Two Dimensional Sediment Transport Simulation around Kamijoro Intake, Yogyakarta, Indonesia

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Abstract: Kamijoro Intake is irrigation water intake structure located in Progo River. The Kamijoro Intake is irrigation water source for 2,365 hectares of irrigation area in Bantul, Yogyakarta, Indonesia. In the operational phase, the Kamijoro Intake cannot operate optimally because of sediment deposition around the intake structure. Thus, the sediment deposition behavior led to conduct research regarding flow pattern and sedimentation characteristic around the intake structure. Two-dimensional mathematical simulation was conducted by using Nays2DH solver provided by iRIC software. This work simulated two hydraulic conditions to enhance understanding of hydraulic and sediment transport behavior under high discharge and low discharge. The simulations result showed that high discharge scenario produced higher value on flow parameter such as water depth, velocity, and shear stress than low discharge scenario. Furthermore, high discharge generated higher value of sediment transport parameter than the low discharge such as river bed deformation, river bed elevation development and bed load parameter. Findings also revealed that immense sediment deposition around Kamijoro Intake is most influenced by small value of river slope.

1 INTRODUCTION

Kamijoro Intake is located at Kamijoro Village, Pajangan Subdistrict, Bantul District, Daerah Istimewa Yogyakarta, Indonesia. The structure is utilized as irrigation water intake for 2,365 hectares of irrigation area. Kamijoro Intake was built in year 1924. In order to be located at free sediment deposition area, Kamijoro Intake positioned at outer section of river bend (see Figure 1). Despite of located at outer river reach bend, sometime Kamijoro Intake cannot operate properly because of sediment deposition flowing inside the intake. The main factor influencing Kamijoro Intake performance in supplying irrigation water is the intake structure location at the Progo River reach having small river slope. Small river slope around Kamijoro Intake generates sediment deposition that must be removed regularly. Progo River sediment source is Merapi Mount. Merapi Mount is one of the active volcanoes in the world.

International River Interface Cooperation (iRIC) is international group consisted of scientist and engineers who want to provide access of state-of-the-art mathematic model software for undergraduate and graduate student to enhance understanding of morphodynamics. Furthermore, the research group released package software consisted of several mathematical solver modules by using similar name as iRIC (Nelson, 2016).

Nays2DH is two dimensional, depth averaged, unsteady, coupled flow, and sediment transport solver provided by iRIC (Kinze, 2015). Nays2DH has capabilities to simulate river flow, sediment transport, and river bed geomorphology.

There are wide range of researches regarding sediment transport and morphological development simulation. Norman (2017) assessed hydraulic and transport sediment behaviour of ephermal stream for restoration purpose, Wickham (2015) found that grain size heterogeneity influences bed load transport, while bed roughness variability do not generated impact in sediment transport, Wongsa (2016) simulated breach morphological development of earthen embankment, and Sarkawt (2017) simulated hydro morphology response of Sandy River in Oregon toward flood occurrence.

Moreover, Ali (2017) demonstrated Nays2DH ability to simulate flow pattern around single groyne with several angles toward approaching flow. The hydraulic simulation also could produce secondary flow well at the downstream of installed groyne.

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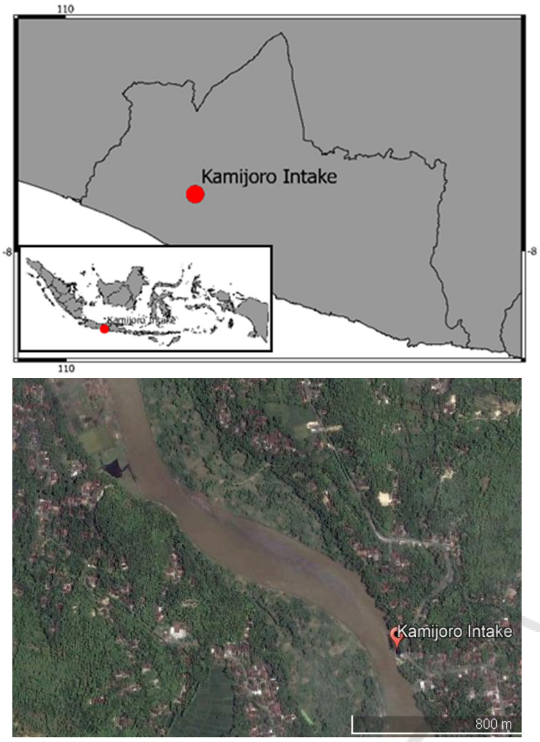

Figure 1: An overview of study area.

