluhur Reservoir reserve runoff discharge from Citarum River in its upstream and the released discharge from Cirata reservoir.

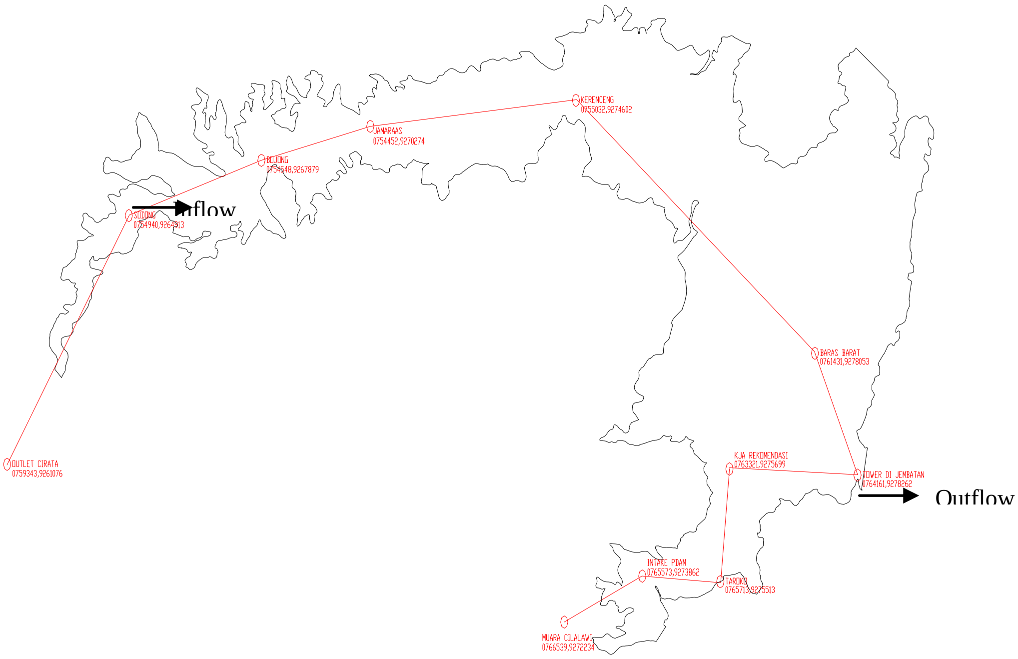

Figure 1 Geometry and Measurement Station of Jatiluhur Reservoir.

Table 1 DO Concentration based on field measurement on 20 February 2005.

Station	Distance (Km)	DO Concentarion (mg/L)
Parungkalong		4.00
Sodong	5.10	2.5
Bojong		2.1
Jamaras	33.8	8.4
Kerenceng	54.1	5.2
Keramba	59.48	7.3
Cilalawi		6.2
PDAM	50.58	7.3
Taroko		7.4
Baras Barat	71.39	7.6
Dam		8.5

In the last two decade, the quality of released water from Cirata reservoir is significantly decreased. In the same time the quality of reserved water in Jatiluhur Reservoir is also decreased due to the accumulated waste from fishery activity in its reservoir. Both conditions cause the decreasing quality of water supply from Jatiluhur Reservoir to Jakarta City. As it is believed that the recirculation flow of the reservoir has significant role to the dynamic of water quality distribution in Jatiluhur Reservoir, the development of tools for assessing the recirculation flow of Jatiluhur Reservoir becomes the most interesting research subject.

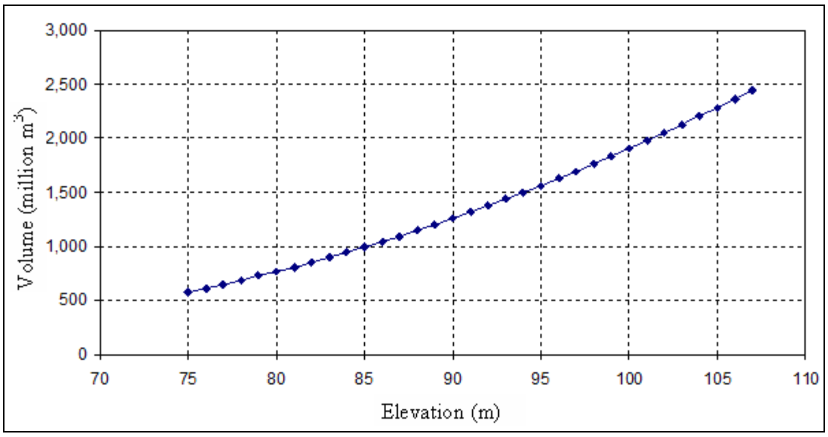

Figure 2 Reservoir mass curve.

