AN OVERVIEW OF DAM SEDIMENTATION ANALYSES, WITH SPECIAL REFERENCE TO BATUJAI DAM

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Abstract

Located in urban and densely populated areas, Batujai Dam was the first dam built in West Nusa Tenggara Province, with a storage capacity of 25,000,000 m^3 and a maximum depth of 18 m. The lifetime of the dam has been proposed for 50 years but after its commissioning in 1982, many researchers believed that the annual loss of storage due to sedimentation is higher than expected. The prediction of sediment deposition in Batujai Dam had been carried out in the past two decades. The common method used by authorities and researchers were measuring deposited sediment by using the echo-sounding technique, an adaptation of bathymetric survey. The results of previous analyses focused on Batujai Dam are overviewed and compared to obtain information on the current state of the dam. All studies observed in this paper agree that Batujai Dam experience a considerable sedimentation problem. This means the state of Batujai Dam that has a shorter lifetime is commonly shared by all researchers. Mitigation measures are urgently needed in order to better manage the sediment rate reduction to maintain the remaining lifetime of Batujai Dam.

Keywords: Dam sedimentation, lifetime, deposition, echo-sounding

INTRODUCTION

The ultimate goal of all reservoirs is to preserve their function within the designated lifetime. Reservoir planning and design should include consideration of potential sediment deposition rates to determine if the proposed lifetime is sufficient to ensure its function. Report published by International Committee on Large Dams (ICOLD), Sedimentation Committee suggest that the average reduction in storage capacity of dams in the world is 0.80% and Asian countries such as China and Philippines experience higher reduction rate (Bassoni, 2008).

Reservoir sedimentation cannot be prevented but can be reduced. The most common procedure for dealing with reservoir sedimentation problems is the determination of a portion of the reservoir capacity as a sedimentary deposit. This method is said to be a negative approach because it will not reduce the build-up of sediments but merely postpones the occurrence of serious problems. Sustainable and preventive measures in reservoir sedimentation are rarely taken into consideration, and the problems are often deal with mitigation measures applied only after commissioning of the dams (Schleiss et al., 2016).

Methods of predicting the volume of deposited sediment are in the form of hydrographic survey, the inflow-outflow method (mathematical model) and the application of remote sensing technology (see Goel et al., 2002; Issa et al., 2013; Gao et al., 2017 amongst others). Direct in situ measurement such as bathymetry or mapping the bottom of the reservoir at any given time by using echo-sounding technique is a very popular choice for dam's owners. This method is very useful but only provides information on the changes in sediment bed elevation as the basis of calculating the volume of deposited sediment. No further and detail information obtained from this method such as the sources of sediment and the main contributor of sediment especially when the river flowing into the reservoir is more than one (Saadi, 2007).

The catchment area of the rivers flowing into Batujai Dam comprises a residential area with a relatively high growth rate so that a rapid change in land use is expected. Degrading catchment area will affect the carrying capacity of the river in the middle and lower course. The ability of catchment to store water decreases so that the magnitude and frequency of floods increases as well as sedimentation in rivers and dams. An example of degrading catchment is experienced by Bengawan Solo River Basin. Expedition of Bengawan Solo River carried out by Kompas Daily Newspaper in 2007 showed that the erosion in the upstream of Bengawan Solo is unavoidable due to land use change. The substitution of hard crop and timber by seasonal vegetation couple with an inappropriate terracing system leads to an increase in soil erosion to the rivers that exacerbates sedimentation in Gajah Mungkur Dam (Kompas Daily Newspaper, 2007).

Uncontrolled conservation of catchment areas, i.e. rapid changes in land use and subsequent increase in the runoff coefficient, may lead to an increase in the flowing discharge downstream as well as an increase in sedimentation due to erosion of soils (Saadi, 2013). Generally, this erosion may be moved through the river which in turn will result in the silting of the river so that the cross sectional area is reduced and flood discharge exceeds channel capacity. Another condition is that the river flow will try to transport the accumulated sediments downstream and if there are reservoirs or dams, there will be a silting process decreasing the lifetime of reservoir. Large volumes of eroded soil due to the land use practices and land use changes can lead to the reservoir closure (see Gellis et al., 2006).