2 THEORIETICAL CONSIDERATION

Nays2DH is mathematic two-dimensional model for simulation of flow, sediment transport, riverbed morphology change, and riverbank. The model is consisted of Nays2D and Morpho2D. The Nays2D is developed by Dr Yasuyuki Shimizu from Hokkaido University and Dr. Hiroshi Takebayashi from Kyoto University Shimizu (2014).

2.1 Basic Equation

Below are continuity equation (1) and momentum equation ((2) and (3)) used by Nays2DH solver in orthogonal coordinate. Nays2DH solver uses following equations in general coordinate in order to be used in irregular mesh shape.

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \qquad (1)$$

$$\frac{\partial (uh)}{\partial t}+\frac{\partial (hu^2)}{\partial x}+\frac{\partial (huv)}{\partial y}= -gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho}+D^x+\frac{F_x}{\rho} \qquad (2)$$

$$\frac{\partial (vh)}{\partial t}+\frac{\partial (huv)}{\partial x}+\frac{\partial (hv^2)}{\partial y}= -gh\frac{\partial H}{\partial x}-\frac{\tau_y}{\rho}+D^y+\frac{F_y}{\rho} \qquad (3)$$

Where h is water depth, t is time, u is velocity in x direction, v is velocity in y direction, g is gravitational acceleration, H is water depth, τ is shear stress, and F is drag force caused by vegetation. Moreover, shear stress (τ) calculation involves riverbed drag coefficient (C_f) that can be determined by (4) and (5). Whereas, the diffusion parameter are calculated as (6) and (7), and drag force influenced by vegetation equation are shown as (8) and (9).

$$\frac{\tau_x}{\rho}=C_f u\sqrt{u^2+v^2} \qquad (4)$$

$$\frac{\tau_y}{\rho}=C_f u\sqrt{u^2+v^2} \qquad (5)$$

$$D^x=\frac{\partial}{\partial x}\left[v_t h\frac{\partial u}{\partial x}\right]+\frac{\partial}{\partial y}\left[v_t h\frac{\partial u}{\partial y}\right] \qquad (6)$$

$$D^y=\frac{\partial}{\partial x}\left[v_t h\frac{\partial v}{\partial x}\right]+\frac{\partial}{\partial y}\left[v_t h\frac{\partial v}{\partial y}\right] \qquad (7)$$

$$\frac{F_x}{\rho}=\frac{1}{2}C_D a_s h_v u\sqrt{u^2+v^2} \qquad (8)$$

$$\frac{F_y}{\rho}=\frac{1}{2}C_D a_s h_v u\sqrt{u^2+v^2} \qquad (9)$$

2.2 Turbulence Model

Turbulence simulation employs turbulent zero-equation model shown by (10).

$$v_t=au_*h \qquad (10)$$

Where v_t is eddy viscosity coefficient, a is 0,07, and u_* is bed shear velocity. The eddy viscosity can expressed as (11) below.

$$v_t=\frac{k}{6}A_e u_* h+B_e \qquad (11)$$

Where k is von Karman coefficient (0,4), A_e is eddy viscosity parameter, and B_e is eddy viscosity parameter.

2.3 River Bed Friction Coefficient

River bed friction coefficient is calculated based on Manning roughness value. The river bed friction coefficient can be computed by using (12), whereas Manning roughness value is expressed by (13).

$$C_f = \frac{gn_m^2}{h^{\frac{1}{3}}} \quad (12)$$

$$n_m = \frac{k_s^{\frac{1}{6}}}{7.66\sqrt{g}} \quad (13)$$

Where C_f is river bed friction coefficient, g is gravitational acceleration, and n_m is Manning roughness value. Furthermore, the Manning roughness value is calculated based on Strickler roughness value.

2.4 Shields Number

Shields number is non dimensional river bed stress used to determine initial sediment movement. Shield number is calculated by using (14) and (15) below.

$$\tau_* = \frac{hI_e}{s_g d} \quad (14)$$

$$\tau_* = \frac{C_f V^2}{s_g dg} == \frac{n_m^2 V^2}{s_g dh^{\frac{1}{3}}} \quad (15)$$

$$V = \sqrt{u^2 + v^2} \quad (16)$$

Where σ_* is Shields number, I_e is energy slope, s_σ is specific weight of bed material in fluid, d is sediment diameter, V is composite velocity, u is velocity toward x direction, v is velocity toward y direction. The composite velocity is analyzed by using (16).

