Estimating Sedimentation Trend of the Wonorejo Reservoir and Dam to sustain the Reservoir's Useful Life

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Abstract. Sedimentation is a natural problem in water-related structures, especially dams and reservoirs. Wonorejo Reservoir, as a multipurpose reservoir, also experienced this. Sedimentation can affect the performance of reservoirs and dams. With the accumulation of sediment, the reservoir volume will change from time to time, so it is necessary to estimate the volume of sediment during the useful life of the reservoir and dam so that they can function optimally. This study was conducted to estimate the volume of sediment deposition during the useful life of reservoirs and dams, which is 50 years. Using the sediment data from the year 2016-2019 with the implementation of methods from other studies that have been carried out in other reservoirs and dams in Indonesia, the volume of the sediment deposition in the year 2050 is estimated at 16.37% of the total storage capacity. Most sediment deposition is located close to the dam. However, based on calculations, it is estimated that up to the service life of the reservoir, the reservoir can still function properly with a sediment content of not more than 20% of the total reservoir volume. Theoretically, the Wonorejo Reservoir can still work until 50 years. However, with the continuous increase in the percentage of sediment to the volume of reservoir capacity, efforts are needed to overcome this so that the useful life of the reservoir is not affected and the reservoir can still work optimally.

1. Introduction

The reservoir is water storage that also functions as a flood prevention building. Sedimentation is an important parameter to assess the life of a reservoir which depends on sediment yield, and sediment yield depends on soil erosion; it is required to predict all three parameters to estimate the life of a reservoir [1]. As a result of a structure that dams the river, naturally, the sediment transport material in the river will be accommodated and deposited in the reservoir. Sedimentation affects the sustainability of operations and projects established in the reservoir or run of the river projects [2]. The sediment deposition causes reservoir effective storage to decrease, and the performance of the reservoir is disrupted, even though the useful life of the reservoir has not been reached. Dams have typically been designed to create a storage volume sufficiently large to contain estimated sediment deposits for 50 years which is known as the economic life of the project [3].

Wonorejo Reservoir is located in Pagerwojo District, Tulungagung, East Java. It is located at the foot of Mount Wilis and is estimated as 12 kilometres from the Tulungagung city centre (Figure 1). It is one of the largest reservoirs in Southeast Asia, discharging water 15000 m^3/s. Wonorejo Reservoir is an annual reservoir that collects water during the rainy season and utilizes it during the dry season. The reservoir of this dam has a water table area of 380 hectares with a capacity of about 122 million cubic meters [4]. The main rivers that supply water to the reservoir are the Gondang River and Wangi River. In addition to storing water, Wonorejo Reservoir is also used for hydroelectric power. The Wonorejo Reservoir is intended to supply clean water for Tulungagung and its surrounding areas as a means of irrigation in the Pagerwojo area and its surroundings and as a mechanism of driving turbines to produce electrical energy. The Tulungagung Government stated that the Wonorejo Reservoir was also introduced as an object that provides comfort and availability of recreational facilities.

