PREDICTION OF RESERVOIR'S LIFETIME BASED ON THE EROSION AND SEDIMENTATION ON SENGGURUH AND SUTAMI RESERVOIRS, INDONESIA

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The lifetime of Sengguruh and Sutami reservoirs have been evaluated based on erosion and sedimentation rate calculated using combination USLE (Universal Soil Loss Equation) method with distributed model in GIS. The sedimentation calculated by distributed model shows a good approximation comparing with the echo-sounding data. Results show that annual sedimentation in the Sengguruh reservoir is predicted around 2,148,000 ton, while Sutami reservoir is around 1,707,600 ton. Comparing with the echo-sounding data from those reservoirs, the error percentages in volume of sedimentation are 9.5% and 13.6% respectively. Their effective storages are predicted full of sediment in 2.78 years and 147.6 years. Finally, the verification indicated that the proposed method is well applicable to predict the erosion-sedimentation and to evaluate the reservoir lifetime in this basin.

Key Words : *reservoir's lifetime, erosion, sedimentation, USLE, distributed model, GIS*

1. INTRODUCTION

The sedimentation is representing a problem in development or operation of reservoir and its way to overcome is not easy to do. To overcome it costs much money, time and needs the sustainable controlling during the reservoir still in function[1)]. Sedimentation rate determines the reservoir's lifetime. Sengguruh reservoir serves as sediment controller for Sutami reservoir. This reservoir directly decreases sedimentation rate in the Sutami reservoir. The effective storage volume of Sengguruh reservoir is around 2.5 million m^3 and the gross storage volume is 21.5 million m^3 [2)]. However, the capacity of Sengguruh reservoir is not enough to trap the sediment. Nippon Koei investigated in 1994 and forecasted in case of no countermeasures, the Sengguruh reservoir will be silted up within 4 years[3)]. Recently the effective storage of Sengguruh reservoir has declined much and it will influence the sedimentation rate in Sutami reservoir at future.

Unfortunately, there are no studies to estimate the erosion and sedimentation of these reservoir basins. The previous experimental research of the erosion was done by BRLKT (Land Rehabilitation and Soil Conservation Agency), but the results are limited for use planning and no comprehensive conclusion has been found[3)]. In order to predict the erosion-sedimentation rate and to evaluate the reservoir's lifetime, this study is carried out. The watershed erosion-sedimentation is calculated using USLE method combined with the distributed model. The USLE method is verified using echo-sounding data in the reservoirs. The reservoir's lifetime and distribution of sedimentation in the reservoir are evaluated using the Area-Reduction Method considering its sedimentation rate.

The area of the study is the upper-part of the Brantas river basin, East Java of Indonesia. The total catchment area is about 1920 km^2. The area is divided into 5 sub-basins based on the main tributaries (Sumber Brantas, Amprong, Bango, Lesti and Metro). The observation of suspended load and bedload are carried out at Pendem(A), Gadang(B), and Tawangrejeni(C). The detail basin map and observed points are as shown in **Fig.1**.

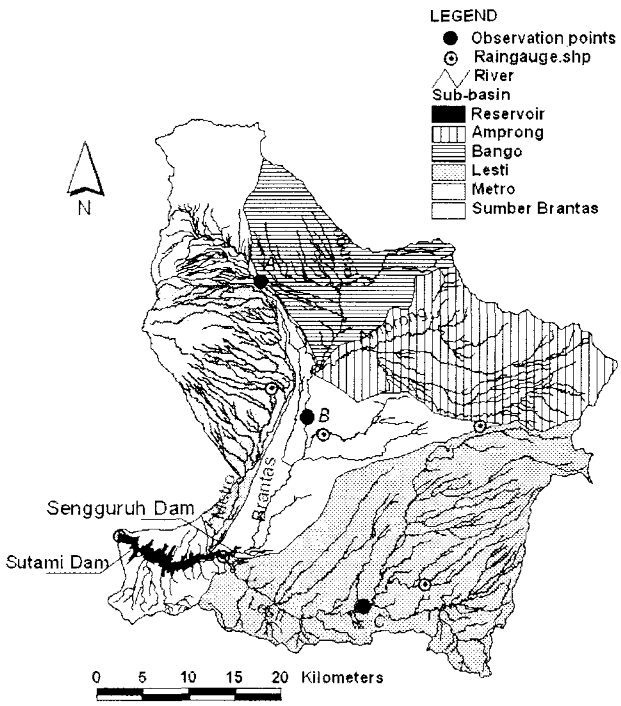

Fig.1 Map of the upper-part of Brantas river basin and the observation points (A,B,C)