2.5 Bed Load Transport

Equation (17) shows Meyer-Peter Muller equation to calculate bed load transport.

$$q_b = 8(\tau_* - \tau_{*c})^{1.5}\sqrt{s_g g d^3} r_b \quad (17)$$

$$r_b = 1 \rightarrow E_{sd} > E_{be} \quad (18)$$

$$r_b = \frac{E_b}{E_{be}} \rightarrow E_{sd} > E_{be} \quad (19)$$

Where q_b is bed load transport, σ_{*c} is critical Shields number, r_b is exchange layer thickness,E_{sd} is sediment layer thickness on fixed bed, E_{be} is equilibrium bed load layer thickness, and E_b is bed load layer thickness. Exchange layer thickness is determined by using (18) or (19).

2.6 Velocity near River Bed

Relation of velocity near river bed with respect to mean velocity is stated by (20) below.

$$\tilde{u}_b^s = \beta V \quad (20)$$

$$\beta = 3\frac{1-\sigma}{3-\sigma} \quad (21)$$

$$\sigma = \frac{3}{\phi_0 k + 1} \quad (22)$$

$$\phi_0 = \frac{V}{u_*} \quad (23)$$

Where $\tilde{u}_b^s$ is velocity near river bed, and $Ø_0$ is velocity coefficient.

3 RESEARCH METHODOLOGY

Boundary conditions used to simulate hydraulic condition around Kamijoro Intake were discharge record obtained from Sapon AWLR station for upstream boundary condition (see Figure 2) and water elevation stage at the downstream of Kamijoro Intake as downstream boundary condition. The elevation stages were analyzed by steady state one dimensional simulation using HEC-RAS.

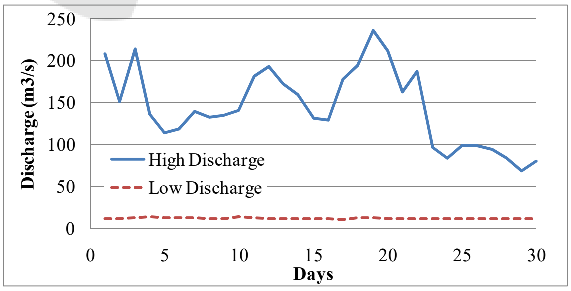

Figure 2 : Discharge data used for simulation.

The mathematical simulation was conducted in two scenarios. The scenarios were high discharge and low discharge in order to analyze the difference hydraulic characteristic between wet season and dry season respectively. Both scenarios were selected in order to investigate hydraulic and sediment transport characteristic near Kamijoro Intake. The hydraulic characteristic around Kamijoro Intake was simulated in unsteady condition and the simulation length for each simulation was 30 days.

Figure 3 below is overview of topographic model used to conduct the simulation hydraulics and sediment transport behaviour near Kamijoro Intake.

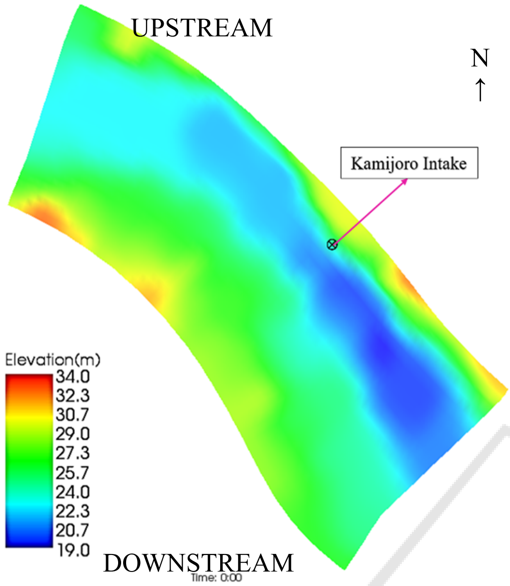

Figure 3: Topographic overview of Kamijoro Intake.

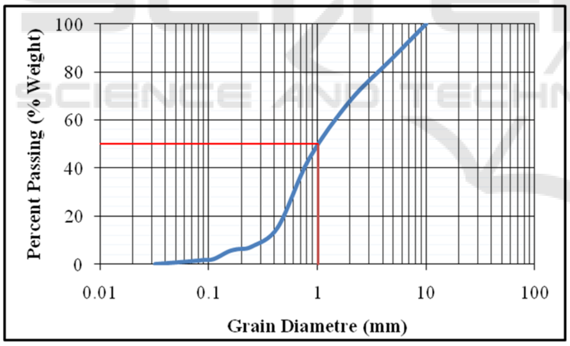

Figure 4 : Grain size distribution.

