The Analysis of Song Putri Reservoir Storage Area on Sedimentation Rate Using Mathematical Model Approach

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Abstract

Song Putri Reservoir is an artificial reservoir with the aim of irrigation channels for rice fields and flood control. This reservoir is located in Eromoko District, Wonogiri Regency. Sedimentation modeling in the Song Putri reservoir is needed to analyze the amount of sediment deposition against the Song Putri Reservoir. To analyze the flow patterns and sediment distribution that occurs in reservoirs, SMS (Surface-water Modelling System) 8.0 Softwarse is used. This study aims to determine the flow patterns and effects of sediment distribution on reservoir changes. The data used include Song Putri Reservoir technical data, daily rainfall data for 10 years (2009-2018), sediment data, reservoir inflow data, and bathymetry maps. To analyze the magnitude of inflow and outflow of Song Putri Reservoir, hydrological analysis using empirical methods is used, while sedimentation modeling simulation uses SMS 8.0. Software based on the simulation, result the highest flow velocity in the 50 year return period is 0.097 m / s and the smallest is 0.00 m / s. Based on the simulation results of changes in the reservoirs base for 720 hours (1 month), the values that in the return period of 50 years, 100 years and the highest 1000 years the highest was 5.795 m and the smallest of 0.001 m, berdasarkan perhitungan prediksi tingkat pertumbuhan sedimen didapatkan hasil tingkat pertumbuhan sedimen dengan persentase untuk periode ulang 50 tahun sebesar 35.68% dengan range persentase antara 19% - 21% dan persentase sebesar 29,103% untuk periode ulang 100 tahun dengan range persentase antara 22% - 24%, sedangkan persentase tingkat pertumbuhan sedimen periode ulang 1000 tahun sebesar 98.20% dengan range persentase antara 55% - 57%.

Keywords: Simulation, Song Putri Reservoir, sedimentation
Background

Reservoir is a place on the surface of the ground that is intended to store / hold water when there is excess water / rainy season, then the abundant water is used for irrigation, flood control, drinking water needs and as embankments to collect runoff water from rivers to reservoirs. Song Putri Reservoir is an artificial reservoir with the aim of irrigation channels for rice fields and flood control, this reservoir is located in Eromoko District, Wonogiri Regency. Song Putri Reservoir has a topographic shape with non-uniform elevation. The non-uniform shape of the Song Putri Reservoir creates a flow pattern that results in the uneven distribution of flow velocity and sediment distribution in reservoirs. This is very influential to changes in reservoir base configuration. Sedimentation that occurs in the Song Putri Reservoir can cause a reduction in the reservoir life span efficiency.

Sedimentation that occurs must be noticed. Particular methods are needed to determine the distribution of flow velocity and sediment distribution in the Song Putri Reservoir, so that the reservoir life control age is efficient. To find out the flow pattern and distribution of flow velocity, as well as the distribution of sediment that enters the Song Putri Reservoir, we need a way to estimate this is needed with the help of computer software. One software that can help in this research is SMS (Surface water Modeling System). This program can be used for the process of simulation of flow patterns and flow velocity distribution using RMA-2 and simulation of sediment distribution using SED2D (Anonymous, 2003).

Rainfall is the amount of water that falls on a flat surface during a certain period measured in millimeters (mm) height above the horizontal surface. Rain can also be interpreted as the height of rainwater collected in a flat, non-evaporating, non-absorbing, and non-flowing place (Suroso 2006). To determine the type of method to be used in rainfall calculations, statistical parameter analysis is performed. There are several methods for calculating the amount of rainfall design. In this study analysis of rainfall design will be carried out using the following methods:

1) Gumbel Type I distribution method,
2) Normal distribution method,
3) Normal distribution method,
4) Pearson Log Type III distribution method.
Table 1 Statistical Parameters for Determining Distribution Types (Triatmodjo, 2008)

| No | Distribution          | Requirements                                                                 |
|----|-----------------------|------------------------------------------------------------------------------|
| 1  | Normal                | Cs $\cong$ 0.0  
     |                        | Ck $\cong$ 3.0                                                            |
| 2  | Normal Log            | Cs = Cv$^2$ + 3 Cv  
     |                        | Ck = Cv$^2$ + 6 Cv$^2$ + 15 Cv$^4$ + 16 Cv$^2$ + 3                         |
| 3  | Gumbel Type I         | Cs $\cong$ 1.14  
     |                        | Ck $\cong$ 5.4                                                            |
| 4  | Log Person III        | If it does not indicate the nature of the three distributions above          |

