Alternative Analysis of Selorejo Reservoir Sediment Control for Maintenance Cost Efficiency

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Abstract—The Selorejo Dam, which was completed in 1970, has experienced a high decline in storage capacity due to sedimentation rates from the upstream Konto river watershed. The maximum reservoir capacity in 1970 was 62.3 million m³ in 2017 to 30.72 million m³. Reservoir maintenance activities, in this case technical sediment control, have not been able to recover or maintain reservoir storage capacity, so alternative reservoir sediment control is needed that is able to maintain reservoir service life and is economically efficient. This research was conducted to analyze the effectiveness and efficiency of sediment control technically from 5 (five) alternatives proposed to be implemented in the Selorejo reservoir. The things considered in the alternative are sediment control volume and method, first according to the last condition carried out by reservoir organizer, next is addition of sediment control volume, and combination of sediment control with reservoir sediment dredging method, sabo dam sediment dredging and establishment check dams. Of the five alternatives proposed in controlling sediment, the 1st alternative with sediment dredging volume of 215 m³ per year resulted reservoir service level 5.62 years, B/C value 1.337 and B-C IDR 40,489,313,011,-, while the 5th alternative with a sediment control volume of 430 m³ per year resulted in a reservoir service level 11.92 years, B/C value 1.090 and B-C IDR 23,316,604,758,-. In implementing the Selorejo reservoir sediment, these 2 alternatives are effective and efficient compared to the alternatives offered.

Keywords—Sediment Control, Selorejo Reservoir, Cost Efficiency.

I. INTRODUCTION

The sustainability of the reservoir in carrying out its main function is determined by the age of the reservoir, its how long the volume of the dead reservoir will be filled with sediment material deposits. The Selorejo Reservoir functions as a flood control Q200 max of 920 m³/sec controlled to 360 m³/sec, Q200 flood control of 680 m³/second is controlled to 260 m³/second, a power plant with 4,500 kW power and an additional discharge in the dry season of 4 m³/sec in the Pare & Jombang irrigation area. The maximum reservoir capacity in 1970 was 62.3 million m³ and in 2017 it was 30.72 million m³ (reduced by 50.69%). Periodically, since 2001 Jasa Tirta I Public Corporation (PJT I) dredged reservoir sediments using dredges with reservoir dredging capacity varying from 50,000 m³ to 300,000 m³ per year. There are limitations to dredging reservoirs: the range of dredger cutter section ladder is limited to effective storage and disposal area/spoilbank capacity has decreased. Other technical efforts to control reservoir sedimentation with sediment control structures are sabo dams or check dams. Sediment control activities carried out to date have not been able to restore or maintain reservoir storage capacity so research is needed to determine the appropriate sediment control methods so that sediment control efforts can maintain the function of reservoir benefits while being economically feasible.

II. OBJECTIVES

This paper will discuss sedimentation conditions in the Selorejo reservoir and to find out the effective and economically efficient alternatives in the context of reservoir sediment control.

III. RESEARCH METHODOLOGY

A. Study Area

This study was conducted at the Selorejo reservoir in the Konto river basin. The Selorejo reservoir is surrounded by mountains Kelud, Kawi and Anjasmor, receiving water from three rivers: the Konto, Pinjal and Kwayangan. Konto watershed with an area of 23,625 ha. Geographically, the Konto sub-watershed itself is located between 11203 '45.89 "East, 7030' 8,234" South Latitude and 112030 '1,716 "East, 7057' 22,423” South Latitude.
B. Data Types and Sources

The type of data used in this study is secondary data from related research and measurement data carried out including erosion data and sedimentation rates, reservoir bathymetry measurements, spoilbank capacity zones and capacities, sediment control building (sabo dam and checkdam) data, and sediment material data.

C. Watershed Erosion Analysis

The erosion process consists of three sequential parts: detachment, transportation, and sedimentation [1]. Factors that cause erosion are erosion factors expressed in erosivity and soil factors expressed in erodibility, namely: climate/rainfall (R), soil type (K), topography (LS), vegetation (C) and management land (P) [2]. Watershed erosion analysis is done by calculating the percentage level of erosion in contributing to the sedimentation rate of tributaries that are dammed by the Selorejo reservoir, from Konto river, Kwayangan river and Pinjal river.

D. Reservoir Sedimentation Conditions Analysis

Analysis is carried out to determine reservoir characteristics and current reservoir conditions due to sedimentation that occurs using data from the measurement of reservoir storage capacity that is routinely carried out. From this analysis we will find changes in storage conditions, trap efficiency, volume, sedimentation rate and age of reservoir service remaining.