Figure 4 above shows grain size distribution of Progo River used for this work. Moreover, sediment specific gravity is 2.65 and d_{50} size is 1.01 mm.

4 RESULT AND DISCUSSION

Simulation result will be discussed to compare hydraulic and sediment transport condition at peak discharge and end of simulation for both simulation scenarios. Result analysis of the end of simulation is intended to compare hydraulic and sediment transport characteristic as result of geomorphology development.

4.1 Velocity

Magnitude and velocity vectors around Kamijoro Intake can be seen at Simulation results express that velocity magnitude at around Kamijoro Intake generated by high discharge is higher than velocity obtained from low discharge. Moreover, the velocity vectors show that high velocity vectors occupy area at the edge of river flow and the velocity flow vectors direction are downstream direction. Although, velocity near Kamijoro Intake has high value but the flow direction does not lead into Kamijoro Intake. Hence, river water condition inside the intake structure is calm. Whereas, velocity vectors generated by low discharge show random direction and occupy area at the middle of river cross section. High value of velocity parameter at outer river bend is similar with the river flow velocity characteristic.

4.2 Water Depth

Simulation results yielded by high discharge show that river water inundated Kamijoro Intake with approximately 2 m (see
Figure 7: Shear stress distribution around Kamijoro Intake.
). While in dry season, the water depth is low. Low water depth on Kamijoro Intake causes the intake structure cannot operate normally. Furthermore, water depth will influences shear stress analyses. Moreover, the bigger water depth will produce higher hydrodynamic pressure that can seize bed load sediment.

4.3 Shear Stress

Shear stress distribution around Kamijoro Intake indicates that high value shear stress only generates by high discharge. The high value shear stress occupy area outer river bend. The phenomenon is similar with river velocity characteristic. In the river bend, the high flow velocity occupies outer bend area. Other three simulation results express that shear stress occurred around Kamijoro Intake is low therefore there will be sediment deposition around Kamijoro Intake. Low value of shear stress can be yielded by small value of river slope.

4.4 Bed Load Flux

Bed load flux distributions show that significant bed load flux is generated by peak of high discharge scenario. The highest bed load flux occupies edge area of river cross section. The significant bed load flux location is similar with finding showed by shear stress parameter, and flow velocity result. All of the simulation result distributions show occurrence of high value of each parameter at the outer of river reach.

4.5 Bed Elevation Change

Elevation change parameter reveals two possibilities. Positive value means sediment deposition, while negative value means sediment aggradations.

High discharge scenario generates more positive elevation change rather than negative elevation change. It means that sediment deposition will occupy in most area than sediment aggradations. The high positive bed elevation change is distributed at the centre of river reach. While at the edge of river reach is occupied by low bed elevation change.

4.6 Bed Elevation Development

This work indicates that there is sediment deposition on both scenarios particulary at the area near with Kamijoro Intake. The sediment deposition around intake structure causes river water unable to flow into Kamijoro Intake. The simulation results also represent that high discharge scenario generates higher river bed levation than low discharge scenario.

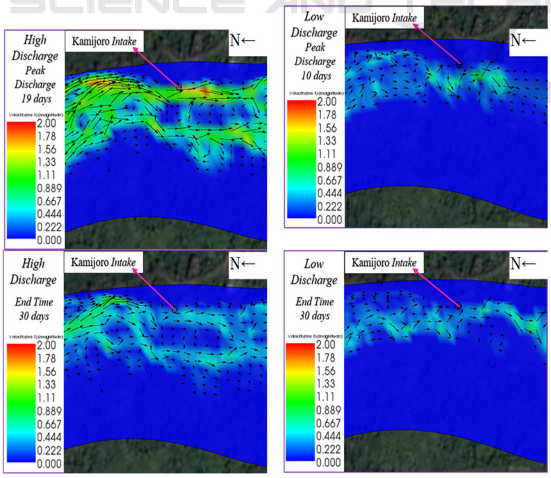

Figure 5: Velocity magnitude and velocity Vector around Kamijoro Intake.