This rainfall intensity calculation uses the Dr. method. Mononobe which is a variation of short-term rainfall equations, the equation is as follows (Soemarto, 1999):

$$I = \frac{R_{24}^{24} \left[ \frac{24}{T} \right]^2}{24}$$  \hspace{1cm} (1)

$I$ : rainfall intensity (mm / hour)

$R_{24}$ : maximum rainfall in 24 hours (mm)

$T$ : duration of rainfall (minutes) or (hours)

Flow discharge is the rate of flow of water (in the form of volume of water) that passes through a cross section of the river per unit time (Asdak, 2002). The discharge unit used cubic meters per second (m$^3$ / s). The most frequently used method for estimating discharges in a watershed where there are no observational data for discharge is the Rational Method. In this case the magnitude of the discharge is a function of the area of the watershed, the intensity of rainfall, the state of land clearing which is expressed in the runoff and slope coefficients (Loebis, 1992). The flood discharge is generic as follows:

$$Q = C \cdot I \cdot A$$  \hspace{1cm} (2)

For the sake of practicality in determining the unit, then:

$$Q_p = 0.278 \cdot C \cdot I \cdot A$$  \hspace{1cm} (3)

Where:

$Q_p$ : Peak Discharge (m$^3$ / sec)

$C$ : Flow coefficient

$I$ : Rain intensity with duration equal to flood concentration time (mm / hour)

$A$ : Watershed area (km$^2$)

The other debit formulas are:

Der Weduwen method used to calculate the maximum discharge in the Jakarta drainage area is formulated as follows: (Kamiana, 2011):

$$Q_{max} = \alpha \times \beta \times I \times A$$  \hspace{1cm} (4)
Where:

- \( Q_{\text{max}} \) = maximum discharge \( (m^3/sec) \)
- \( \alpha \) = flow coefficient
- \( \beta \) = reduction coefficient
- \( I \) = rain intensity \( (m^3/sec/km^2) \)
- \( A \) = area of watershed \( (km^2) \)

The Hapers method used to calculate the maximum discharge is formulated as follows:

\[
Q_{\text{max}} = \alpha \times \beta \times I \times A
\]

(5)

Where:

- \( Q_{\text{max}} \) = maximum discharge \( (m^3/sec) \)
- \( \alpha \) = flow coefficient
- \( \beta \) = reduction coefficient
- \( I \) = rain intensity \( (m^3/sec/km^2) \)
- \( A \) = area of watershed \( (km^2) \)

HSS Nakayasu Nakayasu method used to calculate flood peak discharge is formulated as follows:

\[
Q_p = \frac{A \times R_0 \times (0.3T_p + T_0.3)}{3.6 \times (0.3T_p + T_0.3)}
\]

(6)

Where:

- \( Q_p \) = flood peak discharge \( (m^3/sec) \)
- \( A \) = wide catchment area \( (km^2) \)
- \( R_0 \) = unit rain \( (mm) \)
- \( T_p \) = grace period from the beginning of the flood to the peak of the flood \( (hours) \)
- \( T_{0.3} \) = time required by a decrease in discharge, from peak discharge to 30% of peak discharge \( (hours) \).

**Research Methodology**

The data of the study include Song Putri reservoir technical data, daily rainfall data for 10 years (2009-2018), sediment data, reservoir inflow data, and bathymetry map obtained from BBWS Bengawan Solo. To get good and direct results, a flowchart is made of the plan and the work steps carried out, as shown in the Figure 1.
The steps for data processing in general are as follows:

1) Hydrological analysis using empirical methods. The following processing flow:
   a. Hydrological analysis uses maximum daily rainfall data for 10 years (2009-2018).
   b. Analysis of rainfall data using the Normal Distribution Method, Normal Log Distribution, Gumbel Distribution, and Pearson Log type III Distribution
   c. Test the suitability of frequency distribution with Chi-squared and Kolmogorov Smirnov Test.
   d. The empirical method of calculating the flood discharge plan used is the Rational, Der Weduwen, Haspers and Nakayasu Synthetic Hydrographs. Reschedule flood plans in 5, 10, 25, 50, 100, and 1000 years
e. Modeling of the Song Putri reservoir uses a planned flood discharge in the return period of 50 years, 100 years, and 1000 years.