The storage of a reservoir consists of dead storage, effective storage and flood storage. Effective storage are often also called active storage, because these reservoirs always fluctuate depending on the inflow and outflow of the reservoir to meet needs.

The service life limit of a reservoir is a period or number of years from the start of operation of the reservoir until the reservoir functions are exhausted to be able to regulate output water through intake. Determined by the length of time the dead storage volume is filled by sediment.

From the measurement of sediment collected in the reservoir it can be seen the change in sedimentation rate. To estimate how many years more the amount of sedimentation exceeds the dead storage can be used a linear regression equation, by finding the relationship between the age of use and the amount of sediment.

Linear regression is one of the types of forecasting or prediction analysis that is often used on quantitative scale data (intervals or ratios) [3].

\[ Y = A + BX \]

\[ A = \frac{(\sum Y - B \sum X)}{n} \]

\[ B = \left( \frac{(n \sum X \sum Y - \sum X \sum Y)/(n \sum X^2)}{2} \right) \]

with:

\[ X : \] service life

\[ Y : \] cumulative sediment volume (million m³)

\[ n : \] amount of data

In a simpler way, calculation of reservoir service age can be calculated based on reservoir sedimentation rates per year against the amount of the volume of the dead storage with the following formula [4]:

\[ T = \frac{V}{L_j} \]

with:

\[ T : \] Age of reservoir (year)

\[ V : \] Reservoir dead capacity (m³)

\[ L_j : \] Sediment rate (m³/year)

In determining the age of a dam plan, it is not only necessary to know how much sediment material and type are entering, but also how much sediment will be deposited. The ability of the reservoir to hold and deposit the sediment is called trap efficiency, which is expressed as a percent of the amount of sediment carried by the inflow.

The efficiency of this reservoir depends on the nature of the sediment and the discharge entering the reservoir. The relationship between reservoir efficiency and the ratio between reservoir storage capacity and annual discharge entering the reservoir are formulated [5] as follows:

\[ Y = 100 \left( 1 - \frac{1}{1+ax} \right)n \]

with:

\[ Y : \] Storage efficiency

\[ x : \] Comparison of reservoir storage capacity with annual inflow

\[ a : \] constants, i.e.: \[ a = 100 \] for the average curve

\[ a = 65 \] for the minimum curve

\[ a = 130 \] for the sheath curve

\[ n : \] constants, i.e.: \[ n = 1.5 \] for the average curve

\[ n = 2.0 \] for the minimum curve

\[ n = 1.0 \] for the sheath curve

E. Alternative Analysis of Reservoir Sedimentation Control

Reservoir sedimentation control can generally be divided into three types of activities or businesses [6]:

Fig. 2. Sketch of Dam reservoir.

Fig. 3. Efficiency Trap Curve.
1. Pressing the rate of erosion upstream. Actions to suppress erosion rates in the upstream area can be done structurally (treating civil and vegetation), or non-structural (social) measures.

2. Minimizing the burden of sediment entering the reservoir. Reducing the burden of sediments entering the reservoir can be done in two ways, by catching sediment through a basin channel system (sabo dam/check dam), and diversion of sediment that will enter the reservoir to other areas outside the reservoir (sand bypass).

3. Removing sediment deposits in reservoirs. Removing sediment out of the reservoir is the last effort that must be implemented. Two ways that are often taken are by flushing through the bottom outlet output facilities, as well as dredging.

Reservoir Dredging Process

Four basic components consideration for reservoir dredging covering: 1) sediment to be dredged (dredging location), 2) equipment for dredging, 3) equipment for channeling dredged material such as pipes for dredging hydraulic, and 4) location of dredging material (riverine disposal to the river downstream of the dam or off-stream disposal/spoil bank) [6].

Sediment Control Building

In its application in Indonesia, sabo dam/check dam means a building to hold material from landslides and control material flooding or cold lava flooding. Sabo dam is a type of sediment control building that is usually built in the upstream area. The full Sabo dam still has the ability to temporarily accumulate a number of sediments. These sediment deposits are on the surface of dead storage and are referred to as volume control.

Alternative sediment control reservoirs are planned with two (2) conditions, firstly carried out in accordance with the latest sediment control conditions that have been carried out by reservoir organizer and secondly carried out by adding sediment control volumes and a combination of sediment control methods.