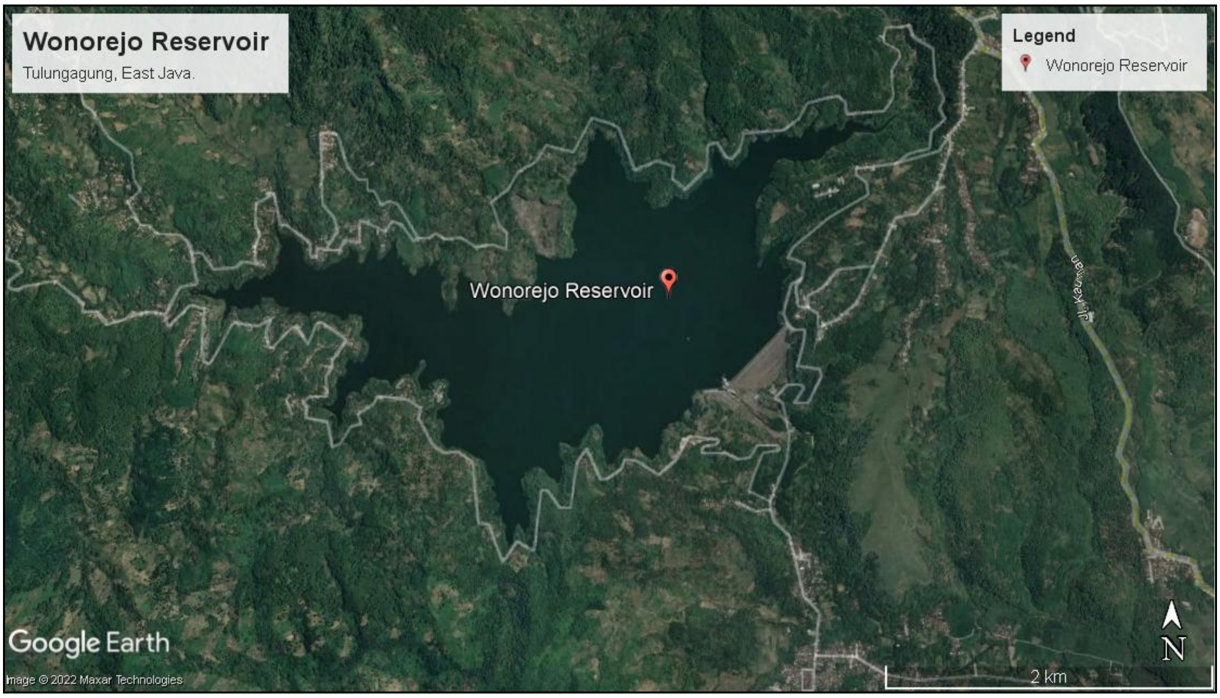


Figure 1. Wonorejo Reservoir (Source: Google Earth)

Studies on sedimentation in the Wonorejo Reservoir have not been widely carried out, even though the Wonorejo Reservoir has a crucial role, especially for residents in Tulungagung. Setyono [4] predicts sediment distribution in the Wonorejo Reservoir using the Empirical Area Reduction Method and the Area Increment Method. The previous study results stated that the most suitable method for predicting the distribution of sedimentation in the Wonorejo Reservoir is the Area Reduction Method. In addition, no other studies were found.

This study aimed to estimate the amount of sedimentation that occurred during the service life of the Wonorejo Reservoir, which is 50 years. In addition, this study also aims to formulate what efforts to handle sedimentation can be made to extend the service life of the reservoir. If handled properly, sedimentation occurs without harming the usage life of the reservoir.

2. Research Methodology

Wonorejo Reservoir is managed by Jasa Tirta 1, an Indonesian state-owned water supply company based in Malang, East Java. Wonorejo Reservoir has a water table area of 380 ha with around 122 million m^3 capacity. The main rivers that supply water to the reservoir are the Gondang River and Wangi River. Wonorejo Reservoir has an essential function as one of the resources of electrical power (hydropower) amounted to 6.02 MW and a source of drinking water at the rate of 8.02 m^3/s. This reservoir also functions as a source of irrigation for 7540 ha of agricultural land and prevents flooding in Tulungagung.

The Technical Data for the Wonorejo Reservoir is as follows:

a) Area of inundation (HWL): 3.85 km^2
b) Flood water level: +185 m
c) High water level (HWL): +183 m
d) Low water level (LWL): +141 m
e) Total reservoir capacity: 122 million m^3

f) Effective reservoir capacity: 106 million m^3

This study was carried out to estimate the amount of sediment in the reservoir based on its usage life. Due to the limited references to previous studies on the Wonorejo Reservoir, a literature study was conducted by analyzing the methods that have been used in other reservoirs in Indonesia. Achsan and Suhartanto [5] estimated future sedimentation volume and sedimentation rate in Bili-Bili Reservoir in South Sulawesi Province by determining the shape of the curve that matches the sediment data from measurement. This method was adopted in carrying out this study.

The data used in this study is the data used in the previous research by Setyono [4], which includes technical data, reservoir capacity volume data, and sediment volume data in 2008 and 2011, as shown in Table 1. All sediment data were taken by echo-sounding measurement, which was published privately through an annual echo-sounding report by Jasa Tirta 1.