The Sengguruh Dam is located just below the confluence between Brantas river and Lesti river. The dam has a height of 33 meters and a crest length of 378 meters. The highest water level (HWL) is at elevation of +292.5 m, while the lowest water level (LWL) is +291.4 m above mean sea level. After joining the Lesti river on left bank and the Metro river on the right bank, the Brantas river reaches the Sutami reservoir. It is an important reservoir in the upper part of the Brantas river basin. Initially, it had an effective storage of 253 million cubic-meters, which is used for various purposes in the basin, mainly for irrigation (34,000 ha), power generation (35 MW) and flood control. The Sutami dam has a height of 100 meters and a crest length of 750 meters. The highest water level (HWL) is at elevation of +272.5 m, while the lowest water level (LWL) is +246 m above mean sea level [4].

The climate of this area is dominated by tropical monsoons with rainy season of about 6 month length, from November to April, and the dry season prevails from May to October. The average annual rainfall over the basin is around 2,000 mm of which more than 80% of it occurs in the rainy season.

Surface geological structure in upper-part of the Brantas river basin can be described as young volcanic rocks, predominantly permeable tuffs and fined grain. The land use of the upper-part of the Brantas river basin is open cultivated area with loose soil that in the rain season it is easy to flow down with runoff water.

In section **2**, we introduce the available data and method to estimate the erosion-sedimentation and to evaluate the reservoir's lifetime. Results and discussion are presented in section **3** and conclusion is in section **4**.

2. DATA AND CALCULATION METHOD

(1) Available data

The basic maps, discharge inflow, and precipitation data at 6 stations of 10 years-observation (1992-2002) are used. The land use map was obtained from BRLKT for 1997 survey. The additional field surveys have been conducted to verify the land use changes. Data of suspended and bedload sediment (2002-2003) at observation points and latest echo-sounding data of the reservoirs are used for verification.

(2) Erosion

The most widely used method for predicting soil loss from overland area, the Universal Soil Loss Equation (USLE) is used to predict average-annual soil loss from sheet, rill and interrill erosion. All of parameters in USLE equations are determined by spatially distributed model using GIS. The general form of the USLE is expressed as follows[5]:

$$A = R\,K\,L\,S\,C\,P \qquad (1)$$

where

A is the average-annual soil loss (ton ha^{-1} yr^{-1})

R is the rainfall erosivity factor (ton ha^{-1}) (cm hr^{-1}). Rainfall erosivity factor is calculated from annual rainfall using the following equations:

$$R = \sum_{1}^{n} \frac{EI_{30}}{100x} \qquad (2)$$

where R = Erosivity factor , n = number of annual rainy days, x = number of years or rain season for base of calculation.

The EI_{30} was calculated from :

$$EI_{30}=6.119(RAIN)^{1.21}(DAYS)^{-0.47}(MAXP)^{0.53} \qquad (3)$$

$RAIN$= annual averaged rainfall (cm), $DAYS$= annual averaged rainy days (day), and $MAXP$= monthly averaged maximum rainfall for 24 hours duration in one year (cm).

K is the soil erodibility factor (ton ha^{-1} yr^{-1} per unit R). Some local researcher has determined K-value for typical soils in Java Island. The suggested value is around 0.10-0.30.

S is slope-steepness factor in %, L is the slope length (m). LS factor computed using Morgan formula[10]:

$$LS = \sqrt{\frac{L}{100}}\left[0.136 + 0.0975S + 0.0139S^2\right] \quad (4)$$

Based on local researcher, Utomo *et al* [5], *CP* value for East Java could be simply determined based on vegetation cover. This value is around 0.001 (undisturbed forest) and 1.0 (bare land).

To predict the sedimentation at the outlet of basin, Sediment Delivery Ratio (*SDR*) has been applied.

$$SDR = \frac{S(1-\alpha A^n) + \alpha A^\beta}{2(S+50n)} \quad (5)$$

where *SDR*=Sediment Delivery Ratio, *A*=Basin Area, *S*=Average of steepness, *n*=Manning roughness, α=0.868 , β= –0.202.

(3) Sedimentation at observation points

In order to evaluate the reservoir's lifetime, the calculation of total load (suspended load and bedload) is needed. The selection of the empirical equations is based on the comparison with the results from distributed model at observation points.

