Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.109.3

Mathematical modelling of hydraulics and water quality characteristics for small dam maintenance

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Keywords: small dam maintenance, hydrodynamics analysis, model validation, numerical modelling

Abstract. Along the inclining events of flooding events, maintenance towards water infrastructure such as urban small dam is needed. The maintenance needs interdisciplinary approach involving hydrology, hydraulics, water quality, and sediment factors. Due to lack of studies in those fields, the study aims to construct a model by using RESOURCE MODELLING ASSOCIATES program to study behaviours of hydraulics and water quality as small dam management. Numerical modelling, hydrology analysis, hydraulics assessment, water quality tests, and field works are employed in this study, with Agathis small dam as a case. The model could run successfully which the result concludes that the model produces reasonable result with acceptable errors and value of R2. A scenario of constructed wetland is proposed and has good accuracy for future maintenance for hydrology, hydraulics, and environmental management. In addition, the models also could be applied to other problem such as an agricultural field also. In the near future, studies about hydrodynamics and water quality modelling especially sediment on small dams need to be more explored because few studies still have limited information meanwhile they have essential impact towards urban water management.

1. Introduction

1-D, 2-D, or 3-D hydrodynamic and water quality modeling are rapidly developing and reaching their contributive applications such as modeling of microbial contamination in coastal and river [1–3], river water quality [4–7], water quality in reservoir and lagoon [8–10], and water quality within basin or watershed [11–13]. Despite the successful modeling in several topics, few studies of water quality, hydraulics, and sediment modeling on urban small dam or lakes have been published. Meanwhile, the modeling on those sites [14–16] is compulsory realized as a strategic process to tackle urban disaster events [17–19].

The most recent example to support the need for this research is the biggest flooding event in Jakarta, Indonesia. Jakarta Flood of January 1, 2020, triggered an enormous stop of construction projects in several places due to high level of inundation area. Table 1 provides the rainfall data in that day. The table indicates that the amount of rainfall makes this flood of the most impactful in the recorded history of Jakarta. The dynamics of hydrology condition and climate change patterns affect environmental damage such as the huge amount of nutrient loading to water resources – lakes and small dams. Because of the declared situation, there is a dire need to protect the water resources from hydrology aspects, improve hydraulics characteristics, and water quality conditions.

Prastica, R.M.S., Soeryantono, H., Marthanty, D.R. Mathematical modelling of hydraulics and water quality characteristics for small dam maintenance. Magazine of Civil Engineering. 2022. 109(1). Article No. 10903. DOI: 10.34910/MCE.109.3

Table 1. 24-hour precipitation on 1 January 2020 (in mm).

Station	Elevation	Value
Halim Perdana Kusuma	–1	377.0
AWS TMII	0	335.2
Pintu Air Pulo Gadung	20	260.0
Citayam	–1	243.0
Sunter Hulu	54	236.0
ARG Tomang	0	225.6
Kedoya	30	211.6
Tangerang Selatan Climatology Station	27	200.0
Waduk Melati	25	191.0
Manggarai	33	189.0
Balai II Ciputat	–1	184.9
Lebak Bulus	–1	176.0
Rorotan	23	172.0
Pasar Minggu	58	155.0
Ragunan	65	155.0
Lemah Abang	14	151.0
Pesanggrahan Depok	86	148.0
Soekarno Hatta Meteorology Station	11	147.9
Istana	30	147.0
Maritim Tanjung Priok Meteorology Station	3	146.1
Kemayoran Meteorology Station	4	145.3
Sunter III Rawabadak	19	144.0
Pakubuwono	54	142.0
Beji Depok	0	142.0
Pompa Cideng	21	135.0
AWS Jagorawi Bogor	0	131.5
Sunter Timur I Kodamar	25	121.0
Angke Hulu	17	120.0
Karet	38	118.0
Teluk Gong	23	113.0
ARG Ciganjur	0	110.4
Setiabudi Timur	29	105.0
Krukut Hulu	80	104.0
Depok 1	93	92.0
AWS IPB Bogor	0	75.8
Citeko Meteorology Station	920	60.0
Katulampa	361	57.4
Stamet Curug	–1	54.0