Regulating the reservoir flow based on the best scenario resulted from such kind of tool is one of the effort that could mitigate the degradation of reservoir water quality. This effort could only be done when the reservoir flow characteristic of each scenario is already known.

3 Model Description

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 [17-20] where governing equation are developed based on the following basic assumptions:

a) Two dimension steady and incompressible flow
b) Cariolis force is negliable
c) Depth averaged velocity is applicable.

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/small reservoir (see M. Syahril B.K et al, [17-20]). The governing equation of the model in depth average velocity form is as follow:

Continuity Equation

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

Momentum equation for x direction

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

Momentum equation for y direction

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

κ equation (Chapman & Kuo)

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

ε equation (Chapman & Kuo)

$$\frac{\partial(h\hat{\varepsilon})}{\partial t}+\frac{\partial\left(hU\hat{\varepsilon}\right)}{\partial x}+\frac{\partial\left(hV\hat{\varepsilon}\right)}{\partial y}=\frac{\partial}{\partial x}\left[\frac{\hat{v}_t}{\sigma_k}\frac{\partial\left(h\hat{\varepsilon}\right)}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{\hat{v}_t}{\sigma_k}\frac{\partial\left(h\hat{\varepsilon}\right)}{\partial y}\right]+\frac{\hat{\varepsilon}}{\hat{\kappa}}\left(C_1p_h-C_2\hat{\varepsilon}h\right)+p_\varepsilon \tag{5}$$

Water Quality Equation

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

where

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

$$p_k=\frac{g}{C^2}q^3,\, p_\varepsilon=\frac{C_2C_\mu^{1/2}g^{5/4}q^4}{hD^{1/2}C^{5/2}},\, \mathrm{q}=\sqrt{\mathrm{U}^2+V^2} \tag{8}$$

C_1, C_2, $C_{\mu,}$, σ_k, σ_ε and D are constant which are teken respectively as 1.44, 1.92, 0.09, 1.0, 1.3 and 0.075. The coefficient of D_x and D_y are taken as in our previous paper (see M. Syahril B.K., et al. [17], [20]). The description of Mac Cormack Scheme, splitting technique and quickest scheme are written in the following form.

a) ***Mc Cormack Scheme:***

$$\frac{\partial \mathrm{W}}{\partial \mathrm{t}}+\frac{\partial \mathrm{F(W)}}{\partial \mathrm{x}}+\mathrm{T(W)}=0 \tag{9}$$

Predictor

$$\tilde{\mathrm{W}}_\mathrm{i}=\mathrm{W}_\mathrm{i}^\mathrm{n}-\frac{\Delta \mathrm{t}}{\Delta \mathrm{x}}\left[\mathrm{F(w)}_{\mathrm{i+1}}^\mathrm{n}-\mathrm{F(w)}_\mathrm{i}^\mathrm{n}\right]-\Delta \mathrm{t}\mathrm{T(w)}^\mathrm{n} \tag{10}$$

Corrector

$$\mathrm{W}_\mathrm{i}=\mathrm{W}_\mathrm{i}^\mathrm{n}-\frac{\Delta \mathrm{t}}{\Delta \mathrm{x}}\left[\tilde{\mathrm{F}}\mathrm{(w)}_\mathrm{i}-\tilde{\mathrm{F}}\mathrm{(w)}_{\mathrm{i-1}}\right]-\Delta \mathrm{t}\tilde{\mathrm{T}}\mathrm{(w)} \tag{11}$$

$$\mathrm{W}_\mathrm{i}^{\mathrm{n+1}}=\frac{\tilde{\mathrm{W}}_\mathrm{i}+\mathrm{W}_\mathrm{i}}{2} \tag{12}$$

b) ***Quickest Scheme:***

$$\phi_i^{n+1} = \underbrace{\phi_i^n + \lambda\left[\widehat{F}(\phi)_{i+\frac{1}{2}} - \widehat{F}(\phi)_{i-\frac{1}{2}}\right]}_{\text{Convection}} + \underbrace{\left[\bar{D}\widehat{F}(\phi)_{i+\frac{1}{2}} - \bar{D}\widehat{F}(\phi)_{i-\frac{1}{2}}\right]}_{\text{Diffusion}} - \underset{\text{Reaction}}{\varphi\phi\Delta t} + \underbrace{q_s C_s \Delta t}_{\text{Source}} \tag{13}$$

c) ***Splitting Scheme:***

$$F^{n+2} = \left[\left(L_x L_y L_{xx} L_{yy} L_s\right) \bullet \left(L_s L_{yy} L_{xx} L_y L_x\right)\right] F^n \tag{14}$$