Combination of the Van Rijn, USBR, MPM and Einstein equations are used. All of the parameters are determined from the observed data.

Van Rijn formulas calculate both of suspended and bedload as follows[6]:

$$\frac{S_s}{Uh} = 0.012\left[\frac{U-U_c}{[gD_{50}(s-1)]^{0.5}}\right]^{2.4}\left(\frac{D_{50}}{h}\right)(D_*)^{-0.6} \quad (6)$$

$$\frac{S_b}{Uh} = 0.005\left[\frac{U-U_*}{[gD_{50}(s-1)]^{0.5}}\right]^{2.5}\left(\frac{D_{50}}{h}\right)^{1.2} \quad (7)$$

$$D_* = D_{50}\left[\left\langle\frac{\rho_s-\rho}{\rho}\right\rangle\frac{g}{\upsilon}\right]^{1/3} \quad (8)$$

The critical mean velocity can be computed by:

$$U_c = 0.19(D_{50})^{0.1} log\left(\frac{12R_b}{3D_{90}}\right),\quad 0.1 \le D_{50} \le 0.5\,mm \quad (9)$$

$$U_c = 8.5(D_{50})^{0.6} log\left(\frac{12R_b}{3D_{90}}\right),\quad 0.5 \le D_{50} \le 2.0\,mm \quad (10)$$

which S_b= bedload transport per unit width and time (m^2/s), S_s= suspended load transport per unit width and time (m^2/s), R_b= hydraulic radius (m), U= mean flow velocity (m/s).

USBR formula is only used to determine suspended load as follows[6]:

$$Q_s = a\,Q_w^{\,b} \quad (11)$$

which Q_s=sediment discharge, Q_w=water discharge and *a, b* are regression coefficients derived from observed data.

Other formulas for calculating bedload are used as follow[7]:

Meyer Peter – Müller :

$$S_b = 8\langle\theta-\theta_c\rangle\rangle^{1.5} D[gD(s-1)]^{0.5} \quad (12)$$

$$\theta = \frac{u_*^2}{gD(s-1)} \qquad s = \frac{\rho_s}{\rho} \qquad D \cong D_{50} \quad (13)$$

Einstein (1942):

$$0.465\frac{S_b}{\omega D} = exp\left\langle\frac{-0.391}{\theta}\right\rangle \quad (14)$$

which D=D_{35} and ω= fall velocity

$$\omega = [gD(s-1)]^{0.5}F \quad (15)$$

$$F = \left[\frac{2}{3} + \frac{36\upsilon^2}{gD^3(s-1)}\right]^{0.5} - \left[\frac{36\upsilon^2}{gD^3(s-1)}\right]^{0.5} \quad (16)$$

(4) Reservoir's lifetime

The data of echo-sounding in the reservoirs from 2002 and 2003[8),9)] are used to verify the USLE calculation of sediment deposited in the reservoirs. To predict reservoir's lifetime and distribution of sedimentation in reservoir, the empirical Area-Reduction Method developed by Borland and Miller (1960) revised by Lara (1962) is used[7]. The reservoir's lifetime is evaluated based on the area and capacity curves from 2003 observation and empirical sedimentation rate selected. The major steps of this study are as **Fig.2**.