METHODOLOGY

In this study, past researches on Batujai Dam's sedimentation have been examined to find out if there are strong relationships between measurements, which can be adopted as a basis of mitigation measures by dam's owner. Four researches were selected in which one of them comparing the other three previous results including the results from engineering consultants. The prediction of lifetime of the Batujai Dam has been predicted by using linear regression analyses. The aforementioned researches are briefly explained in the following paragraphs.

The first selected research was the one carried out by Saadi about 11 years after the operation of the Batujai Dam (Saadi, 1993). The research that was intended as an undergraduate thesis only analyzed the potential sedimentation rate based on a very limited secondary data. More than a decade later Saadi (2007) tried to develop method by combining secondary data with field measurement and hydrological analysis based on available rainfall data with a minimum duration of 20 years. Three main rivers flowing into Batujai Dam were selected for suspended sediment measurement. Those are Leneng River, Triwubare River and Surabaya River respectively (see Figure 1).

Figure 1. The distribution of rivers in Batujai Dam

Later, Wakidi (2016) gathered data in the form of secondary data such as an echo-sounding, temperature, rainfall and discharge data obtained from an Automatic Water Level Recorder (AWLR) Station. Echo-sounding data obtained from measurement carried out by an engineering consultant in 2005. The temperature data are semi-monthly data from 2005 to 2015, while the temperature data from 2016 to 2048 based on Global Climate Model data. Semi-monthly rainfall data of Penujak Village from 2005 to 2015 were obtained from nearby station, while rainfall data from 2016 to 2048 were originated from Global Climate Model. The discharge from AWLR station was the outflow data of Batujai Dam from 1982 to 2015. The primary data collection was obtained from the field survey conducted in accordance with the selected method using echo-sounder.

The latest research on Batujai Dam sedimentation was carried out by Supardi (2018). In this research a linear regression was used for dam sedimentation analysis while the analysis of deposited sedimentation distribution in the impounding area was using Artificial Neural Networks (ANNs) software. The data used in this research were secondary data obtained from previous researches. Those were the main data during construction of the dam, the extent of land use from 2005-2017, the inflow and outflow data, and the flood discharges of 2005-2017 taken from AWLR Station. The area and storage capacity from 2005-2017 and the echo-sounding data were also taken from previous researches.

RESULTS AND DISCUSSION

Research by Saadi (2007) focused on obtaining the relationship between river flow and suspended sediment transport. Therefore, the measurements of discharge were conducted. Measurement of flow velocity was carried out by using a flow meter wading set provided by Hydraulic and Coastal Laboratory University of Mataram. Suspended sediment collection is carried out in accordance with the provisions mentioned in SNI 03-3414-1994 (National Standardization Board, 1994). The equipment used was a cylinder water sampler since a proportional dimension of the cylindrical measuring instrument can provide more accurate measurement results with trap efficiency of 0.8 to 1.2 for a moderate flow (van Rijn, 2006). Sufficient measurements of discharge and suspended sediment in the observed rivers were carried out at different locations to obtain samples representing the actual conditions of the river as accurately as possible.

The relationship between discharge and suspended sediment concentration is actually a correlation between the two factors at the time of measurement. It was assumed that increasing the number of measurement in various locations can be used as a basis for estimating suspended sediment concentration for the following years. Only data derived from long-term observations were accepted and used. Average inflow and average daily discharge data of 10 years from 1994 to 2004 published by Karya Utama Jaya General Consultant (2005) were adopted and the average monthly discharges as well as the monthly inflow from each river were obtained. The results showed that Surabaya River had much larger volume when compared to Leneng River and Triwubare River respectively. This is understandable as Surabaya River has a catchment area twice larger than Triwubare River or about seven fold larger than that of Leneng River.

The rating curve, which is a graph of the relationship between river flow discharge and sediment concentration, is based on the data of discharge observations and suspended sediment concentration in each river. The condition of reach and the river channel in which the sample was taken will determine the measurement results. Sampling at adjacent sites can provide different relationship between the discharge and suspended sediments concentration. Figure 2 present the suspended sediment rating curve for three rivers in Batujai Dam.