Table 1. Reservoir Capacity and Sediment Volume Data

	Reservoir Capacity (10^6 m^3)			**Sediment Volume (10^6 m^3)**		
Year	**Total Storage**	**Dead Storage**	**Effective Storage**	**Total Storage**	**Dead Storage**	**Effective Storage**
2000	122.000	16.000	106.000	0.000	0.000	0.000
2008	109.615	10.571	99.040	12.390	5.430	6.960
2011	108.682	10.080	98.602	13.318	5.920	7.398

Source: Jasa Tirta 1 (2011) on Setyono [4]

In addition, the latest available data are echo-sounding data conducted in 2016-2019, as shown in Table 2. All data were also from Jasa Tirta 1, published privately through the annual echo-sounding report. For sediment computation, the inflow and outflow data are also available. These data are used as input data in sedimentation analysis.

Table 2. Reservoir Capacity Data 2016-2019

Year	**Reservoir Capacity (10^6 m^3)**		
	Total Storage (Elev. +183)	**Dead Storage (Elev. +141)**	**Effective Storage**
2016	105.971	8.471	97.500
2017	107.656	9.407	98.248
2018	109.415	10.112	99.303
2019	109.454	10.289	99.164

Source: Jasa Tirta 1 (2019)

Based on Table 2, the reservoir capacity measurement increases after 2016. The increasing reservoir capacity is because the echo-sounding measures more area in the reservoir. Moreover, the distance between each measurement path of the echo-sounding is also closer than the previous year.

Table 3. Sediment Volume Calculation

Year	**Sediment Volume (10^6 m^3)**		
	Total Storage	**Dead Storage**	**Effective Storage**
2016	16.028	7.528	8.499
2017	14.343	6.592	7.751
2018	12.584	5.887	6.696
2019	12.545	5.710	6.835

With the calculation discrepancy of the reservoir volume after the year 2016, the results of the sediment calculation also experienced inaccuracies. As shown in Table 3**,** the calculation results of the sediment volume decreased from 2016. In reality, the sediment volume is unlikely to decrease in the field if no dredging or flushing is carried out. Therefore, the data used for future estimation is the data from 2017 instead of 2016 to minimize inaccuracies. All the data used for estimation are shown in Table 4. The sediment percentage tends to increase yearly as the sediment volume increases while the total reservoir capacity decreases.

Table 4. Sediment Percentage Calculation

Year	**Duration (year)**	**Sediment Volume (10^6 m^3)**	**Sediment Average per Year (10^6 m^3)**	**Reservoir Total Capacity (10^6 m^3)**	**Sediment Percentage (%)**
2008	8	12.385	1.548	109.615	11.30%
2011	11	13.318	1.211	108.682	12.25%
2017	17	14.344	0.844	107.656	13.32%

In addition to the amount of sedimentation, its distribution is not less important. Therefore, the sediment distribution modelling was carried out using the SSIIM program. SSIIM is an abbreviation for Sediment Simulation In Intakes with the Multiblock option. SSIIM uses a finite volume hydrodynamic and sediment transport model based on an unstructured grid system [6]. The program was used in river, environmental, hydraulic and sedimentation engineering. The main strength of SSIIM compared to general-purpose CFD programs is the capability of modelling sediment transport with a movable bed in complex geometry. It includes several algorithms for different sediment process sizes, including sorting, bedload and suspended load, bedforms and the effect of sloping beds.

SSIIM is a very commonly used program to solve the problems related to sedimentation, bedload transport and bed morphology. Shamloo et al. [7] used different turbulence models available in the SSIIM 2 program to estimate velocity and turbulent kinetic energy in different sections of the main channel and intake to investigate problems associated with the sedimentation in the lateral intakes. Esmaeili et al. [8] utilized SSIIM to reproduce the 3D flow field in a shallow rectangular reservoir. The obtained outcomes from the research work showed that the numerical model represented many hydrodynamic aspects in different shallow reservoir geometries. Moreover, SSIIM successfully showed the effect of geometry on the flow pattern. It can also be used for reproducing the symmetric and asymmetric flow pattern under various hydraulic and geometric conditions.

The SSIIM program computes the water velocities and sediment transport in rivers, channels and reservoirs with the Navier-Stokes equations, which are solved with different turbulence models on a three-dimensional non-orthogonal grid. The k-ε model is the default turbulence model in SSIIM.