Furthermore, even without flash flooding, Jakarta as the urban area has an initial issue of high demand for infrastructure construction every year. Rapid urban development makes it difficult for rainwater to infiltrate the ground due to dense impervious cover. In recent years the population growth snowballs [20] along with the development of settlement for them to live. In addition, urbanization attracts population growth to particular areas. Urbanization becomes a threat worldwide, especially in developing countries. According to Thorn et al. [21], the main threat comes from the impervious surface. Wong et al. [22] stated that the impervious surface could be defined as buildings, roads, and other infrastructures. This water-resistant surface is highlighted as the main root of flooding in urban areas. Also, the changes in land cover drive ecosystem changes [21].

Urban small dam or lake management plays a proper role in flood risk management and ensures a construction project runs well. Henny et al. [23] mention that urban lake management gives a contribution to watershed management to reduce the impact of flash flooding. Urban lakes situated in the large watershed are small, shallow, and surrounded mostly by impervious land [23]. Natural lakes that are usually found in rural regions differ from man-made lakes or urban lakes. Most natural lakes are sources of pollution of different kind. Lakes suffer eutrophication along with the increasing of agricultural activities, for example, fish aquaculture, crops, and livestock farming [24–26]. Industrial and urban activities, as well as regional construction bring urban lakes' contaminants, such as sediment that contains heavy metals harmful to the aquatic environment [27, 28]. As small dam conservation is in high demand due to the declining of lake quality and lack of hydraulics management, hence, it is important to construct hydrodynamic and water quality model for small dams which could describe cost-effective urban dam management and maintenance.

From the above review, we can conclude that the development of mathematical modeling to simulate hydrodynamics, water quality, and sediment for urban small dam maintenance is necessary due to limited published works on water management and strategy of future condition.

According to the declared problems, the research aims to create mathematical model, provided by Resource Modelling Associates (RMA) program, to describe and obtain detailed characteristics of hydraulics and water quality, especially for sediment, in small dams. The model is studied in one of small dams in urban area of West Java, Agathis. After the model is well-constructed and represented the field condition, proposed scenario is tested as water management and strategy.

2. Methods

Hydraulics, hydrology, and water quality problems are usually investigated by means of individual methods, while the optimum maintenance for civil infrastructures needs all of those aspects. Table 2 shows the current methods to develop a solution to the declared problems. Research gap in Table 2 provides opportunities for further research. The gap defines the involvement of hydrology, hydraulics, and water quality quantifications. In this research, all aspects are employed to obtain the research goals.

Table 2. Methods of evaluation and maintenance for water infrastructures.

Cases	Research Method	Research gap	Location	Reference(s)
Damage of building due to flooding	Hydrology assessment	Quantitative and deterministic models	United Kingdom	[29]
Flood disaster	Hydrology forecasting, hydrodynamics model	No hydraulics and environmental analysis	Malaysia	[30]
Floods and landslide hazard	Spatial technology	No hydraulics and environmental analysis	Malaysia	[31]
Flooding	Hydrology and hydraulics assessment	Water quality	Philippines	[32]
Impact of climate change to flood regimes	Hydrology and spatial analysis	Water quality	France	[33]
Flash floods	Hydrology assessment, spatial simulation	Water quality	Australia	[34]
Chronic flood-affected areas	Qualitative research	Hydrology, hydraulics, and water quality assessment	India	[35]
Flood hazard	Hydro-geomorphological study	Hydraulics and water quality	Morocco	[36]
Frequent flooding	Interviews	Hydrology, hydraulics, and water quality assessment	Africa	[37]
Damage of building structures to flood	Field survey, laboratory experiments, interviews	Hydrology, hydraulics, and water quality assessment	Tanzania	[38]
Structural flood damage	Computational fluid dynamics	Hydrology, water quality	United Kingdom	[39]
Flood and high rainfall	Spatial analysis	Hydraulics, water quality	Japan	[40], [41]
Flooding	Spatial analysis	Hydraulics, water quality	Australia	[42]

Cases	Research Method	Research gap	Location	Reference(s)
Flooding	Spatial model	Hydrology, hydraulics, and water quality assessment	Indonesia	[43]
Flooding	Low impact development	Water quality assessment	Greece	[44]
Flooding	Hydrology, hydraulics, and water quality assessment	–	Indonesia	This research