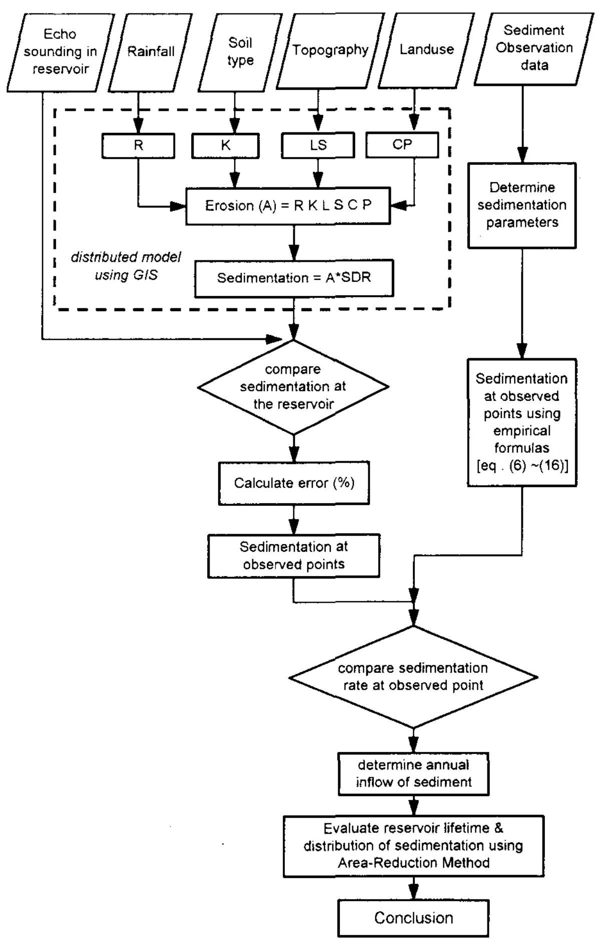

Fig.2 Major steps of calculation

3. RESULTS AND DISCUSSION

The results of calculation by using USLE of erosion in upper part of the Brantas river is shown in **Fig.3**.

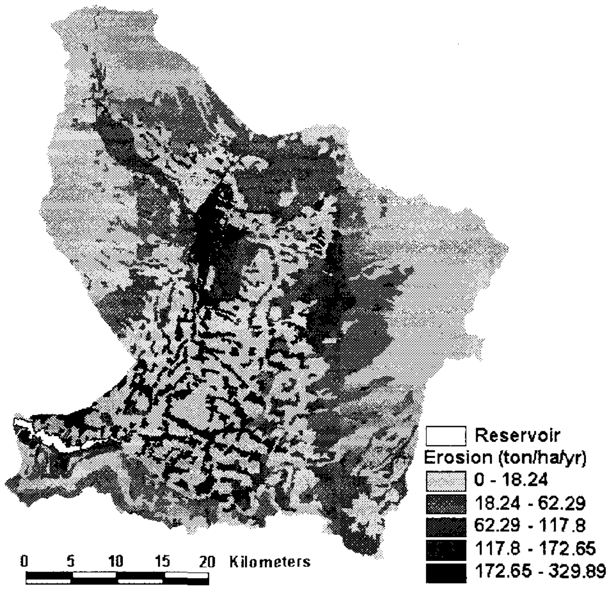

Fig.3 Estimated potential erosion using USLE method

It shows that higher potential of erosion comes from almost all sub-basins. The highest potential erosion is at the Sumber Brantas sub-basin. Comparing with field survey, it is probably due to extensively changes of land use in this area for homestead and also due to deforestation. Other critical area comes from the Lesti sub-basin. The field survey shows that many areas become to be bareland due to deforestation.

Based on criteria from BRLKT, the hazard of erosion map is derived from relationship between the soil solum depth and the rate of erosion (A). It is as shown in **Fig.4**.

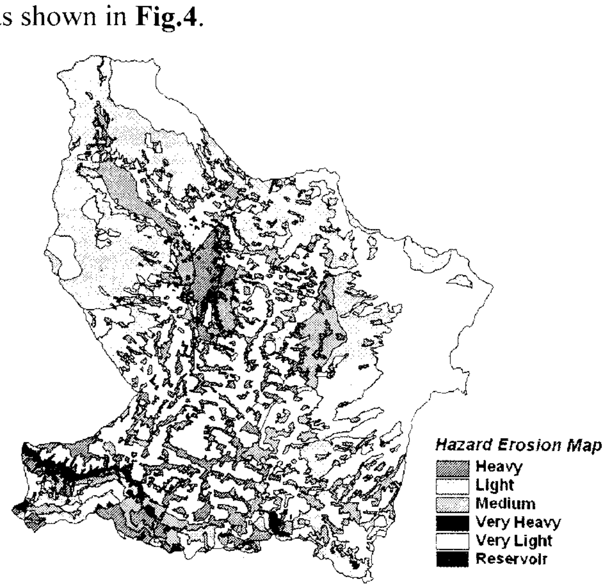

Fig.4 Hazard potential of erosion of reservoir basins

The amount of sediment deposited at the outlet is calculated by multiplying erosion (A) with Sediment Delivery Ratio (SDR), the results as in **Fig.5**.