The Navier-Stokes equations for non-compressible and constant density flow can be modelled as:

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(-P\delta_{ij} - \overline{\rho u_i u_j}\right) \qquad (1)$$

The first term on the left side of the equation is the transient term. The next term is the convective term. The first term on the right-hand side is the pressure term, followed by the Reynolds stress term. A turbulence model is required to evaluate this term. Because of the complexity of sediment transport processes, all existing sediment transport formulas are empirical or semi-empirical [9]. Significant differences may exist among these formulas when applied in real-life engineering. The sediment transport formulas applied in SSIIM are Meyer-Peter and Müller, van Rijn, and Wu formula.

The input files commonly used in SSIIM simulation are control, koordina, timei, and unstruc files, whose function is based on the SSIIM User's Manual by Olsen [6]. The control file gives most of the parameters the model needs and consists of various data sets with different functions. The main parameters are the size of the arrays used for the program. Koordina file contains the bed of the geometry and water surface location. Timei file is an input file for discharge time series, water level, sediment concentration and control for output. The geometry data is stored in the unstruc file. This file contains the coordinates of all gridline intersections, where cells are connected with other cells.

In this study, to make a koordina file, the geodata file has to be made. The coordinate data (X and Y data) and base elevation data of the Wonorejo Reservoir (Z data) is used as input for the geodata file to create a grid for SSIIM. This file is read automatically by the SSIIM program as a reservoir template. Grid creation is essential in SSIIM numerical modelling because the quality of the grid in the geodata file will determine whether the study can be run or not [6].

In addition, this study also proposed efforts to maintain the useful life of the reservoir, which are composed of analyzing proposals from previous studies on other reservoirs in Indonesia.

3. Results and discussion

Sedimentation in the Wonorejo Reservoir can be calculated based on the volume of sediment from the measurement results. The sediment volume estimation is done by determining the shape of the curve that matches the distribution of sedimentation volume data in 2008, 2011, and 2017 as shown in the graph in Figure 2.

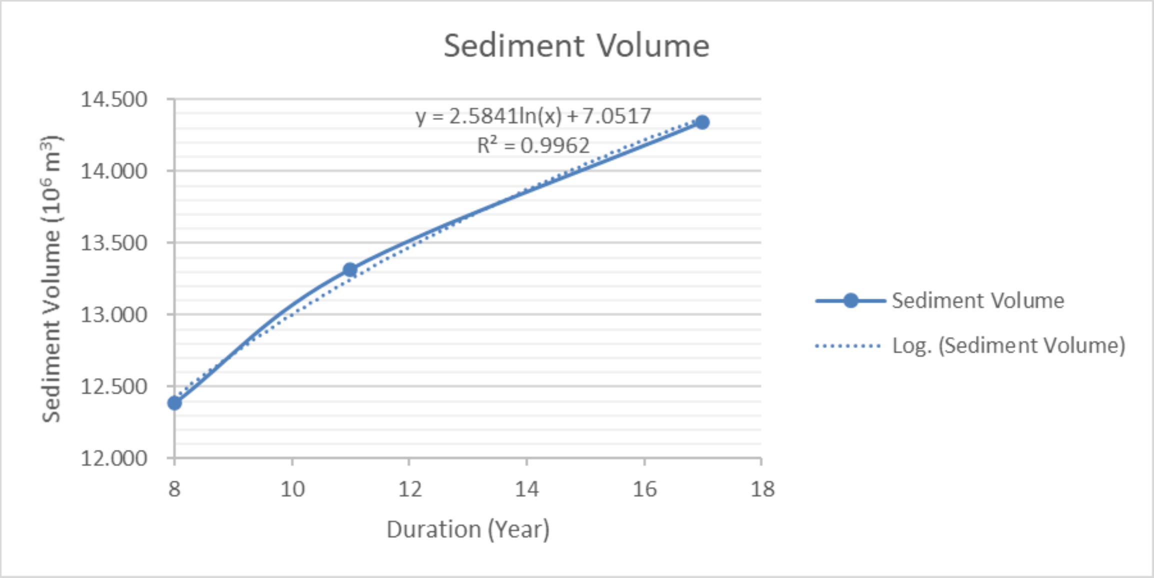


Figure 2. Sediment Volume Graph

Based on the Figure 2, the regression line equation is obtained:

$$y = 2.5841 \ln(x) + 7.0517 \quad (2)$$

The prediction of the sedimentation volume of the Wonorejo Reservoir in the future is used by Equation 2. Prediction of future reservoir capacity volumes can also be calculated using this method. Based on Figure 3, the regression line equation is obtained:

$$y = -2.584 \ln(x) + 114.95 \quad (3)$$

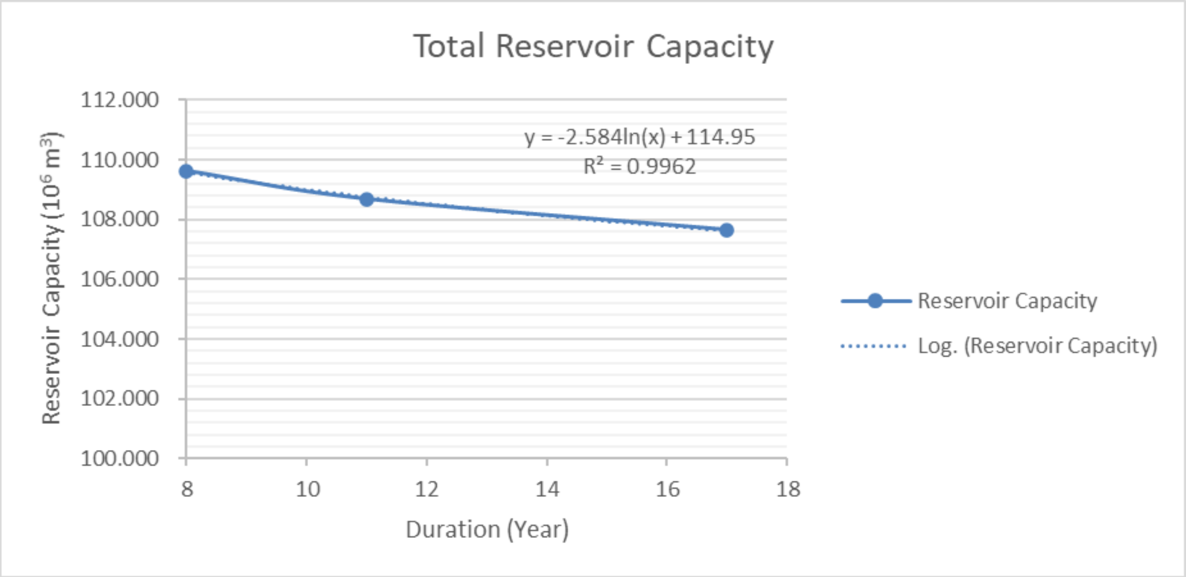


Figure 3. Reservoir Capacity Graph

The results of estimating sediment volume and total reservoir capacity during the reservoir's useful life up to 2050 using Equation 2 and Equation 3 are presented in Table 5. The percentage of sediment volume tends to increase until it fills 16.37% of the total reservoir capacity. This phenomenon shows that the distribution of sediment deposits is growing over time. The average volume of sediment each year has decreased. Each year, the decreasing sediment volume can be due to the increasing amount of sedimentation, causing an equilibrium point in several reservoir areas, where there is no sediment transport anymore. The total reservoir capacity also decreased due to sedimentation.

Table 5. Sediment Volume and Reservoir Capacity Estimation

Year	Duration (years)	Total Sediment Volume (10^6 m^3)	Average Sediment Volume per year (10^6 m^3)	Total Reservoir Capacity (10^6 m^3)	Sediment Percentage (%)
2018	18	14.521	0.807	107.471	13.511%
2019	19	14.660	0.772	107.332	13.659%
2020	20	14.793	0.740	107.199	13.800%
2021	21	14.919	0.710	107.073	13.934%
2022	22	15.039	0.684	106.953	14.062%
2023	23	15.154	0.659	106.838	14.184%
2024	24	15.264	0.636	106.728	14.302%
2025	25	15.370	0.615	106.622	14.415%
2026	26	15.471	0.595	106.521	14.524%
2027	27	15.568	0.577	106.424	14.629%
2028	28	15.662	0.559	106.330	14.730%
2029	29	15.753	0.543	106.239	14.828%
2030	30	15.841	0.528	106.151	14.923%
2035	35	16.239	0.464	105.753	15.356%
2040	40	16.584	0.415	105.408	15.733%
2045	45	16.888	0.375	105.104	16.068%
2050	50	17.161	0.343	104.831	16.370%