To achieve the research goals, the research recalls the hydrodynamics equations as basic hydrology, hydraulics and water quality characteristics of the water body. They are described in the following equations:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \quad (1)$$

$$\rho\left[\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]=\frac{\partial\left(\sigma_x-p\right)}{\partial x}+\frac{\partial \tau_{xy}}{\partial y} \quad (2)$$

$$\rho\left[\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]=\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial\left(\sigma_y-p\right)}{\partial y} \quad (3)$$

$$\sigma_x=2\mu\frac{\partial u}{\partial x} \quad (4)$$

$$\sigma_y=2\mu\frac{\partial v}{\partial y} \quad (5)$$

$$\tau_{xy}=\mu\left[\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right] \quad (6)$$

where u and v represent the components for velocity, p is interpreted as pressure, ρ describes density, and μ describes the viscosity. According to the substitution of Equations (1) – (6), the system of relations for velocity distribution formulae is described as Equation (7) for x direction and Equation (8) for y direction:

$$-\rho\left[\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]+\frac{\partial}{\partial x}\left[2\mu\frac{\partial u}{\partial x}-p\right]+\mu\frac{\partial}{\partial y}\left[\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right]+ \\ +u\frac{\Delta t}{2}\frac{\partial}{\partial x}\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]+v\frac{\Delta t}{2}\frac{\partial}{\partial x}\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]=0, \quad (7)$$

$$-\rho\left[\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]+\frac{\partial}{\partial y}\left[2\mu\frac{\partial v}{\partial y}-p\right]+\mu\frac{\partial}{\partial x}\left[\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right]+ \\ +u\frac{\Delta t}{2}\frac{\partial}{\partial x}\left[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]+v\frac{\Delta t}{2}\frac{\partial}{\partial x}\left[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]=0. \quad (8)$$

Furthermore, the governing equation of water quality is affected by the advection and dispersion aspects and depicted as the following Equation (9) [45]. In this research, total suspended solids, as one of the most problematic issues in urban areas, is used as a study model in the water quality section.

$$\partial_t(HS)+\partial_x(HuS)+\partial_y(HvS)+\partial_z(w_sS) \\ =\partial_x(HA_H\partial_xS)+\partial_y(HA_H\partial_yS)+\partial_z\left(\frac{A_v}{H}\partial_zS\right)+Q_s \quad (9)$$

where H is water depth;

u and v are horizontal velocity component in horizontal Cartesian x and y;

w is vertical velocity in coordinate vertical stigma of z;

w_s is sediment settling velocity;

S is sediment concentration;

A_v and A_H are vertical and horizontal turbulent diffusion coefficient;

Q_S is external source and sink.

Based on the declared governing equations and research background, the analysis is employed by using "Resource Modelling Associates (RMA)" program. The program could visualize the analysis with an in-depth and comprehensive result. The problem associated with the research takes place in the urban small dam. Therefore, a model of the urban lake is proposed to the research to develop the model. The research uses Agathis Lake site which is located in Depok, West Java, Indonesia.

From the continuity governing equation (1) – (8), partial differential equation is analyzed through discretization, approximation, and finally the last form of momentum equation for both x and y directions, as described in Equations (10) and (11).

Momentum equation for x direction is:

$$\begin{aligned}&\int_V \left[\left(\rho\psi\psi^T \frac{\partial u}{\partial t}\right) + \rho\left[\psi\left(\psi^T u\right)\frac{\partial \psi^T}{\partial x} + \psi\left(\psi^T v\right)\frac{\partial \psi^T}{\partial y}\right]\right] udV \\ &+ \int_V \left[2\mu\frac{\partial \psi}{\partial x}\frac{\partial \psi^T}{\partial x} + \mu\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial y}\right] udV \\ &+ \frac{\Delta t}{2}\int_V \left[uu\frac{\partial \psi}{\partial x}\frac{\partial \psi^T}{\partial x} + uv\frac{\partial \psi}{\partial x}\frac{\partial \psi^T}{\partial y} + vu\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial x} + vv\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial y}\right] udV \\ &+ \int_V \left[\left(\mu\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial x}\right) v - \left(\frac{\partial \psi}{\partial x}\phi^T\right) p\right] dV = \int_V \rho\psi f_i dV\end{aligned} \tag{10}$$