2) Surface-water modeling system 8.0 is done using 3 steps, among others as follows: Geometric modeling, The process of simulating flow patterns and flow velocity distribution with RMA-2 and simulation of sediment distribution with SED2D.

Research Result

Rainfall analysis using Arithmetic/Algebra Method. In this study there are three rain gauge stations which are considered relevant to represent rain observations in the study area (Song Putri Rain Station, Nawangan Rain Station and Parangjoho Rain Station).

Table 2 Calculation of Maximum Daily Average Rainfall by Arithmetic Method

| No | Year | Sta. Song Putri (mm) | Sta. Nawangan (mm) | Sta. Parangjoho (mm) | Rh Plan |
|----|------|----------------------|--------------------|----------------------|---------|
| 1  | 2009 | 104,00               | 83,00              | 73,00                | 85,67   |
| 2  | 2010 | 171,00               | 121,00             | 84,00                | 125,33  |
| 3  | 2011 | 103,00               | 97,00              | 75,00                | 91,67   |
| 4  | 2012 | 91,00                | 112,00             | 79,00                | 94,00   |
| 5  | 2013 | 33,00                | 97,00              | 51,00                | 60,33   |
| 6  | 2014 | 48,00                | 98,00              | 43,00                | 63,00   |
| 7  | 2015 | 47,00                | 105,00             | 49,00                | 67,00   |
| 8  | 2016 | 67,00                | 114,50             | 63,00                | 81,50   |
| 9  | 2017 | 80,00                | 351,90             | 166,00              | 199,30  |
| 10 | 2018 | 87,50                | 94,00              | 62,00                | 81,17   |

Distribution Method

Frequency distribution analysis is intended to obtain the amount of rainfall that is determined based on certain design benchmarks. For the purposes of the analysis set with return periods of 5, 10, 25, 50, 100, and 1000 years, as shown in the Table 3.

Table 3. Recapitulation of XT Value in Each Distribution Method

| Types Of Distribution | Return Period | Value XT |
|-----------------------|---------------|----------|
|                       | 5             | 129,589  |
|                       | 10            | 147,710  |
|                       | 25            | 170,771  |
|                       | 50            | 179,420  |
|                       | 100           | 190,951  |
|                       | 1000          | 222,249  |
| NORMAL                | 5             | 123,495  |
|                       | 10            | 148,298  |
|                       | 25            | 186,462  |
|                       | 50            | 204,602  |
|                       | 100           | 226,783  |
|                       | 1000          | 264,996  |

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Rainfall Intensity Graph

This rainfall intensity calculation uses the dr. method. Mononobe which is a variation of short-term rainfall equations, the equation is as follows (Soemarto, 1999):

\[ I = \frac{R_{24}^{2}}{24 \left[ \frac{24}{t} \right]^{\frac{2}{3}}} \]  

(4)

Below is a graph of the intensity of rainfall in the Alang watershed.

Flow Search

In the flow tracking method which is carried out using the reservoir tracking method, a volume of runoff will be obtained from the reduction in the value of the inflow and the outflow of water as the result of data processing by the Nakayasu HSS. The overflow of water is water volume units which can later be used as design plan for storage volume of polder ponds (storage) to be used.