By using the technique of fitting curve based on the least square method (Akai, 1994), the relationship between river flow discharge and suspended sediment concentration in the form of logarithmic equation were obtained as follows:

- Leneng River : $Q_s = 0.239\ Q_w^{0.228}$ (1)
- Triwubare River : $Q_s = 0.466\ Q_w^{1.173}$ (2)
- Surabaya River : $Q_s = 0.221\ Q_w^{0.046}$ (3)

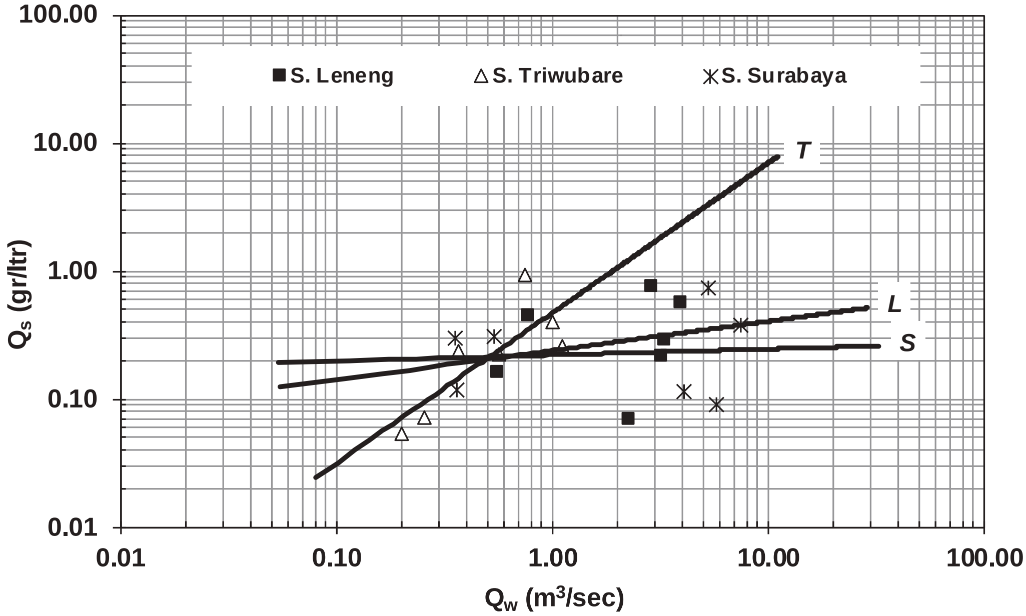

Figure 2. The relationship between river flow discharge and suspended sediment concentration (After Saadi, 2007)

Based on empirical equations and the inflow of the observed rivers, the volume of suspended sediments transported through each river can be obtained. It can be seen from rating curve that there is a considerable difference in the relationship between flow discharge and suspended sediment concentration of Triwubare River in comparison to Leneng River and Surabaya River. This difference affects the volume of suspended sediments estimated to be transported through each river. Compared with Leneng and Surabaya Rivers, Triwubare River was the largest contributor of suspended sediment entering Batujai Dam, whilst the Leneng River contributed the least volume. An interesting feature is shown by Triwubare River. Although it had less catchment areas than Surabaya River, its contribution to suspended sediment transport rates was much greater, ie 139,405.770 tons per year while the Surabaya River transported 67,429.892 tons during the corresponding period. It is believed that the presence of weirs in the upper part of Surabaya River showed a fairly effective performance in trapping suspended sediment. However, this requires further investigation in order to obtain more detailed information.

Given the difficulties in measuring the bed load transport in the field, Saadi (2007) decided to calculate bed load based on the percentage of suspended load. However, the use of Table of Preliminary Appraisal as suggested by Strand and Pemberton (1982) was avoided to prevent both overestimate and underestimate calculation. Thus, sample of materials from all three rivers were taken. Sieve analysis was conducted to separate the material based on the grain size and grouped into suspended load and bed load. The percentage of bed load to the suspended load was used to obtain the total volume of sediments derived from three rivers.