while momentum equation for y direction is:

$$\begin{aligned}&\int_V \left[\left(\rho\psi\psi^T \frac{\partial v}{\partial t}\right) + \rho\left[\psi\left(\psi^T u\right)\frac{\partial \psi^T}{\partial x} + \psi\left(\psi^T v\right)\frac{\partial \psi^T}{\partial y}\right]\right] vdV \\ &+ \int_V \left[2\mu\frac{\partial \psi}{\partial x}\frac{\partial \psi^T}{\partial x} + \mu\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial y}\right] vdV \\ &+ \frac{\Delta t}{2}\int_V \left[uu\frac{\partial \psi}{\partial x}\frac{\partial \psi^T}{\partial x} + uv\frac{\partial \psi}{\partial x}\frac{\partial \psi^T}{\partial y} + vu\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial x} + vv\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial y}\right] vdV \\ &+ \int_V \left[\left(\mu\frac{\partial \psi}{\partial y}\frac{\partial \psi^T}{\partial x}\right) u - \left(\frac{\partial \psi}{\partial y}\phi^T\right) p\right] dV = \int_V \rho\psi f_i dV\end{aligned} \tag{11}$$

where Q is weight function for Galerkin method, pressure weight;

W is velocities weight;

Ψ is interpolation function;

Φ is interpolation function;

u is velocity vector;

v is velocity vector;

p is pressure vector.

With the same ways as the continuity equation, the governing Equation (9) of sediment transport for advection and dispersion components are elaborated into Equation (12), as follows:

$$\int_V \left[\frac{\partial (H)}{\partial t} \sum_{k=1}^{m} S_k \frac{\partial \varphi_j}{\partial t} + \frac{\partial (Hu)}{\partial x} \sum_{k=1}^{m} S_k \frac{\partial \varphi_j}{\partial t} \right] dV + \int_V \left[\frac{\partial (Hv)}{\partial y} - \frac{\partial (HA_H)}{\partial x} \sum_{k=1}^{m} S_k \frac{\partial \varphi_k}{\partial x} \frac{\partial \varphi_j}{\partial x} \right] dV - \int_V \left[\frac{\partial (HA_H \partial_y)}{\partial y} \sum_{k=1}^{m} S_k \frac{\partial \varphi_j}{\partial y} \right] dV - \int_V Q_s dV = 0 \quad (12)$$

3. Results and Discussion

3.1. Study Area

The study area, depicted in Fig. 1, is in Agathis small dam, West Java, Indonesia. The small dam is also close to The Greater Jakarta. The green and red mark a constructed wetland area which does not exist yet, but will be modelled after the calibration stage of the model. Location I is inlet of sediment trap, Location II indicates its outlet, Location III is floodway, Location IV indicates the inlet of the small dam, Location V is the water body, while Location VI is the small dam's outlet.

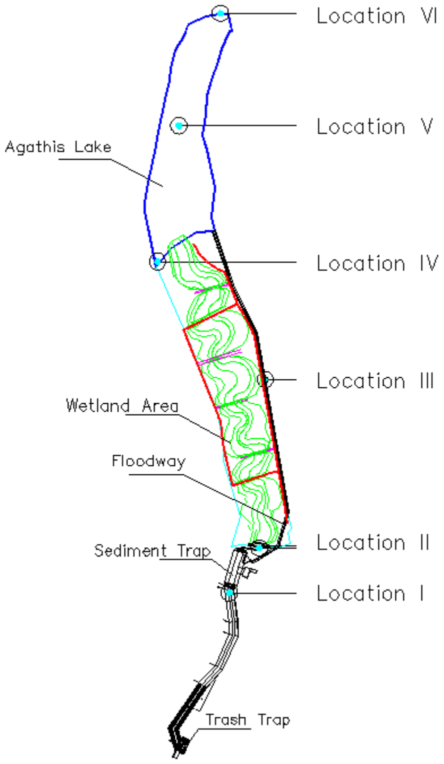

Figure 1. Agathis small dam physical features.