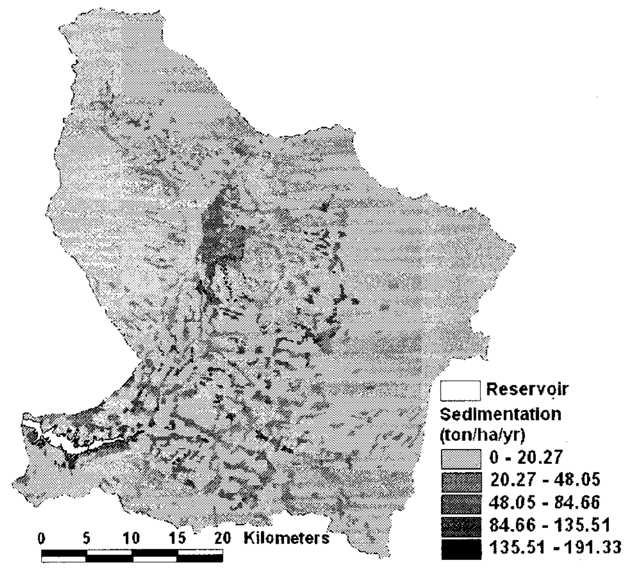

Fig.5 Sedimentation using USLE method

Finally, the summarized result of the erosion and sedimentation in the upper-part of the Brantas river basin is shown in **Table 1**.

Table 1 Predicted erosion and sedimentation in the upper-part of the Brantas river basin using USLE method combined with distributed model

Sub-basin	Area (ha)	Erosion (ton/yr)	Sedimentation (ton/yr)
Sumber Brantas *	50,000	3,180,000	897,000
Amprong *	33,000	948,000	256,000
Bango *	23,000	1,375,000	254,000
Lesti *	61,000	2,800,000	741,000
Metro	25,000	698,000	204,000

* means the sub-basin into Sengguruh reservoir

The sediment deposited in Sengguruh reservoir is contributed from Sumber Brantas, Amprong, Bango and Lesti sub-basins which are marked (*) in **Table 1**. Total sedimentation in Sengguruh reservoir is about 2,148,000 ton/yr. According to the Nippon Koei, the trap efficiency of Sengguruh reservoir is assumed 30% and 70% of sediment is released to Sutami reservoir[2)].

The sediment deposited in Sutami reservoir is also contributed from Metro basin. The total sedimentation in Sutami reservoir is about 1,707,600 ton/yr. It consists of released sediment from Sengguruh reservoir (1,503,600 ton/yr) and Metro basin contribution (204,000 ton/yr).

The echo-sounding survey[8,9)] shows that the average of annual sedimentation of these reservoirs are almost 2,371,413 ton/yr in Sengguruh reservoir and 1,503,382 ton/yr in Sutami reservoir.

Therefore, the percentages of error of sedimentation calculated by the USLE method comparing to the echo-sounding data is calculated as follows:

$$\left|\frac{2{,}148{,}000 - 2{,}371{,}413}{2{,}371{,}413}\right| \times 100\% = 9.5\% \quad \text{(Sengguruh)}$$

$$\left|\frac{1{,}707{,}600 - 1{,}503{,}382}{1{,}503{,}382}\right| \times 100\% = 13.6\% \quad \text{(Sutami)}$$

The high value of percentages error in Sutami reservoir may be due to the assumption of trap efficiency using 1994 observation[2)]. However the recent study about their trap efficiencies is not available yet.

By using with USLE result, which is showing reasonable fit to the echo sounding data, the most suitable empirical equations for sedimentation rate in the basin is chosen. The total load (suspended load and bedload) is calculated by the MPM-USBR, Van Rijn, and Einstein-USBR equations. MPM-USBR means that MPM formula is used to calculate bedload and USBR method is used to calculate suspended load while Einstein-USBR means that Einstein formula is used to calculate bedload and USBR method is used to calculate suspended load. The comparison results of sedimentation at observed points (A, B, C in **Fig.1**) are shown in **Table 2**.

Table 2 Comparison results of sediment deposited at observed points in ton/yr

Point	Location	USLE+ distributed model	Observed data using		
			MPM-USBR	Van Rijn	Einstein-USBR
A	Pendem	78,400	82,800	688,600	287,200
B	Gadang	551,700	472,000	153,000	471,900
C	Tawangrejeni	268,500	116,500	1,405,200	107,900

From **Table 2**, the MPM-USBR gives nearly same results as USLE method for each location rather than others. It is probably due to their parameters are better approximated by the observed data, than others equations. The schematic of the erosion-sedimentation budget is drawn as in **Fig.6**.