In order to estimate sediment volumes after certain period of deposition, the average density of all sediment deposited in T years of operation should be determined. Prior to this, the calculation of sediment volume in a solid state after one year of operation was conducted by dividing the total amount of sediment by the density of deposited sediment (ρb) obtained from sediment samples from three rivers. The composition of clay, silt and sand contained in the samples together with the density coefficient for each material and the reservoir operation type of Batujai Dam, produced the ρb value of 1,365.458 kg/m^3. Thus, the volume of sediment deposited after one year was 184,609.187 m^3. The sediment volume during the lifetime of the dam was calculated based on the average density of sediment after T years of operation (τ_{bT}). The lifetime of Batujai dam was proposed for 50 years. Impounding began in October 1981 so that the reservoir officially operated in the following year. Taking into account the trap efficiency of the dam, the volume of deposited sediment in year 2007 or 25 years after the operation can be estimated. According to the Dam Measurement Report published by Karya Utama Jaya General Consultant (2005) it was estimated that the dam's effective storage in 2005 was 18,219,000 m^3 and the annual average inflow based on the 22 years of recording period (1983-2004) was 195,900,000 m^3. Hence, the ratio of reservoir capacity to annual average inflow of Batujai dam was 0.093. Based on the Brune curve (Strand and Pemberton, 1982) this gave the dam’s trap efficiency of 87%, resulting in the sediment volume of 3,949,955.151 m^3 from three rivers had been deposited in 2007 or 25 years after dam in operation.

A noticeable difference is obtained from calculation conducted by Wakidi (2016). The analysis of the discharge calculation and sedimentation rate shows that in year 2016 the volume of sedimentation of Batujai Dam was 1,445,129 m^3 exceeding the dead storage proposed volume capacity of 1,400,000 m^3. When the dam reaches its 50 years of operation in year 2032 the volume of sediment would be 2,482,222 m^3. This means the amount of sedimentation volume has exceeded the prediction of the dead storage capacity by 1,082,222 m^3. These calculations suggest that Batujai Dam is no longer in operation since the proposed dead storage capacity has been exceeded in 2016. Considering the fact that the dam is still in operation, Wakidi (2016) argued that dredging activities conducted by Nusa Tenggara I River Basin Organization (BWS NT I) in 2014 is the main reason that preserve the function of the dam. Further analysis however, state otherwise. Wakidi (2016) included the dredging data from BWS NT I in 2014 when 95,187.68 m^3 of deposited sediment were taken from the impounding area. This inclusion only postponed the exceedance of dead storage capacity a year later, which means in year 2017 Batujai Dam is no longer in operation with 1,402,731 m^3 of sediment was deposited in the dead storage. Further argument has been forwarded that long time practices in traditional brick making during dry season by resident from nearby village contribute to the preservation of Batujai Dam.

Contrary to the calculation above, Wakidi (2016) produced a chart estimating the sediment volume from the 1st to the 65th year of Batujai Dam operation (see Figure 3). The results are relatively low, where the average sedimentation rate within the period of 1982 to 2015 was 41,118 m^3 and increased to 68,872 m^3 within the period of 2016 to 2048. Considering this calculation, a longer time than that stated in the previous paragraph to fill the dead storage of Batujai Dam can be expected.

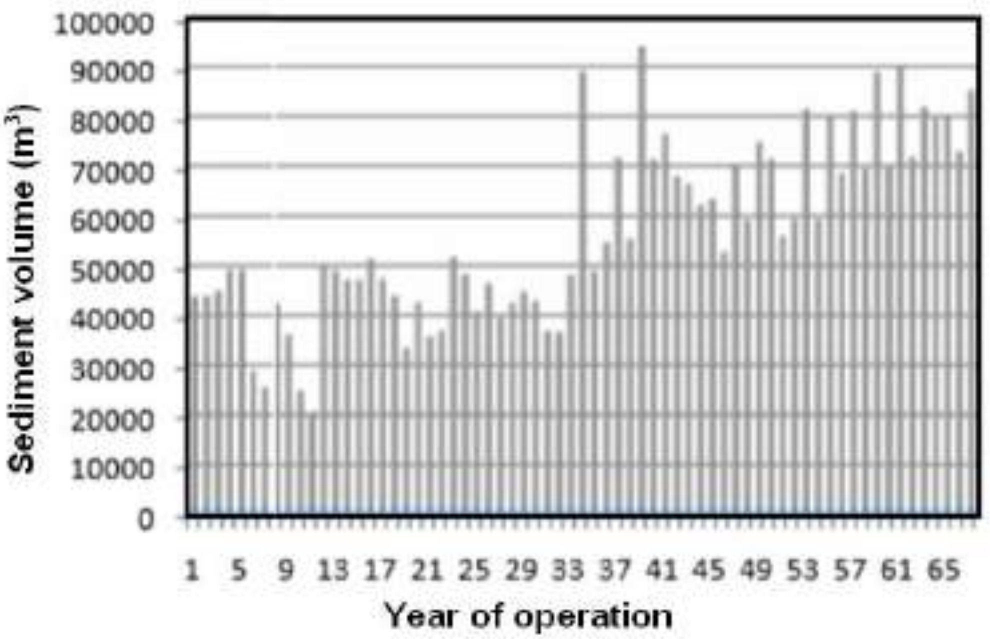

Figure 3. Prediction of sediment volume from 1st to 65th year of Batujai Dam operation (Courtesy of Wakidi, 2016)