3.2. Model Calibration and Accuracy

According to the relations (7), (8), and (9), RMA is developed to simulate both computational and field experiments. RMA is divided into two main running programs: RMA-10 for hydraulics analysis and RMA-11 for water quality analysis. Firstly, the research constructs urban small dam on the basis of the finite element method theory. The results of RMA-10 and RMA-11 are depicted in Fig. 2 and Fig. 3, respectively. The programs are running well to model velocity distribution for hydraulics management and total suspended solid distribution for water quality analysis, but they should be verified by the actual condition in the field. Thus, field and laboratory experiments are conducted. The main purpose of model calibration and validation is to create scenarios for small dam evaluation and management.

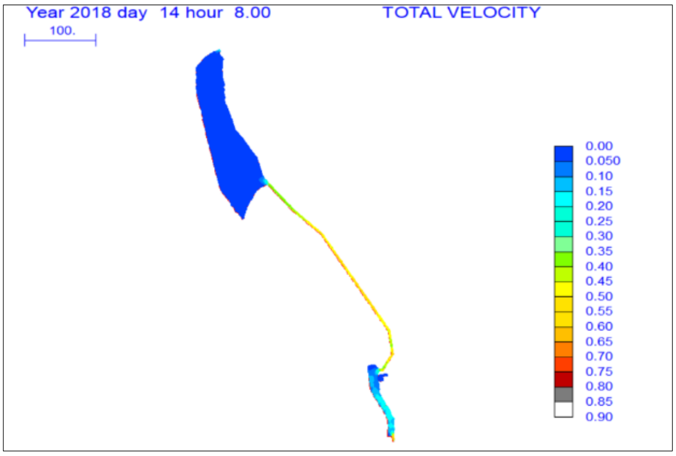

Figure 2. Agathis small dam in RMA-10 program visualization.

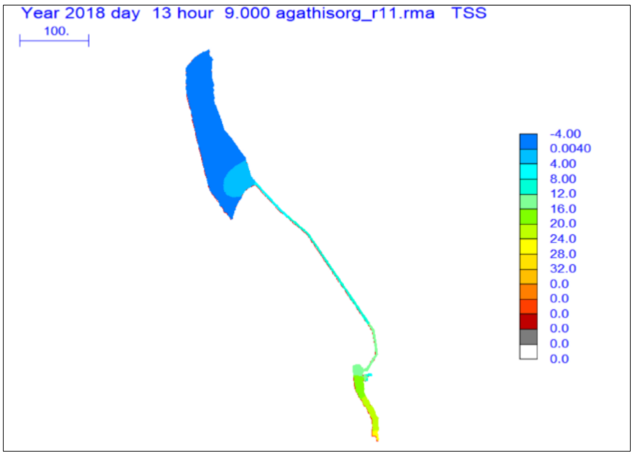

Figure 3. Agathis small dam in RMA-11 program visualization.

Data validation and calibration need velocity and total suspended solid data for RMA-10 and RMA-11 programs. The field experiments are carried out in 24-hour sampling time. After laboratory works, Table 3 illustrates the data result and the predicted data for model calibration. The experiments failed in inlet location at 1.00 – 2.00 pm due to inability to take appropriate samples caused by harmful and poisoned contaminants at the location access, so the errors are not calculated.

Table 3. Data for model calibration in small dam.