In order to know more about the spatial distribution of the sediment, SSIIM can visualize the distribution based on the data provided from the echo sounding process. Grid processing in the SSIIM program started with a geodata file as an input. The geodata file consists of the reservoir's X, Y, and Z coordinates. The coordinate from the geodata file can be presented in SSIIM as geodata points and generated as a grid through the grid editor function, which resulted as shown in Figure 4.

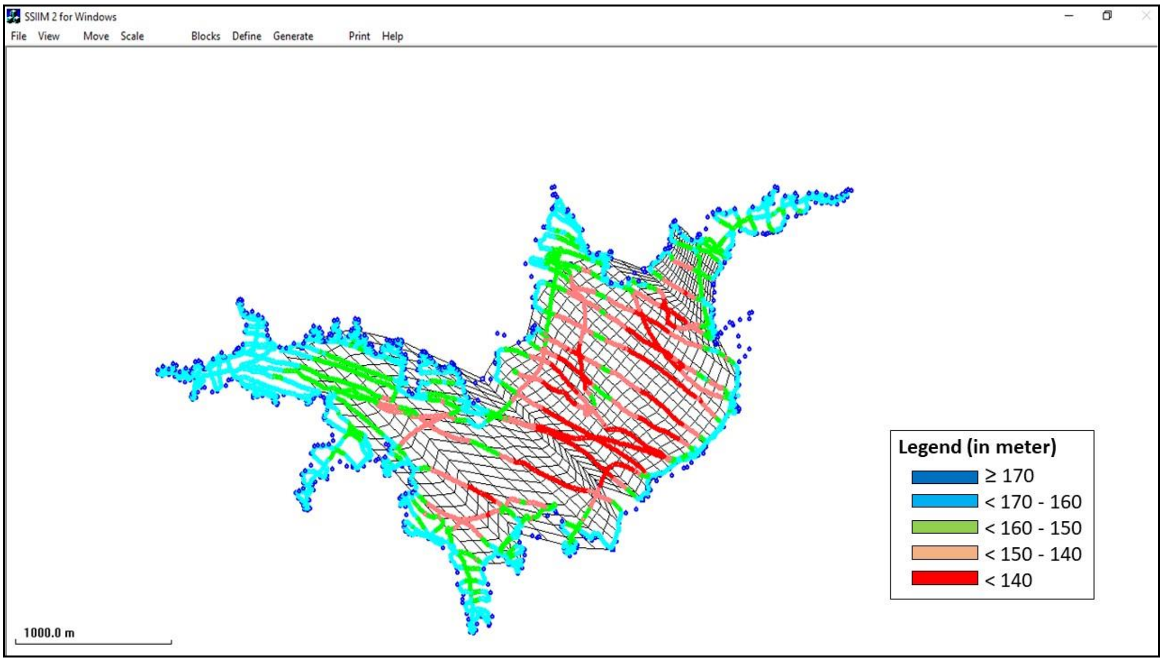
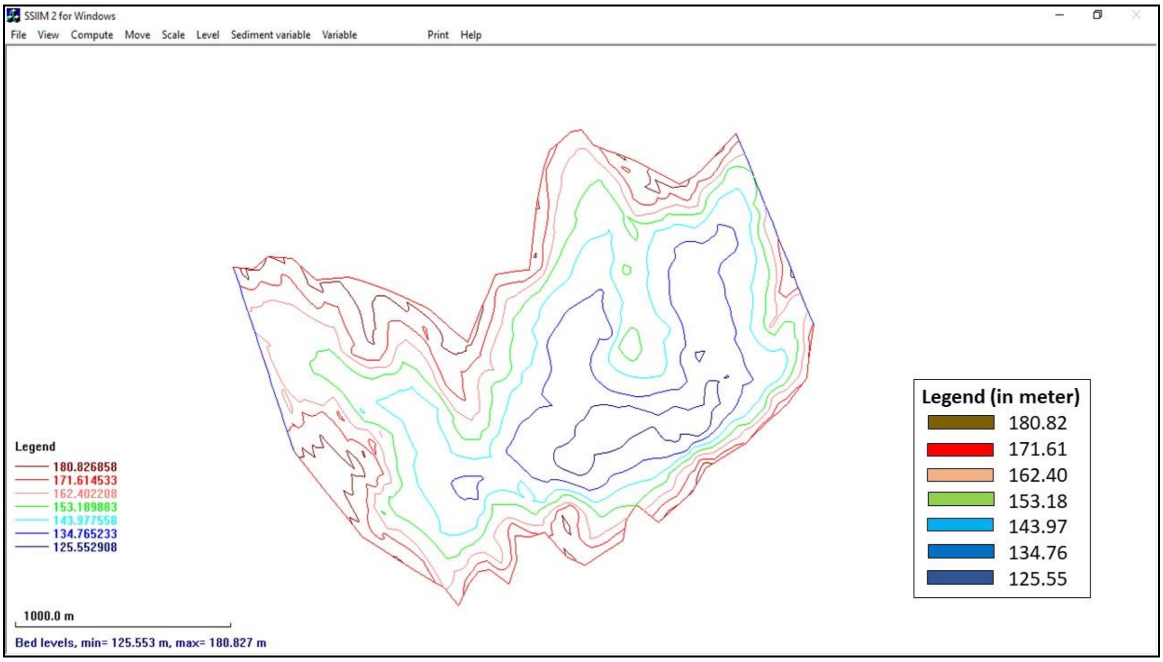