More encouraging results for dam's authorities may be presented by Supardi (2018). The results of echo-sounding measurement carried out in 1982, 2005, 2012 and 2017 were compared. The area of echo-sounding measurement was divided into sections for more accurate results in the calculation of sediment volume. There are considerable changes in the storage capacity of Batujai Dam suggesting that the sedimentation process took place in the impounding area (Figure 4).

Figure 4 shows that the storage capacity decreased from 24,824,200 m^3 in 1982 to 18,615,000 m^3 in 2005. The capacity continued to decrease but at a slower rate. In 2012 the storage capacity was predicted equal to 16,669,200 m^3 and decreased further to 15,587,200 m^3 in 2017. It can be summarized that from 1982 to 2017 Batujai Dam has loss a considerable sum of 9,236,900 m^3 or 37.72% of its capacity. Considering the proposed effective storage capacity of 23,502,000 m^3 the remaining effective storage capacity of Batujai Dam is about 66.32%. The analyses of echo-sounding measurement also show an increased in bed level from +79.00 m in year 1982 to the elevation of +82.50 m above sea level in year 2005. In year 2017 the corresponding elevation was +84.00 m above sea level indicating a slight decrease rate from the previous period. On average the bed level of Batujai Dam annually increased 0.143 m due to the deposited sediment.

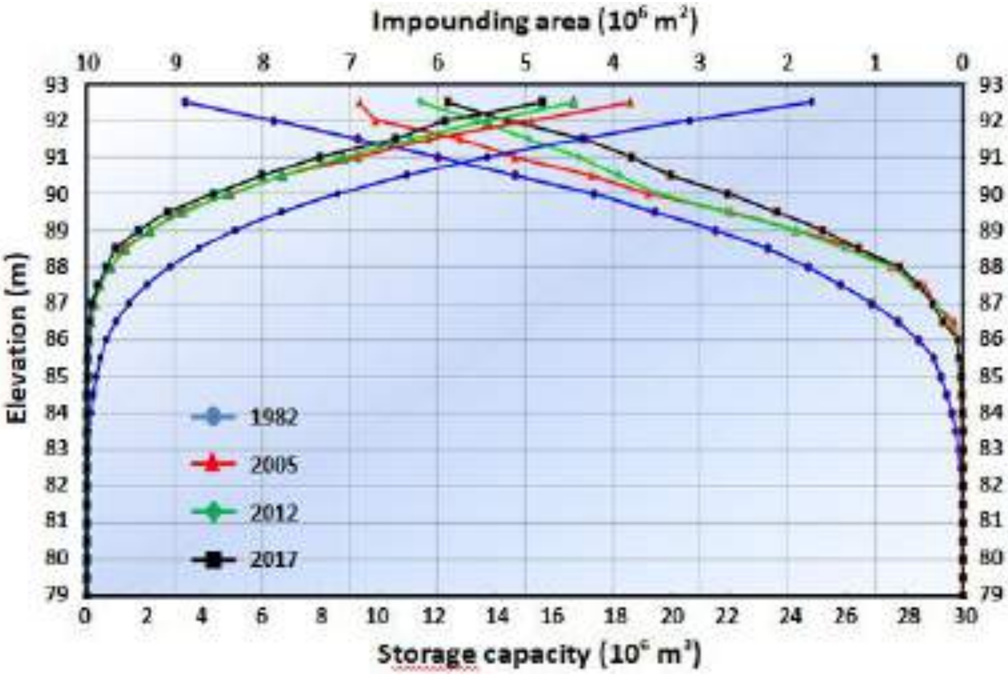

Figure 4. Area and capacity curve for Batujai Dam based on the echo-sounding measurements of 1982, 2005, 2012 and 2017 (Courtesy of Supardi, 2018)

In order to predict the lifetime of Batujai Dam, Supardi (2018) analysed the sedimentation rate based on sediment elevation from 1982 to 2017 and found out that using linear regression the lifetime of the dam would be achieved by 2024 or 42 years after the operation (Figure 5). This means the dam stop its function 8 years earlier than originally proposed.