Time	Location	TSS field data (mg/l)	Model prediction of TSS data (mg/l)	SSE (%)	Velocity field data (m/s)	Model prediction of velocity data (m/s)	SSE (%)
8:00:00 AM	Inlet Sediment Trap	30	29.37	2.10	0.47	0.51	8.51
9:00:00 AM	Inlet Sediment Trap	27.7	25.52	7.87	0.45	0.45	0.00
10:00:00 AM	Outlet Sediment Trap	13.3	11.42	14.14	0.32	0.32	0.00
11:00:00 AM	Inlet floodway	13.5	8.678	35.72	0.3	0.32	6.67
12:00:00 PM	Floodway	4.0	5.66	41.50	0.4	0.42	5.00
1:00:00 PM	Inlet	2.7	8.79	NA	0.15	0.21	NA
2:00:00 PM	Inlet	2.6	8.38	NA	0.18	0.21	NA
3:00:00 PM	Water body	0.9	0.93	3.33	0.01	0.01	0.00
4:00:00 PM	Water body	1.1	0.91	17.27	0.01	0.01	0.00
5:00:00 PM	Water body	2.0	1.98	1.00	0.01	0.01	0.00
6:00:00 PM	Water body	3.0	2.59	13.67	0.01	0.01	0.00
7:00:00 PM	Water body	3.0	2.60	13.33	0.01	0.01	0.00
8:00:00 PM	Outlet	1.3	1.02	21.54	0.05	0.04	20.00
9:00:00 PM	Outlet	1.3	1.02	21.54	0.04	0.04	0.00
7:00:00 AM	Outlet	2.5	2.19	12.40	0.04	0.04	0.00
8:00:00 AM	Outlet	2.5	2.19	12.40	0.04	0.04	0.00

To make the validation of hydraulics characteristic clearer, we sampled data at certain times in several places. Fig. 4 depicts the result of the hydraulics experiment with velocity measured at certain distances and in specific time intervals. Not only hydraulics but also water quality analyses are conducted in the same manner. The calibration result of water quality is described in Fig. 5, where the concentrations are observed in several time steps. The correlation coefficient of both hydraulics and water quality calibration are 0.8686 and 0.9340, respectively.

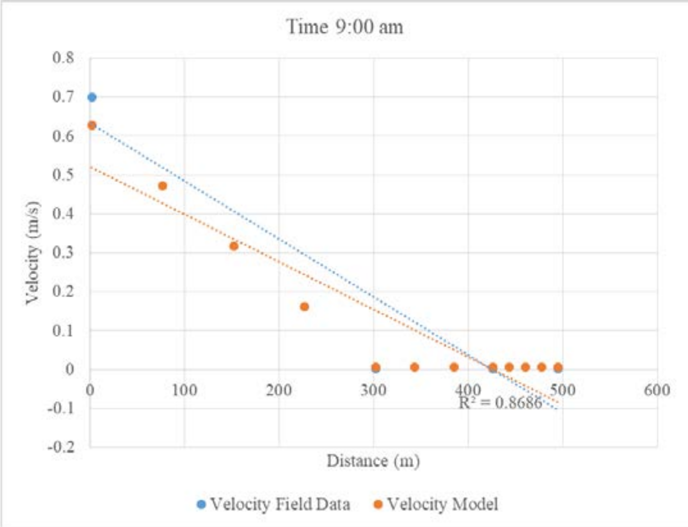

Figure 4. Calibration data of hydraulics characteristic.

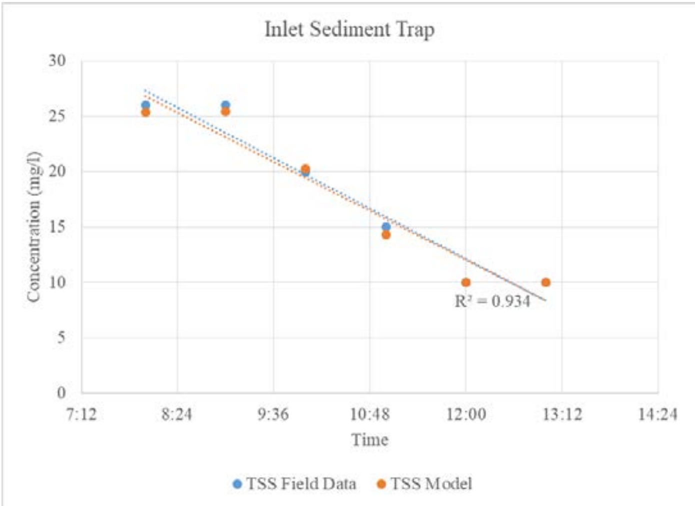

Figure 5. Calibration data of water quality characteristic.

Study in Lake Tenkiller [45] had the same procedures and experiments but different model and type of water quality parameter to simulate. The study observed dissolved oxygen (DO) with relative errors varying from 10.86 % to 28.26 %. Ji [45] concluded that the model was applicable to process comprehensive and detailed demonstration of several case scenarios. As a result, compared to this study with the error varying from 1 % to 41.50 %, the model can be seen as a well-designed simulation. However, further studies need to be developed due to limited and different parameters observed.