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

The model domain is discretized by using 91 x 63 orthogonal grids of Δx & Δy. The use of orthogonal grid in the grid system give a straight boundary line of the reservoir geometry. The grids system is arranged to fit the simplified reservoir geometry. The simplification is done to get a homogeneous square element along the complex reservoir shore line so that related numerical instability and error could be avoided (see Figure 3 and Table 2). Those grids are taken equal as long as 200 m/grid. The time interval Δt is taken as 0.5 second. The model is run during 120 hours.

Table 2 Total Grid over the model domain of Jatiluhur Reservoir.

Parameters	**Unit**	**Physical Condition**	**Numerical Model**
Surface Area	M^2	$83\ 10^6$	$83.08\ 10^6$
Grid in water surface	Grid	2075	2077
Grid in land surface	Grid	3658	3656
Grid inside reservoir	Grid	5733	5733

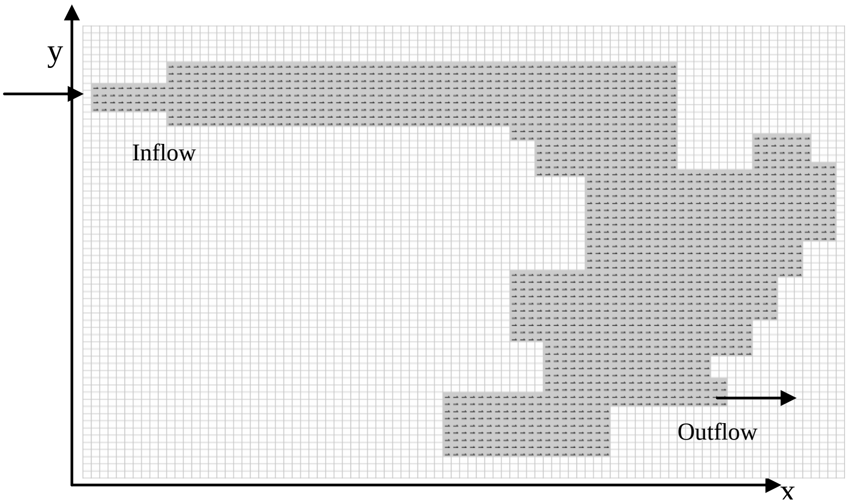

Figure 3 The grid system of the model.

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 consider only water flow and wind blow velocity as the generator parameter of water aeration.

3.3 Model Scenario

The purpose of this model is to see the capacity of recirculation flow in increasing the DO distribution in the reservoir. In this case, this daily inflow is usually too small for generating recirculation flow in the reservoir so that it could not be encountered for increasing the DO concentration. That is why this paper discusses the possibility of using the maximum incoming flow to generate the recirculation flow which could increase the DO concentration in the reservoir. In this case the simulations were conducted for the following scenarios:

a) **Scenario 1 : Maximum incoming flow during the rainy season**
As the initial condition, it is assumed that the reservoir have reached its maximum water elevation at +111.5 m above sea level, its DO concentration as it is shown in table 1 and its flow velocity at 0.02 m/sec. The boundary condition is set up by inflowing the maximum incoming flow with discharge as large as 3,000 m^3/sec that should be released from Cirata during the rainy session 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).

b) **Scenario 2 : Maximum incoming flow in the dry season**
As the initial condition, it is assumed that the reservoir have reached its minimum water elevation at +107 m above sea level where its flow velocity at 0.02 m/sec and its DO concentration is shown in Table 1. The boundary condition is set up by inflowing the maximum incoming flow with discharge as large as 3,000 m^3/sec that should be released from Cirata during the dry period and controlling the water level above the spillway by $Q=CLH_e^{3/2}$.