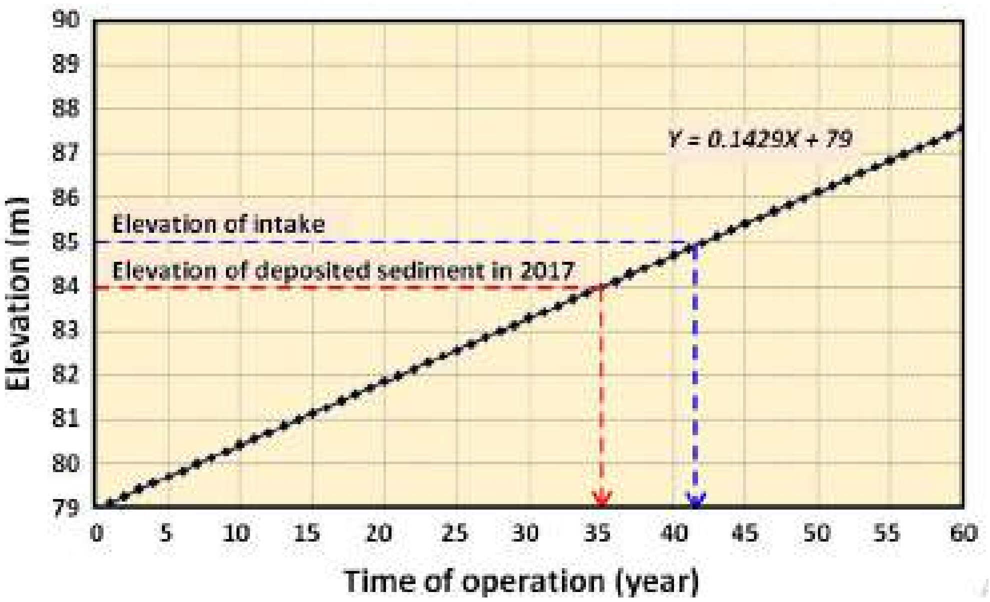

Figure 5. Estimated life time of Batujai Dam based on the sediment deposition rate (Courtesy of Supardi, 2018)

All results suggest noticeable differences in the sediment rate as well as the prediction of deposited sediment in the impounding area of Batujai Dam. This leads to the difficulty in quantifying the quantity of actual annual storage loss in the dam due the sedimentation. For the dam's owner, this situation can be confusing as no basis for undertaking mitigation measures at the reservoir as well as conservation measures in the catchment area. Thus, a systematic capacity surveys should be conducted periodically and systematically to allow a better interpretative capability of researchers in the prediction of Batujai Dam's lifetime.

CONCLUSION AND RECOMMENDATION

This paper has sought to overview the methods and the results of the past researches on sedimentation of Batujai Dam. Information on the limitations found in the approaches of both field observation and calculation has also been presented. From the discussion some important points can be drawn as follows:

1. The prediction results that Batujai Dam has a shorter lifetime is commonly shared by all researchers, but there is a big difference in sedimentation rate in which one researcher is found to have a relatively extreme assumption than others. This reflects the complexity in predicting sedimentation behavior related to the performance of Batujai Dam.
2. The method in predicting the sedimentation rate of Batujai Dam can be in the form of a very simple technique and solely based on the nature phenomenon, the others found difficulty when human intervention such as dredging works in the dam should be taken into account.
3. In order to allow sedimentation preventing activities, measurement of suspended sediment concentration as well as bedload are necessary. This method allows the identification of the main contributor of sediment especially when the rivers flowing into the dam are more than one.
4. Despite a negative approach, echo-sounding measurement is still very useful in the investigation of dam sedimentation where the rate of deposited sediment can be obtained. In this case the interval years between measurements should be as close as possible.

Sediment management practices in the dam tend to treat the symptom of a problem rather than its cause. This leads to the costly and time-consuming activities. Thus, the following points are to be recommended:

1. More sustainable approach in dealing with sediment supply is necessary although this idea may not be easy to carry out particularly for the dam with more than one river flowing into it.
2. The removal works of deposited sediment through the dredging activities should be planned and not be randomly carried out.
3. The measurement point within the impounding area should not be selected based on the researcher's convenience to allow a fair and accurate comparison between measurements.