Figure 4. Grid Processing on SSIIM Program

The shape of the Wonorejo Reservoir grids needs to be simplified before modelling using the SSIIM program because the original grids are too unstructured. Its simplification takes a reasonably long trial and error process until it finally becomes Figure 5.



Bed levels, min= 125.553 m, max= 180.827 m

Figure 5. Simplified Wonorejo Reservoir Model

The simplified model can model the computation of inflow and outflow discharge and the magnitude of sedimentation. In this study, the process of computing inflow and outflow does not result in any reasonable outputs. It is probably because the simplified model does not represent the actual condition. Therefore, other auxiliary programs may be used in modelling sedimentation in the Wonorejo Reservoir.

Even though the study did not manage to compute the estimation of future sedimentation using SSIIM, the presentation of echo-sounding data can be done using the SSIIM program. The spatial distribution shown in Figure 6 shows that the crucial locations where more attention is needed can be seen to control sediment buildup in these locations.

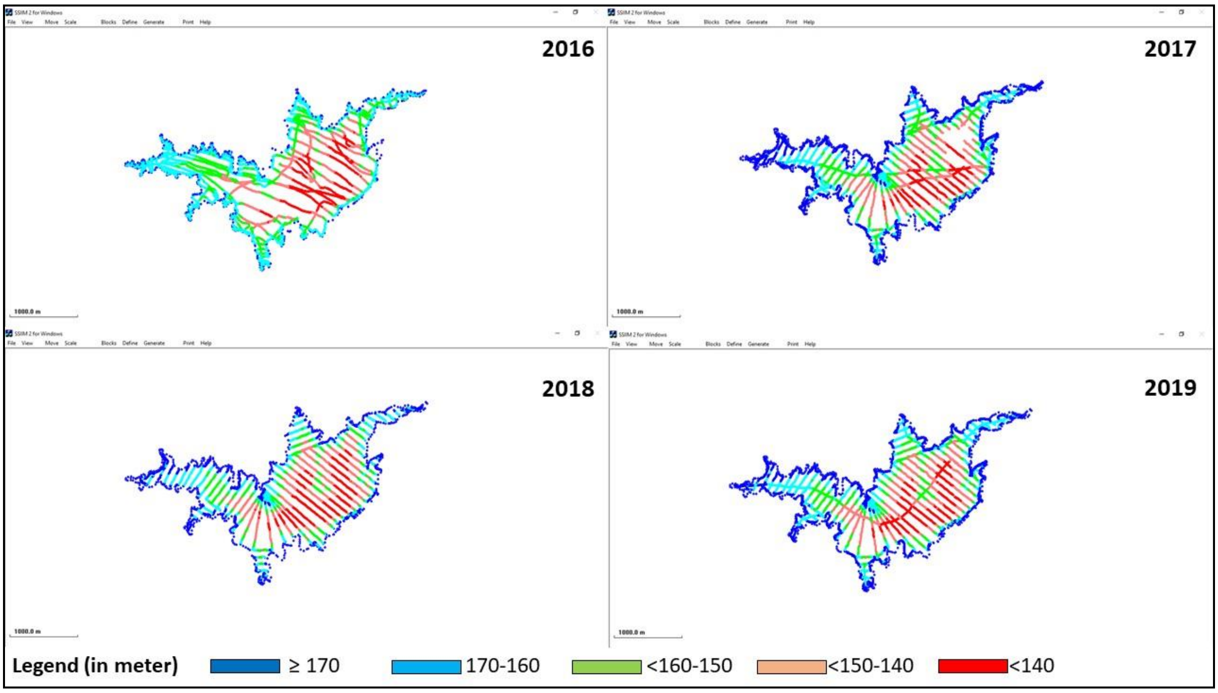


Figure 6. Echo sounding results data presented in SSIIM for the year 2016-2019

Due to the echo-sounding area in the reservoir and the echo-sounding measurement path being denser than the previous year, there is a significant difference between the 2016 echo-sounding image and the following year (2017, 2018, 2019). From the echo-sounding image, it can be seen that the sediment buildup (red colour) is located close to the dam. However, based on calculations presented in Table 5, it is estimated that up to the service life of the reservoir, the reservoir can still function properly with a sediment content of not more than 20% of the total reservoir volume. The limit of 20% is taken because the reservoir dead storage capacity is typically 20-25 % of total storage.

Although sediment volume percentage is still relatively small (below 20%), efforts to control it are still needed because sedimentation will continue. With the continued increase in the rate of sediment to the volume of reservoir capacity, efforts are required to overcome this so that the useful life of the reservoir is not affected and the reservoir can still work optimally.