Due the large surface ratio of reservoir to its river inlet, as it could be seen from Figure 2, the influence of the incoming flow to the reservoir water level increment is usually low so that the gradient of reservoir surface water is small. AS k and ε under quiescent conditions is theoretically zero, sufficiently small values of k and ε are set as initial values. Trial computations have shown that these initial conditions, could give a stable and near-equilibrium state within several hours of simulation, indicating that valid conditions are formed prior to intrusion of incoming flow under the boundary condition used in this study. The incoming flow velocity at the upstream end is given uniformly along the cross section of the intake. The velocity was obtained by dividing the flow rate at each time point by the area of the cross section.

4 Results and Discussion

Based on the model results it is shown that for scenario 1, the incoming flow of 3,000m^3/s could generate an outflow of 1,600 m^3/s in the fist hour of running time and then increase until it reached 3,000 m3/s in the 20th hours of running time when the depth over the spillway crest reached 4.7 m. No identification on the storage impact as the maximum reservoir level is set up as initial condition but the outflow discharge is approximately 7 % higher than the incoming flow (see Figure 4a). Meanwhile for scenario 2, the incoming flow of 3,000m^3/s could generate an outflow of 1,000 m^3/s in the 35th hour of running time and then increase until it reached 2,500 m3/s in the 120th hours of running time. The gap between the incoming and the outcoming flow in scenario 2 (see Figure 4b) is generated by the storage impact as it is seen in Figure 2 where in the beginning the inflow discharge is used to store the water in the reservoir. Both scenario generate a subcritic flow (low froude number) as the flow depth of the reservoir is significantly increased compared to the river depth in its entrance. Most of DO concentration assessed by both scenario are smaller but have the same tendency compared to those of field observation where it is increasing toward to reservoir downstream.

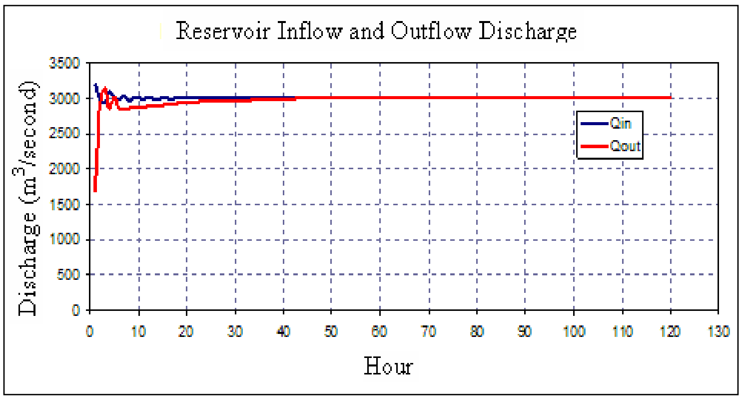

Figure 4a Storage Impact on Inflow and outflow discharge for scenario 1.

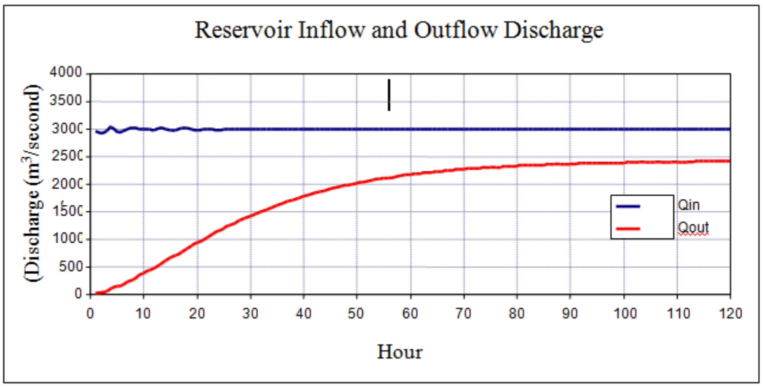

Figure 4b Storage Impact on Inflow and outflow discharge for scenario 2.