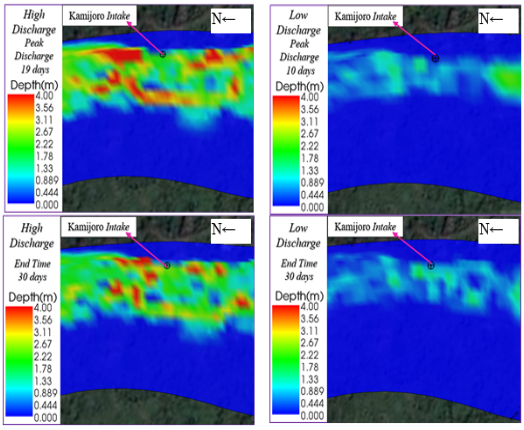

Figure 6: Water depth distribution around Kamijoro Intake.

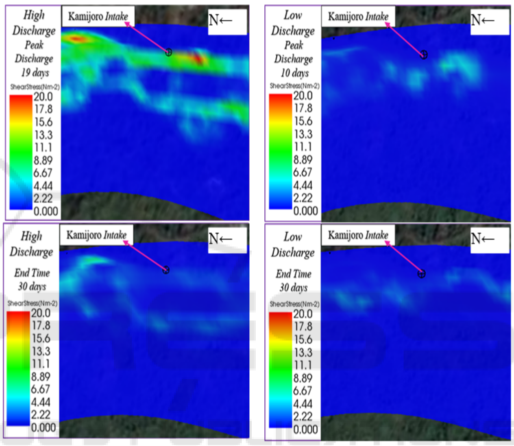

Figure 7: Shear stress distribution around Kamijoro Intake.

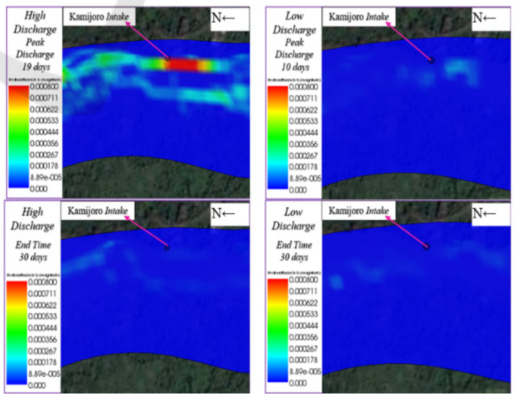

Figure 8: Bed load flux distribution around Kamijoro Intake.

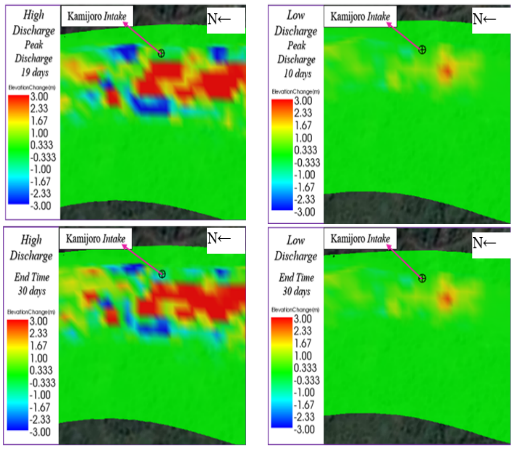

Figure 9: Bed elevation change distribution around Kamijoro Intake.

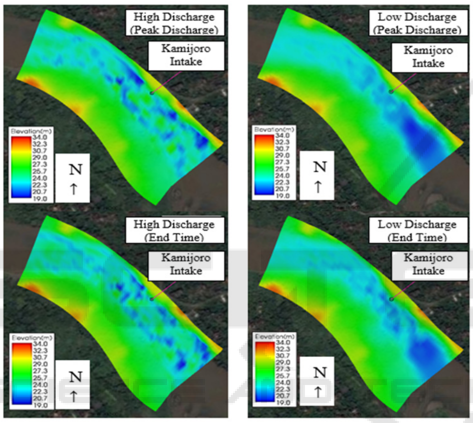

Figure 10: Bed elevation development distribution around Kamijoro Intake.

5 CONCLUSION

This work shows that sediment deposition near Kamijoro Intake is influenced mostly by small value of river slope. Either flow velocity and water depth cannot produce enough shear stress to entrain bed load at location near Kamijoro Intake. Based on elevation change distribution produced by high discharge scenario, Kamijoro Intake will be surrounded by high sediment deposition. Thus, river water cannot flow into Kamijoro Intake.

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