Recapitulation of Flood Discharge Calculation Results, as show in Table 4.
### Table 4 Recapitulation of Flood Discharge Calculation Results

| No | Period | Rasional | Weduwen | Haspers | Nakayusu |
|----|--------|----------|---------|---------|----------|
| 1  | Q5     | 34.053   | 62.159  | 58.108  | 63.44    |
| 2  | Q10    | 40.051   | 73.106  | 68.342  | 74.62    |
| 3  | Q25    | 47.729   | 87.121  | 81.444  | 88.92    |
| 4  | Q50    | 53.521   | 97.695  | 91.328  | 99.72    |
| 5  | Q100   | 59.401   | 108.428 | 101.362 | 110.67   |
| 6  | Q1000  | 79.948   | 145.932 | 136.422 | 148.95   |

### Table 5 Flow Tracking Using 50 year Inflow Outflow Discharge

| t (hour) | Inflow (m³/dt) | Outflow (m³/dt) |
|----------|----------------|-----------------|
| 0        | 0.000          | 0.000           |
| 1        | 5.500          | 1.100           |
| 2        | 29.029         | 10.206          |
| 3        | 27.011         | 28.625          |
| 4        | 17.536         | 25.116          |
| 5        | 11.385         | 16.306          |
| 6        | 8.515          | 10.811          |
| 7        | 6.385          | 8.089           |
| 8        | 4.787          | 6.065           |
| 9        | 3.589          | 4.547           |
| 10       | 2.691          | 3.409           |
| 11       | 2.018          | 2.556           |
| 12       | 1.513          | 1.917           |
| 13       | 1.134          | 1.437           |
| 14       | 0.850          | 1.077           |
| 15       | 0.638          | 0.808           |
| 16       | 0.478          | 0.606           |
| 17       | 0.358          | 0.454           |
| 18       | 0.269          | 0.340           |
| 19       | 0.201          | 0.255           |
| 20       | 0.151          | 0.191           |
| 21       | 0.113          | 0.143           |
| 22       | 0.085          | 0.108           |
| 23       | 0.064          | 0.081           |
| 24       | 0.048          | 0.060           |

### Table 6 Flow Tracking Using 100 year Inflow Outflow Discharge

| t (hour) | Inflow (m³/dt) | Outflow (m³/dt) |
|----------|----------------|-----------------|
| 0        | 0.000          | 0.000           |
| 1        | 6.104          | 1.221           |
| 2        | 32.218         | 11.327          |
| 3        | 29.979         | 31.770          |
| 4        | 19.463         | 27.876          |
| 5        | 12.635         | 18.097          |
| 6        | 9.451          | 11.998          |
| 7        | 7.086          | 8.978           |
| t (hour) | Inflow (m$^3$/dt) | Outflow (m$^3$/dt) |
|---------|-------------------|--------------------|
| 0       | 0.000             | 0.000              |
| 1       | 8.215             | 1.643              |
| 2       | 43.361            | 15.245             |
| 3       | 40.348            | 42.759             |
| 4       | 26.194            | 37.517             |
| 5       | 17.006            | 24.357             |
| 6       | 12.720            | 16.149             |
| 7       | 9.537             | 12.083             |
| 8       | 7.150             | 9.060              |
| 9       | 5.361             | 6.793              |
| 10      | 4.020             | 5.093              |
| 11      | 3.014             | 3.818              |
| 12      | 2.260             | 2.863              |
| 13      | 1.694             | 2.146              |
| 14      | 1.270             | 1.609              |
| 15      | 0.952             | 1.207              |
| 16      | 0.714             | 0.905              |
| 17      | 0.535             | 0.678              |
| 18      | 0.401             | 0.509              |
| 19      | 0.301             | 0.381              |
| 20      | 0.226             | 0.286              |
| 21      | 0.169             | 0.214              |
| 22      | 0.127             | 0.161              |
| 23      | 0.095             | 0.120              |
| 24      | 0.071             | 0.090              |

Table 7 Flow Tracking Using Inflow Outflow Discharge 1000 Years Period

Based on the results of the analysis of the flow tracking that has been done, it can be shown the flow of incoming water (Inflow) and the outflow of water (outflow) that occurs so that it can be described in graphical form as this Figure 3.
Results of Modeling Flow and Sedimentation