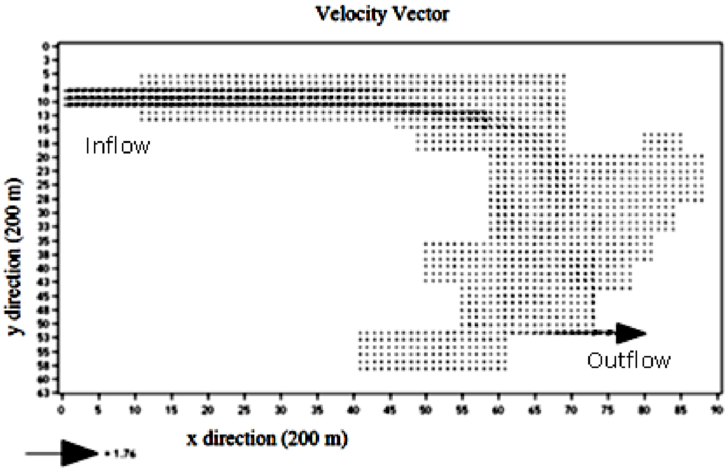

Figure 5a Velocity pattern in scenario 1.

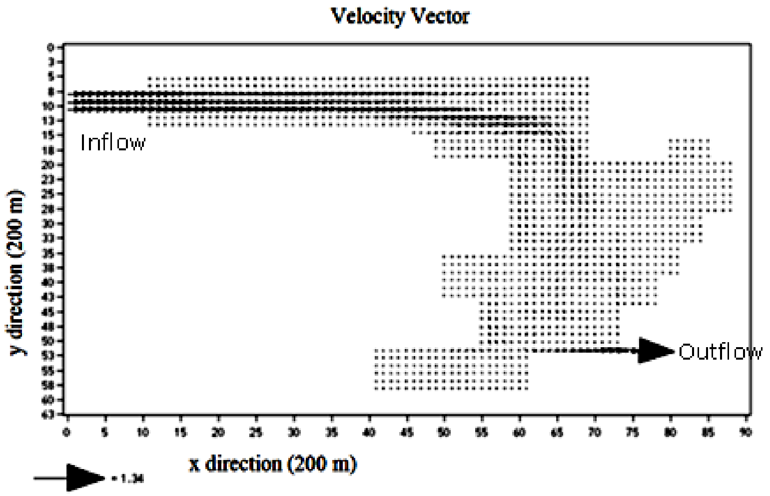

Figure 5b Velocity pattern in scenario 2.

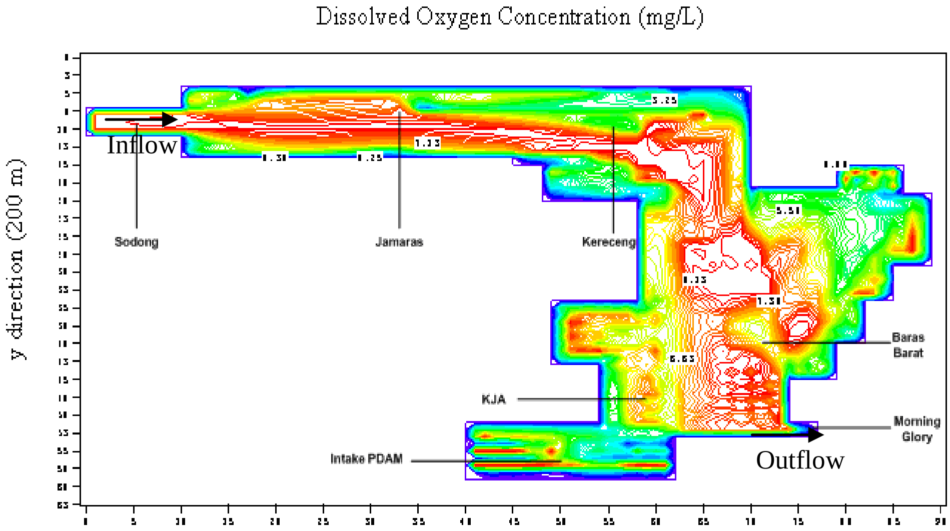

Figure 6a DO distribution after 120 hour for scenario 1.

Compared to the scenario 2, the scenario 1 generate higher average velocity as there is higher outflow to generate reservoir flow. This cause scenario 1 has more capacity in generating recirculation flow and distributing higher DO concentration as it is significantly presented in Figure 5 and Figure 6. Based on the above results, it could then be concluded that the flood incoming flow could be used to increase the DO concentration more effective if the reservoir flow is regulated using the scenario 1.