Based on the sedimentation rate result from the MPM-USBR and the echo-sounding data of reservoir surface area and capacity at 2003, the sediment distribution in those reservoirs is calculated using Area-Reduction Method. This method recognizes that sediment distribution in a reservoir depends on the manner of reservoir operation, texture and size of deposited sediment particles, shape of reservoir and volume sediment deposited in the reservoir. The results are as shown in **Fig.7** and **Fig.8**.

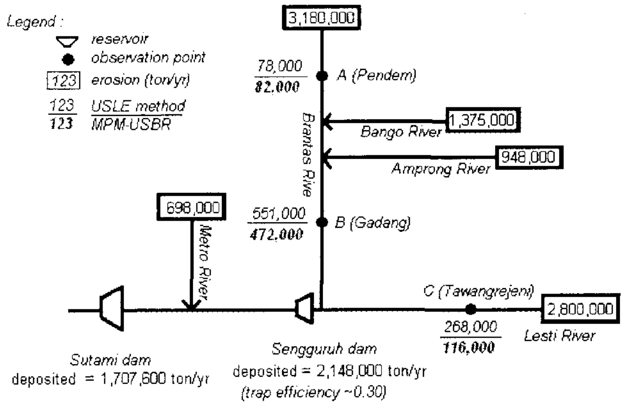

Fig.6 Estimated erosion – sedimentation budget in upper-part of the Brantas basin

Fig.7 shows that after 2.78 years from 2003, the effective storage of Sengguruh reservoir (el. +291.4 m) will be filled full of sediment.

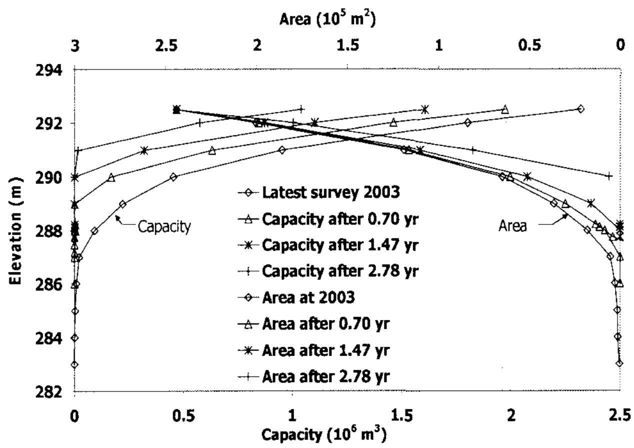

Fig.7 Area and capacity curves for Sengguruh reservoir calculated by Area-Reduction Method

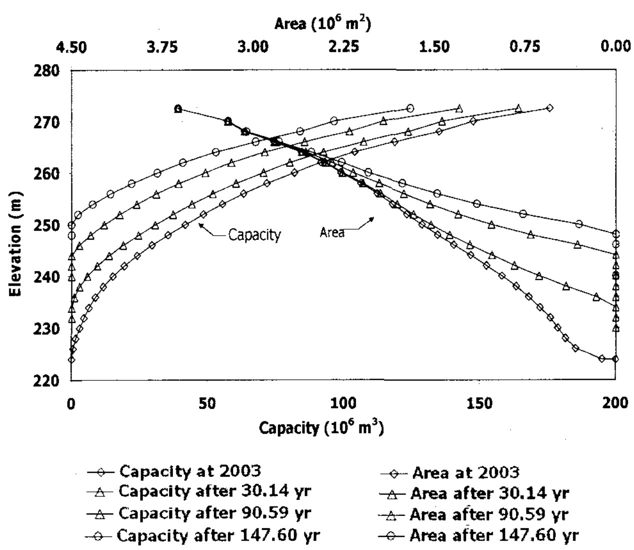

Fig.8 Area and capacity curves for Sutami reservoir calculated by Area-Reduction Method

Fig.8 shows that the effective storage in Sutami reservoir (el. +246 m) takes 147.6 years from 2003 to be filled full of sediment.

It means that the lifetime of these reservoirs is predicted 2.78 years and 147.6 years for Sengguruh and Sutami reservoir in case of no countermeasures, because when these elevations are reached, it is no meaning to operate these reservoirs.

The Sengguruh reservoir is single purpose facility. Decrease of the effective storage of the Sengguruh reservoir is only causing decrease of the operation hours of peak power generation. However, in case of silting up of the Sengguruh reservoir, sediment discharge from upstream basin will flow directly into the Sutami reservoir and be deposited herein. Therefore, if no sand trapping effect of Sengguruh reservoir, the effective storage volume of Sutami reservoir will dramatically decrease in future.