Geometric modeling is the basis for modeling, before modeling with RMA2 and SED2D. Geometric modeling is based on bathymetry data that has been obtained and modified in the form of dxf files. Modeling flow patterns using the RMA2 module as the simulation. Flow pattern simulation will be modeled as many as 3 models, It is uses the results of calculations Inflow and reservoir outflow in the return period of 50 years, 100 years, and 1000 years. In the flow pattern simulation (RMA2) the results are reviewed by analyzing the flow pattern characteristics and the value of the horizontal flow velocity distribution at the point of review. Analysis of flow pattern characteristics in each review period can be displayed 3 review points. Location of Point of Review, as show in Figure 4.
From the results of the simulation of flow patterns in the form of vectors, it can be seen the characteristics of flow patterns at points A, B, and C at each return period by obtaining the same flow pattern characteristics. In condition A, the flow of water entering the reservoir is not similar because the flow velocity changes with distance due to changes in appearance from small to large. Hence the flow direction spread to fill every part of the reservoir. In condition B, the water flow is trapped on one side of the reservoir so that the direction of flow tends to spin. These conditions can be caused by differences in the viscosity of the water so that there is a change in speed that causes the water to move irregularly to form a vortex. And in condition C, the water flow is not uniform because the flow velocity changes with distance due to containment in the reservoir downstream.

There is no significant difference between the characteristics of flow patterns at each return period, but the difference can be seen based on the magnitude of the velocity distribution resulting from the simulation results. The recapitulation of the horizontal flow velocity distribution of the simulation results at each review point on the return period of 50 years, 100 years, and 1000 year for 24 hours can be seen in table 8.

Figure 5 The results of running RMA2 on flow patterns in the 50-year return period in vector form.
Figure 6 The results of running RMA2 on flow patterns in the 100-year return period in vector form.

Figure 7 The results of running RMA2 on flow patterns in 1000-year return periods in vector form.

Table 8 Distribution of Flow Velocity (m/s)

| Review Point | Location             | Reset period 50 year | Reset period 100 year | Reset period 1000 year |
|--------------|----------------------|-----------------------|------------------------|------------------------|
| 1            | Inflow               | 0.038                 | 0.042                  | 0.058                  |
| 2            | Middle of the reservoir | 0.008                | 0.009                  | 0.012                  |
| 3            | West of the reservoir | 0.001                 | 0.002                  | 0.002                  |
| 4            | Middle of the reservoir | 0.004                | 0.005                  | 0.006                  |
| 5            | East of the reservoir | 0.000                 | 0.000                  | 0.001                  |
| 6            | Outflow              | 0.035                 | 0.037                  | 0.053                  |
|              | The smallest         | 0.000                 | 0.000                  | 0.000                  |
|              | The biggest          | 0.097                 | 0.107                  | 0.145                  |
The results of sedimentation simulation in the form of changes in the base of the Song Putri Reservoir in the return period of 50 years, 100 years, and 1000 years during 720 can be seen in the following figure 8. Changes in the base of the Song Putri Reservoir (bed change) in the 50 year return period.

Recapitulation of the horizontal flow velocity distribution of simulation results at each point of view in the return period of 50 years, 100 years, and 1000 years for 24 hours can be seen in table 9.

| Review Point | Location          | Bed Change (Reset Period) |
|--------------|-------------------|---------------------------|
|              | Location          | 50 year | 100 year | 1000 year |
| 1            | Inflow            | 4.382    | 4.512    | 4.782     |
| 2            | Middle of the reservoir | 0.511    | 0.526    | 0.570     |
| 3            | West of the reservoir | 0.020    | 0.020    | 0.024     |
| 4            | Middle of the reservoir | 0.068    | 0.069    | 0.089     |
| 5            | East of the reservoir | 0.031    | 0.032    | 0.040     |
| 6            | Outflow           | 0.106    | 0.115    | 0.120     |
| The smallest |                   | 0.001    | 0.001    | 0.001     |
| The biggest  |                   | 5.795    | 5.795    | 5.795     |

Figure 8 Changes in the reservoir base (bed change) at the 50-year return period.
Figure 9. Changes in bed reservoirs at 100 years of return.

Based on flood measurement data (Q) and sediment concentration (Cs), suspension discharge (Qs) can be computed and the suspension discharge curve is made (graph of the relationship between Q and Qs). Using these equations, the prediction of sediment growth rate can be calculated which is presented in Table 10.