Some efforts that have been implemented or recommended in other reservoirs and dams in Indonesia are as follows:

a) Improvement of hydrological flow in the watershed so that rainwater can be stored and used in the dry season and finding alternatives for irrigation water supply, as recommended by Wahyudi [10] for Cacaban Reservoir.
b) Sediment dredging activities in river mouths for maintaining the Wonorejo Reservoir and Dam, as studied by Sejati et al. [11] for the Bili-Bili Dam, where the economic value, the volume of dredging spoil conducted by the availability of existing banks is planned at 200,000 m 3 per year have the highest effectiveness.

c) According to Marhendi [12], handling reservoir sedimentation, in general, can be divided into four types of activities or businesses; suppressing the erosion rate in the upstream area, minimizing the load of sediment entering the reservoir, minimizing the amount of sediment that settles in the reservoir and removing sediment deposits in the reservoir. In addition, vegetative and social handling is also needed, such as conservation of upstream areas to reduce or prevent sediment from entering reservoirs and development of community participation in upstream areas.

d) Approach using a model like Ilyas and Arief [13] studied in the Citarum watershed. Using a model approach to predict erosion and spatial sedimentation can provide a comprehensive picture of the level of erosion and sedimentation in rivers and reservoirs in the watershed.

4. Conclusions and suggestions

The percentage of sediment volume tends to increase until it fills 16.37% of the total reservoir capacity. It shows that the distribution of sediment deposits is growing over time. At the same time, the reservoir volume capacity decreases with the presence of these deposits. However, theoretically, the Wonorejo Reservoir can still function optimally until 50 years.

Some sedimentation management efforts include improving hydrological flow in the watershed, sediment dredging activities, vegetative and social handling, and approaches using models.

In addition, for future studies, it is recommended to use sediment data for a more extended period to get more accurate results and do the sedimentation modelling of the Wonorejo Reservoir using different modelling programs to describe the spatial distribution of sediment more precisely.

5. References

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