The Sutami Dam is multi purposed dam and the only one facility on the mainstream of the Brantas River, to enhance water in dry season and to control flood discharge in rainy season. Therefore the sedimentation is the most serious problem for the water use in the Brantas River.

From field survey, another problem in Sengguruh reservoir is coming from a thickly growing of Enceng Gondok (Water Hyacinth), due to eutrophication of water in Sengguruh reservoir.

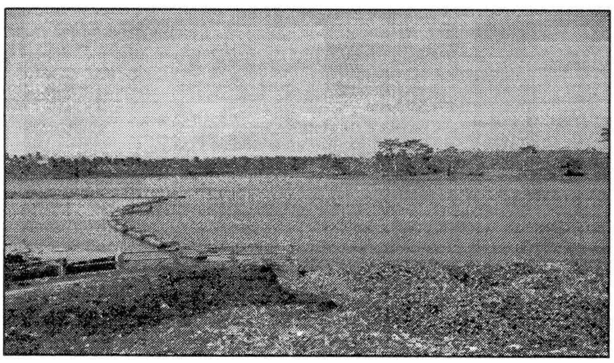

Fig.9 Enceng Gondok (water hyacinth) in the Sengguruh reservoir

In general, there are some efforts to control sediment in the reservoir, such as reforestation and civil works in the area of sediment yields. Considering the existing storage capacity of the Sengguruh dam and requirement of quick response, it is recommended to continue to remove the deposited sediment every year in rainy season by mechanical dredging. For the Sutami reservoir, a nowadays countermeasure such as mechanical dredging is also recommended to be continued.

From previous studies[2)3)], it was mentioned that material deposited in both of reservoirs was almost same. They consist of fine sand. However, the major sources is not clearly stated came from fly-ash of Mt. Semeru eruption or debris flow. For further research, the qualitatively analysis of sedimentation sources based on physical characteristic of sediment deposited in both reservoirs is needed to carry out.

4. CONCLUSION

The erosion and sedimentation rate in the upper-part of Brantas basin is higher now. It is the most serious problem of the water use in the Brantas River, while Sutami reservoir is the only facility of mainstream of the Brantas River.

In this research, the annual sedimentation in the Sengguruh reservoir is predicted around 2,148,000 ton/yr and Sutami reservoir is around 1,707,600 ton/yr. The percentages errors are 9.5% and 13.6% for Sengguruh and Sutami reservoir. It is indicated that USLE method and MPM-USBR are applicable to this basin. Their lifetimes are predicted as 2.78 years and 147.6 years respectively, in case of no countermeasures. Finally, the erosion prevention in this basin is not only in the techniques aspects but also must consider to the social aspects.

ACKNOWLEDGMENT: The authors express their deep thanks to Jasa Tirta I and other authorities for providing useful data. This work has been supported by CREST of JST (Japan Science and Technology Agency).

REFERENCES

1) Varshney, R.S.: Engineering Hydrology, Roorke, India, 1979.
2) KOEI, NIPPON LTD.: The Study on Comprehensive Management Plan for The Water Resources of Brantas River Basin in The Republic of Indonesia, Main Report, 1998
3) KOEI, NIPPON LTD.: The Study on Comprehensive Management Plan for The Water Resources of Brantas River Basin in The Republic of Indonesia, Supporting Report, 1998.
4) NARBO.: Digest of The Location of Site Visit February 26, 2004 (leaflet), Jasa Tirta I, Indonesia, 2004.
5) Utomo, Wani Hadi.: Erosi dan Konservasi Tanah (in Indonesian). Communications Soil Science UNIBRAW No. 23, Brawijaya University- Indonesia, 1987.
6) Pilarczyk, K.W.: River Training Techniques, Fundamentals, Design and Applications, A.A.Balkema, Rotterdam, 1995.
7) Yang, CT.: Sediment Transport, Chapter 8, Reservoir Sedimentation, McGraw-Hill, Singapore, pp. 267-314, 1996.
8) Jasa Tirta.: Laporan Pengukuran Echo Sounding Waduk Sengguruh (in Indonesian), 2002.
9) Jasa Tirta.: Laporan Pengukuran Echo Sounding Waduk Sengguruh (in Indonesian), 2003.

(Received September 30, 2004)