In addition, a study in Lake Manzala [46] on salinity parameter employed MIKE21 software and the same procedures of calibration as in this study. The error of total period for salinity varied from 0.088 to 0.282 and value of R^2 varied from 0.985 to 0.991. Since this study has a sample of R^2 value with 0.8686 and 0.934, again, the results can be used as a good model for the same characteristics but still cannot be applied to lakes of various conditions due to different parameters and limited studies on them.

Researches conducted in Tanglin Bay, Guozheng Bay, Shuiguo Bay, and Yingwo Bay [47] concluded that the model result could provide reasonable patterns and magnitudes of reproduction to model water quality parameters without providing extended explanation about the occurred errors in the model. Researchers only displayed the model result, as depicted in Fig. 6 as TP modelling result. The model simulated both total nitrogen (TN) and total phosphorus (TP). Again, the results could not be well compared due to different parameters and water bodies.

Different water quality constituents, COD, TN, and TP were modelled in Xi'an Yanming Lake, China [48] as well. The research provided the errors and R^2 value in one sample point for COD, TN, and TP with 0.15, 0.16, and 0.0086 error value, respectively, and 0.99, 0.9972, and 0.987 for R^2 value in the other, respectively.

Furthermore, Hg and VOP studies on North China Plain were conducted by employing both WHYSWESS-WQ and MIKE 11 [49]. The simulation accuracy of MIKE 11 hydrodynamic module in the research was 0.56 % of maximum error, and deemed to be an acceptable result, because of MIKE 11 validation parameter varying from -0.24 % to 0.56 % [49].

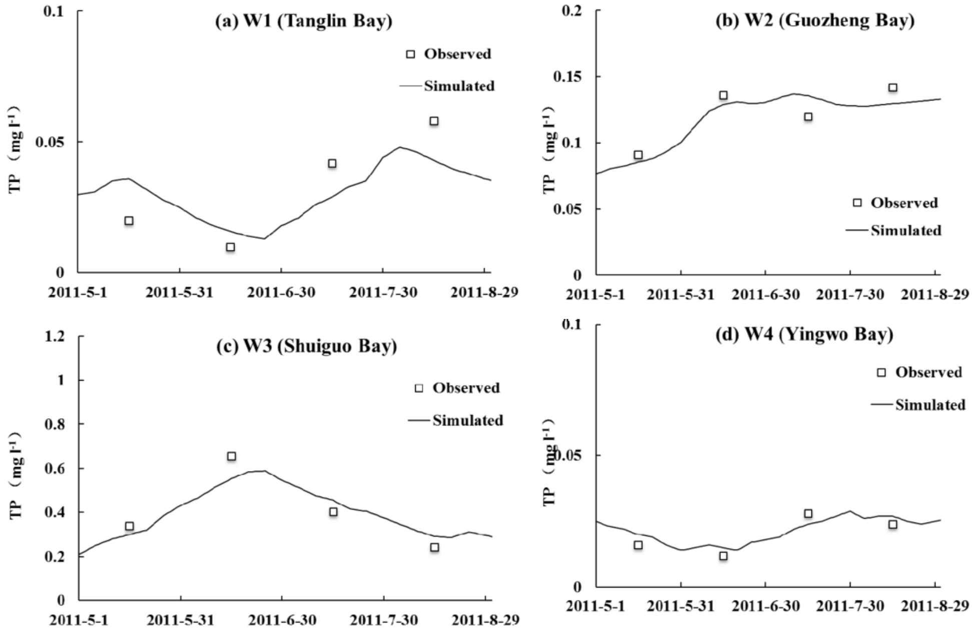

**Figure 6. Comparison of predicted and observed value of TP at Bays of:
(a) Tanglin; (b) Guozheng; (c) Shuiguo; and (d) Yingwo [47].**

Due to lack of sufficient studies about this research field, the occurred errors which vary from 1 % to 41.50 % and R^2 value sample with 0.8686 and 0.934 could be accepted as reasonable model results according to mentioned literature studies. Furthermore, all mentioned models do not provide 24-hour analysis of predicted and observed data as this study does. Hence, the reviews indicate the importance to develop further hydrodynamic modelling on lakes or small dams to simulate hydraulics, water quality, and sediment altogether.