4. The most important aspect is to design an effective sediment control measures aimed at reduction of sediment yield from the catchment area.

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REFERENCES

Akai, T.J., 1994. *Applied Numerical Method for Engineers*, John Wiley & Sons, New York.

Bassoni, D.L., 2008. Sediment Management Strategies for Sustainable Reservoir, *Proceeding the Inernational Symposium on Dam for A Changing World*, 80th Annual Meeting and 24th Conress of ICOLD, Kyoto.

Gao, Y., Xie, Y., and Zou, D., 2017. Using ANNs to analyse effects of the Three Gorges Dam on Sedimentation in Dongting Lake, China. *Hydrological Sciences Journal*, Vol. 62(10): 1583-1590, DOI:10.1080/02626667.2017.1338833.

Gellis, A.C., Webb, R.M.T., McIntyre, S.C., and Wolfe, W.J., 2006. Land-use effects on erosion, sediment yields, and reservoir sedimentation: A case study in the Lago Lozia Basin, Puerto Rico. *Physical Geography*, Vol. 27(1): 39-69.

Goel, M.K., Jain, S.K., and Agarwal, P.K., 2002. Assessment of sediment deposition rate in Bargi Reservoir using digital image processing. *Hydrological Sciences Journal*, Vol. 47: S81-S92, DOI:10.1080/02626660209493024.

Issa, I.E., Al-Ansari, N., and Knutsson, S., 2013. Sedimentation and new operational curves for Mosul Dam, Iraq. *Hydrological Sciences Journal*, Vol. 58(7): 1456-1466, DOI:10.1080/02626667.2013.789138.

Karya Utama Jaya General Consultant, 2005. *Reservoir Measurement Report, Sediment Control Study and the Optimization of the Function of Batujai Dam*, Nusa Tenggara I River Basin Organization (BWS NT I) and Karya Utama Jaya General Consultant (in Bahasa Indonesia).

Kompas Daily Newspaper, 2007. *Seeing Indonesia through Bengawan Solo River*, Saturday Edition, 7 July 2007, pp. 33-38 (in Bahasa Indonesia).

National Standardization Board, 1994. *Suspended Sediment Sampling Method in River by Using Depth Integration Method Based on the Discharge Division*, SNI 03-3414-1994, Ministry of Public Works (in Bahasa Indonesia).

Saadi, Y., 1993. Observation of Accumulated Sediment in Two Dams within Catchment Area (Observation to Batujai and Pengga Dams), *Undergraduate Thesis*, Department of Civil Engineering, University of Mataram (in Bahasa Indonesia, unpublished).

Saadi, Y., 2007. Sediment Flow Rating Curve for Estimating Reservoir Sedimentation (Case Study of Three Rivers in Batujai Dam), *Proceeding of National Seminar on Sustainable Infrastructure Development*, Department of Civil Engineering, Graduate School, University of Udayana, Denpasar, pp. 56-70 (in Bahasa Indonesia).

Saadi, Y., 2013. Post Construction problems of Embung in Lombok Island and the operation and maintenance works. *Procedia Engineering*, 54: 648-660, Elsevier Ltd., DOI: 10.1016 /j.proeng.2013.03.059.

Schleiss, A.J., Franca, M.J., Juez, C., and Cesare, G.D., 2016. Reservoir sedimentation. *J. Hydraulic Research*, DOI:10.1080/00221686.2016. 1225320

Strand, R.I., and Pemberton, E.L., 1982. *Reservoir Sedimentation, Technical Guideline for Bureau of Reclamation*, Sedimentation and River Hydraulics Section, Hydrology Branch, Denver, Colorado.

Supardi, 2018. Study of Sediment Rate, Location Distribution and Lifetime of Batujai Dam in Central Lombok Regency, *Master Thesis*, Department of Civil Engineering, Graduate School, University of Mataram (in Bahasa Indonesia, unpublished).

Van Rijn, L.C., 2006. *Manual Sediment Transport Measurements, Report S304*, Delft Hydraulics, The Netherland.

Wakidi, 2016. Effect of Climate Change on the Remining Lifetime of Batujai Dam, *Master Thesis*, Department of Civil Engineering, Graduate School, University of Mataram, in Bahasa Indonesia (in Bahasa Indonesia, unpublished).