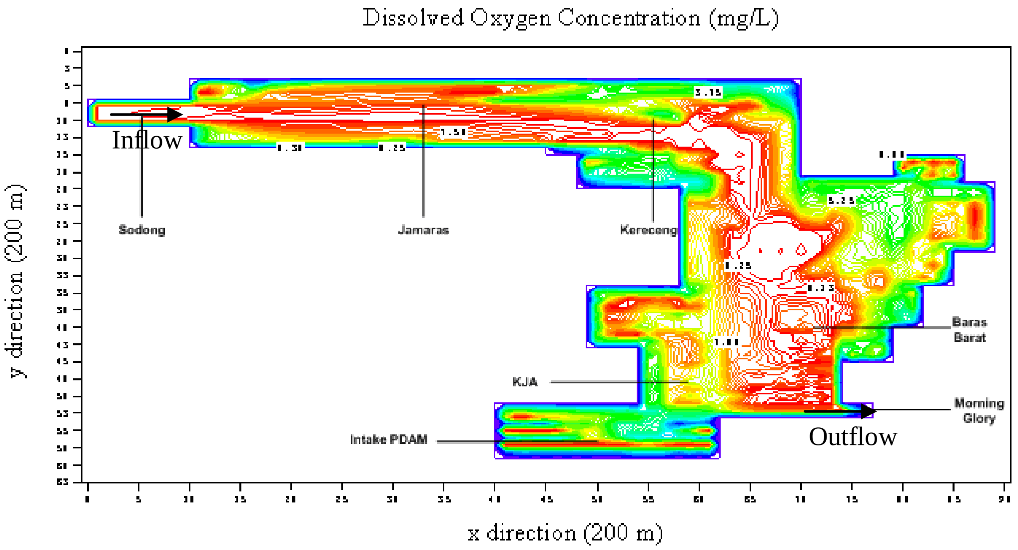

Figure 6b DO distribution after 120 hour for scenario 2.

The recirculation flow generated by both scenario as free shear layer, that started along reservoir thalweg and then horizontaly propagated accross the reservoir expantion with low velocity as it is found from visual field observation. However its instability, which is developed under the influence of depth variation and shape variation of reservoir beach, is less shown in the model results. Application of the depth averaged velocity, large grid and simplification of reservoir geometry have a significant contribution to the lack of this model in assessing this phenomenon. Therefore, further detail and accurate study based on three dimention model with more dense grid should be conducted to see more acuurate result in simulating this phenemoneon. In this case, field observation of vertical velocity distribution should be conducted to provide more accurate data for determening flow characteristic.

5 Conclusion

The simulation of recirculation flow in Jatiluhur reservoir generated by incoming flow released from Cirata Reservoir is conducted based on turbulent κ-ε model. The model is conducted by implementing maximum incoming flow in two scenario: rainy season scenario and dry season scenario. Good comparison is found between the model results and field measurement. The maximum incoming flow released in the rainy season generated greater average velocity, more recirculation flow and better DO concentration than that in the dry season. Further study is required to perform more accurate results by developing three dimention model where more dense grid should be applied and more important reservoir paramater should be encountered such as its three dimention geometry, its vertical velocity distribution and its stratified vertical density. .

Notations

$\hat{\nu}_t$ $= C_\mu \dfrac{\hat{k}^2}{\hat{\varepsilon}}$ = Depth averaged turbulent viscosity (Prandtl–Kolmogorov-Relationship, m^2/s)

g = gravitation (m/s^2)

$\hat{\varepsilon}$ = epsilon or dissipation rate of turbulent energy per unit mass (m^2/s^3)

$\hat{\kappa}$ = kappa or turbulence kinetic energy per unit mass (m^2/s^2)

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 (m/s)

V = Depth Average Velocity in y Direction (m/s)

H = Mean flow depth (m)

ρ_a = Air density (kg/m^3)

C* = Ekman Coeficient = 0.026

W_x = Wind Velocity in x direction (m/s)

W_y = Wind Velocity in y direction (m/s)

W $= \sqrt{W_x + W_y}$

Φ = Flux, water quality concentration

h = flow depth (m)

ρ = Fluid Density (kg/m^3)

μ = Dynamic Viscosity (Kg/ms)

υ = Kinematic viscosity (m^2/s)

D_x = Turbulent diffusion Coef in x direction (m^2/s)

D_y = Turbulent diffusion Coef in y direction (m^2/s)

C = $\frac{R^{1/6}}{n}$ = Chezy Coeficient ($m^{1/2}/s$)

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