F. Sediment Control Costs Analysis

Dam/reservoir maintenance activities are activities required to maintain dam/reservoir functions including dredging of sediment reservoirs, repairing canals, constructing sediment control structures and dredging. The amount of the fee depends on the capacity, reservoir life, problems and methods of maintenance and or repairs carried out. Costs are incurred over and over again and are required to operate and maintain the item in question for its useful life [7].

From each of the alternative sediment control costs will be calculated. The unit price value is calculated from the value of salary, material and equipment prices.

G. Steps for Cost Benefit Analysis (CBA) Economic Analysis

Project Alternative Identification

The main purpose of CBA is to find the most appropriate sediment management project, among several project alternatives.

Identification of Costs and Benefits

Project costs and project benefits are the main elements in CBA, the identification of cost and benefit elements depends on the perspective of the organization in the project.

Net Present Value (NPV)

Method of calculating net value at the present time. The present assumption is to explain the initial time of the calculation to coincide with the time of the evaluation or in the zero year period (0) in the cash flow calculation. The NPV method basically transfers cash flow that spreads throughout the life of the project to the initial investment time or present condition. Generally, PV can be calculated using the following formula [8]:

\[ PV = \frac{FV}{(1+i)^n} \]

Parameter Analysis

CBA uses three (3) economic parameters to analyze projects, which include the Benefit Cost Ratio (B/C ratio), Net Benefit (B-C) and Internal Rate Return (IRR). In this study, the parameters used are limited to B/C Ratio and B-C.

B/C Ratio provides a value comparison between the benefits (benefits) obtained with aspects of costs and losses to be borne (cost). If the B/C ratio does not exceed 1.0, the project is considered unfeasible. If it is exactly 1.0, it is considered a marginal project, and if it exceeds 1.0, then the project is feasible.

\[ B/C \text{ Ratio} = \frac{\sum \text{benefits}}{\sum \text{costs}} \]

Net Benefit is defined as a reduction of all profits to the sum of all costs. Projects with higher net benefits are considered the most economical projects.

\[ \text{Net Benefits} = \sum \text{benefits} - \sum \text{costs} \]

IV. RESULT AND DISCUSSION

A. Selorejo Reservoir Sedimentation Rate Analysis

The results of erosion transported to the Kali Konto flow through its tributaries finally settled in the Selorejo reservoir. It is the main cause of sedimentation problems in the Selorejo reservoir.

The measurement of the reservoir volume of the Selorejo is h periodically starting at the beginning of the inundation of the reservoir in 1970 until the measurement in 2019. The method used in the measurement is echo sounding of the
reservoir, the result of which is the contour map of the Selorejo Echosounding Reservoir.

Based on the results of the 2019 echo sounding measurements, the total storage capacity was 31.81 million m$^3$, the effective storage capacity was 31.28 million m$^3$ and the dead storage capacity was 0.53 million m$^3$. Compared to the initial conditions in 1970, the effective storage volume was reduced by 18.82 million m$^3$.

### Table 1. Selorejo reservoir volume from echosounding measurement

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Reservoir Volume (juta m$^3$)</th>
<th>Sediment Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Th 1970</td>
<td>Th 2019 (%)</td>
</tr>
<tr>
<td>HWL = + 622,00</td>
<td>62.30</td>
<td>31.81</td>
</tr>
<tr>
<td>LWL = + 598,00</td>
<td>12.20</td>
<td>0.54</td>
</tr>
<tr>
<td>Efektif Volume</td>
<td>50.10</td>
<td>31.27</td>
</tr>
<tr>
<td></td>
<td>18.83</td>
<td></td>
</tr>
</tbody>
</table>

The condition of the reservoir capacity of the Selorejo Reservoir from 1970 and 2019 can be seen in Table 1 and the periodic changes with the curved capacity presented in Figure 7. Selorejo reservoir sediment profile measurement results in 2019 are shown as in Figure 8.