3.3. Model Scenario

After the model is well constructed and calibrated, it could be used as an estimation in various civil engineering problems. The results are used to predict the hydrological condition of water infrastructure in small dams, to prevent flooding as the construction project barrier, and to estimate better dimension for irrigation [50–54] and drainage system [55–61] which have issues like sediment and nutrient loading. According to these phenomena, the incoming trend to model hydraulics, hydrology, and water quality would facilitate construction and engineering activities.

To study the model, the research evaluates one scenario of the existing wetland in the surrounding water infrastructure. The study examines the effect of constructed wetland in terms of decreasing contamination of Agathis small dam. The simulation is conducted by employing RMA. Fig. 7 depicts the result of wetland discretization. The study concludes that the wetland could reduce the amount of contaminants in the small dam 35 %, involving the direct influence of the velocity and hydraulics dimension of the small dam. Fig. 5 depicts the visualization of the new model. According to the research study, there are more issues for investigation in the field of water resource and environmental engineering. In this research, the reduction of nutrient loading is calculated numerically. Since we could also investigate it with respect to physical parameters, the future research could present a comparison of both the methods.

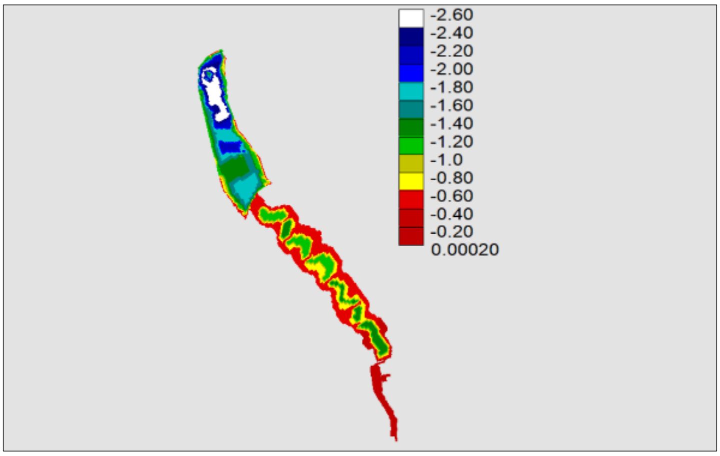

Figure 7. Agathis small dam with the constructed prospective wetland.

4. Conclusion

The hydrodynamics equations, both hydraulics and water quality, became the basis for developing a model in the RMA programs. The models are then verified by field investigation and laboratory tests to ensure comprehensive analysis. A 24-hour sampling produces various packages of data which allow us to draw a general conclusion that the model ran successfully. Conclusions obtained in the course of this study are summarized in the following component statements.

1. Continuity and hydrodynamics equations in both x and y directions support the finite element method analysis to describe the hydraulics and water quality characteristics of small dams.

2. The model error ranges between 1 % and 41.5 % and values of R^2 vary from 0.8686 and 0.934 after 24-hour sampling to analyze prediction and observation data. The model could describe the condition more comprehensively due to the hours instead of days' simulation.

3. The water quality and hydraulic characteristics on small dams are successfully simulated by Resource Modelling Associates program.

4. The conducted numerical studies of scenario using constructed wetland infrastructure indicate the reduction of sediment or erosion pollutants from urban areas. Any intervention to the existing small dam such as the construction of wetland could reduce the flooding rate and level of contamination by 35 %. Further scenarios could be developed too.

5. Due to lack of studies in the field of hydraulic, water quality, and sediment on small dams, there is still a need for further observations.

5. Acknowledgement

The research was fully supported by Hydrology and River Laboratory, Universitas Indonesia, and Hydraulics and Water Infrastructure Laboratory, Universitas Gadjah Mada. The first and third authors dedicate this research to our beloved late lecturer and researcher, Herr Soeryantono, Ph.D. for his dedication to spread out knowledge in water resources and hydraulics engineering to the current engineers in Indonesia. Rest in peace.

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