Table 10 Results data from the calculation of the re-debit and modeling SMS 8.0.

| Reset Period | Q    | V    | Cs  | Qs   | Vol          |
|--------------|------|------|-----|------|--------------|
|              | m³/dt| m/dt | kg/m³| kg/dt| m³           |
| Q50          | 99.72| 0.038| 0.378| 37.692| 8615400.101  |
| Q100         | 110.67| 0.042| 0.382| 42.276| 9561901.787  |
| Q1000        | 148.95| 0.058| 0.411| 61.218| 12869234.437 |

Figure 10. Changes in the reservoir base during a 1000 year return period.
Based on the calculation of predicted sediment growth rates the results of sediment growth comma with a percentage for a 50 year return period of 35.68% with a range of percentages between 19% - 21% and a percentage of 29.103% for a 100 year return period with a percentage range between 22% - 24%, while the percentage of sediment growth rates for 1000 year return periods is 98.20% with a range of percentages ranging from 55% - 57% (Figure 11 and Table 11).

**Figure 11 Suspended Debit Curve Curves**

**Table 11 Predictions of Sediment Growth Rates**

| Review Period | Accretion Year (x) | Sediment Growth Rate (y) | Growth Rate (%) | Range (%) |
|---------------|-------------------|--------------------------|-----------------|-----------|
| Q50           | 50                | 17.103                   | 35.68           | 19%-21%   |
| Q100          | 100               | 29.103                   | 41.23           | 22%-24%   |
| Q1000         | 1000              | 1613.103                 | 98.20           | 55%-57%   |
| **Amount**    |                   |                          | **175.11**      |           |
| **Average Growth Rate** |                  |                          | **58.37**       |           |

**CONCLUSIONS**

Based on the analysis, the following conclusions can be drawn:

The calculation of rainfall using the Log Pearson III resulted for a 5 year return period of 119,920 mm, a 10 year return period of 141,040 mm, a 25 year return period of 168,078 mm, a 50 year period of 188,478 mm, a 100 year return period of 209,185 mm, and the 1,000 year return period is 281,539 mm.

The flow patterns that result from the simulation for 24 hours in the return period of 50 years, 100 years, and 1000 years do not have a significant difference. In each return period, the water cycle in the reservoir is formed.

Based on the simulation results of the highest flow velocity in the 50 year return period of 0.097 m / s and the smallest of 0.00 m / s with details of each review point (Inflow of 0.038 m / s; middle of 0.008 m / s and 0.004 m / s; west and east of 0.001 m /
s and 0.00 m / s; outflow of 0.035 m / s). In the 100 year return period the highest flow velocity is 0.107 m / s and the smallest is 0.00 m / s with details of each review point (Inflow of 0.042 m / s; middle of 0.009 m / s and 0.005 m / s; west and east 0.002 m / s and 0.00 m / s; outflow of 0.037 m / s). The highest flow velocity in the 1000 year return period is 0.145 m / s and the smallest is 0.00 m / s with details of each review point (Inflow of 0.058 m / s; middle of 0.012 m / s and 0.006 m / s; west and east 0.002 m / s and 0.001 m / s; outflow of 0.053 m / s).

Based on the simulation results of changes in the reservoir base for 720 hours (1 month) the values obtained in the return period of 50 years, 100 years and 1000 years the highest of 5.795 m and the smallest of 0.001 m, with details of each review point that is the return period 50 years (Inflow of 4.382 m; middle of 0.511 m and 0.068 m; west and east of 0.020 m and 0.031 m; outflow of 0.106 m), while 100-year return periods (Inflow of 4.512 m; middle of 0.526 m and 0.069 m; west and east of 0.020 m and 0.032 m; outflow of 0.115 m), and 1000 year return period (Inflow of 4.782 m; middle of 0.570 m and 0.089 m; west and east of 0.024 m and 0.040 m; outflow of 0.120 m).

Based on the calculation of predicted sediment growth rates the results of sediment growth comma with a percentage for a 50 year return period of 35.68% with a range of percentages between 19% - 21% and a percentage of 29.103% for a 100 year return period with a percentage range between 22% - 24%, while the percentage of sediment growth rates for 1000 year return periods is 98.20% with a range of percentages ranging from 55% - 57%. Thus it can be concluded that the greater the year increase, the greater the percentage of sediment growth rate in the Song Putri reservoir.

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