### Table 2. Calculation of trap efficiency the Selorejo reservoir

<table>
<thead>
<tr>
<th>Year</th>
<th>a</th>
<th>n</th>
<th>Reservoir capacity (million m$^3$)</th>
<th>Annual Inflow (million m$^3$)</th>
<th>x</th>
<th>Trap Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>100</td>
<td>1.5</td>
<td>62.30</td>
<td>347,850</td>
<td>0.179</td>
<td>92.17</td>
</tr>
<tr>
<td>1993</td>
<td>100</td>
<td>1.5</td>
<td>48.87</td>
<td>350,127</td>
<td>0.140</td>
<td>90.14</td>
</tr>
<tr>
<td>1997</td>
<td>100</td>
<td>1.5</td>
<td>47.61</td>
<td>259,237</td>
<td>0.184</td>
<td>92.36</td>
</tr>
<tr>
<td>2003</td>
<td>100</td>
<td>1.5</td>
<td>44.01</td>
<td>264,966</td>
<td>0.166</td>
<td>91.60</td>
</tr>
<tr>
<td>2006</td>
<td>100</td>
<td>1.5</td>
<td>42.90</td>
<td>300,850</td>
<td>0.143</td>
<td>90.33</td>
</tr>
<tr>
<td>2007</td>
<td>100</td>
<td>1.5</td>
<td>41.69</td>
<td>313,581</td>
<td>0.133</td>
<td>89.69</td>
</tr>
<tr>
<td>2009</td>
<td>100</td>
<td>1.5</td>
<td>39.61</td>
<td>361,111</td>
<td>0.110</td>
<td>87.73</td>
</tr>
<tr>
<td>2011</td>
<td>100</td>
<td>1.5</td>
<td>38.25</td>
<td>537,571</td>
<td>0.071</td>
<td>82.10</td>
</tr>
<tr>
<td>2012</td>
<td>100</td>
<td>1.5</td>
<td>38.11</td>
<td>365,877</td>
<td>0.104</td>
<td>87.15</td>
</tr>
<tr>
<td>2013</td>
<td>100</td>
<td>1.5</td>
<td>38.57</td>
<td>428,117</td>
<td>0.085</td>
<td>84.70</td>
</tr>
<tr>
<td>2014</td>
<td>100</td>
<td>1.5</td>
<td>38.32</td>
<td>389,471</td>
<td>0.089</td>
<td>85.30</td>
</tr>
<tr>
<td>2016</td>
<td>100</td>
<td>1.5</td>
<td>32.10</td>
<td>381,368</td>
<td>0.084</td>
<td>84.50</td>
</tr>
<tr>
<td>2017</td>
<td>100</td>
<td>1.5</td>
<td>31.64</td>
<td>411,540</td>
<td>0.077</td>
<td>83.24</td>
</tr>
<tr>
<td>2018</td>
<td>100</td>
<td>1.5</td>
<td>31.27</td>
<td>377,990</td>
<td>0.083</td>
<td>84.57</td>
</tr>
<tr>
<td>2019</td>
<td>100</td>
<td>1.5</td>
<td>31.81</td>
<td>318,685</td>
<td>0.100</td>
<td>86.66</td>
</tr>
</tbody>
</table>

The calculations using discard data for 1993, 1997, 2003, 2006, 2007, 2009, 2011, 2012, 2013, 2014, 2016, 2017, 2018 and 2019, the constants a and n are the values for the average curve, i.e. $a = 100$ and $n = 1.5$ results of the Selorejo reservoir efficiency trap in table 2 shows a declining trend. This is proportional to the reduction in reservoir storage capacity to accommodate sediment.
B. Reservoir Service Age Remaining Analysis

From the calculation of linear regression with the help of MS. Excel shown as in Figure 9 obtained the regression equation as follows:

\[ Y = 0.1258X + 5.3524 \]

By entering the planned reservoir reservoir dead capacity of 12.2 million m³, it can be concluded that the service life of the Selorejo reservoir is based on the actual sedimentation rate deposited in the reservoir and sediment control activities that have been carried out up to 2019 are 54.43 years or up to 2023.

C. Selorejo Reservoir Sedimentation Control Analysis

From the accumulation of reservoir dredging up to 2019 if it is reviewed since the completion of reservoir construction (1970) it can be seen that the work of dreading Selorejo reservoir sediment in reducing the average sedimentation rate per year is 49.518 m³/year.

Upstream of the Selorejo reservoir, a number of sabo dams and check dams have been built, both from the river stone pair and from the gabion. Currently some sediment control structures whose construction is still in good condition are full of sediment storage, while others (some of gabions check dam) are in a damaged condition. So that sediments coming from upstream will enter the waters of the Selorejo reservoir.

Proposed sediment control methods are technical control with a combination of reservoir sediment dredging methods, sabo dam dredging and check dam construction with the volume of alternative sediment control activities of 215,000 m³ and 430,000 m³. It can be calculated that the addition of reservoir service life for the two alternatives is as follows:

Alt. 1 = dead storage capacity in 2019 / (average sediment rate that occurs x percentage of sedimentation in dead storage) = 540,000 m³ / ((622,000 - 215,000) x 23.592%) m³ = 5.62 years since the last measurement (2019)

Alt. 2 = dead storage capacity in 2019 / (average rate of sediment occurring x percentage of sedimentation in dead storage) = 540,000 m³ / ((622,000 - 430,000) x 23.592%) m³ = 11.92 years since the last measurement (2019)

<table>
<thead>
<tr>
<th>Table 3. Alternative matrix of reservoir sediment control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt.</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

The cost calculation is carried out by multiplying the unit price of the work by each alternative volume of sediment control work. The recapitulation of sediment control volumes and costs for each alternative is shown in table 4.
D. Benefits Analysis

In the analysis of the benefits of electricity production after sediment management service costs are used the average electricity production volume in the last 10 years. With the water resource management service costs (BPJSDA) hydropower plant (PLTA) tariff of IDR 167/kWh, the economic value of the Selorejo hydropower is IDR 4,651,821 million/year, the Mendala hydropower IDR 12,883,768 million/year and the Siman hydropower plant of IDR 9,393,918 million/year with a total of 3 (three) hydropower plants in the amount of IDR 26,929,507 million/year.

The economic value of water for irrigation purposes is calculated based on the BPJSDA value for Brantas river area irrigation which is IDR 824,741 ha [9], so that the total benefits for irrigation offered by the Selorejo reservoir are IDR 4,701,024 million/year.

Flood control (in the downstream area of Konto river) is a maximum flood (1000 years) of 920 m³/sec can be controlled to 360 m³/sec. And 200-year floods of 680 m³/sec can be controlled to 260 m³/sec. Damage that can be avoided due to flooding is IDR 1,500,000,000/year [10].

E. Economic Analysis

The assumptions used in economic analysis include the interest rate is 9.95% and the inflation rate is 2.96%. The interest rate is used to determine the present value of costs and benefits while the inflation rate is used to determine the value of the increase in costs and benefits per year. From the results of economic analysis, by controlling sediment for 10 years, B/C and B/C parameters of each alternative are shown as shown in Table 5.

F. Efficiency and Effectiveness of Alternative Sediment Control Analysis

From the results of economic analysis using the parameters B/C and B-C, alternatives 1, 2, 3, and 5 show the value of B/C> 1 and B-C is positive so it is feasible to be implemented with alternative 1 giving the value of B/C and B-C is the highest or most economically efficient of the 5 alternatives. Based on the calculation of reservoir service age, alternative 1 adds reservoir service age by 5.62 years while alternatives 2, 3, 4 and 5 together add reservoir service age by 11.92 years, with the same additional service age as alternatives 2, 3 and 4, alternative 5 is the most economically efficient compared to alternatives 2, 3 and 4.

V. CONCLUSIONS

The reservoir capacity of the Selorejo reservoir in 2019 is 31.81 million m³ (total storage), 31.28 million m³ (effective storage) and 0.53 million m³ (dead storage) with sediment volume of 11.66 million m³ (dead storage) and 18.83 million m³ (effective storage). The sedimentation rate of the Selorejo reservoir is contributed from 3 (three) rivers it contains, including the Konto river, the Kwayangan river and the Pinjal river. The trap efficiency of the Selorejo reservoir shows a declining trend in proportion to the reduction in reservoir storage capacity with a value in 2019 of 86.66%. The average sedimentation rate of 0.622 million m³/year. Based on the existing sedimentation conditions assuming the dredging volume is in accordance with the average sediment dredging that has been carried out, it is known that the service life of the Selorejo reservoir is 54.43 years or up to 2023.

Considering the volume of reservoir sediment control and resources in sediment control, among others: dredging capacity and available spoilbank storage and capacity and condition of sediment control structures upstream and downstream of the reservoir, a proposed sediment control method with a combination of reservoir sediment dredging methods, sabo dam dredging and making check dams in 5 (five) alternative sediment control.

TABLE 6. Alternative matrix sediment control and costs incurred per year

From the calculation of the value of benefits and the addition of reservoir service life in each alternative, the following results are obtained:

a. The value of the benefits of alternative sediment control 1 is IDR 160,644,115,316 with an additional service age of 5.62 years.

b. The value of the benefits of alternative sediment control 2, 3, 4 and 5 were IDR 282,781,322,778 respectively, with an additional service life of 11.92 years, respectively.

Alternative 1 has the highest level of efficiency but is only able to increase the service life of the reservoir for 5.62 years.
and alternative 2 has the level of efficiency in the second rank by increasing the service life of the reservoir for 11.92 years.

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