Useful Life of Ngancar Reservoir Due to Erosion and Sedimentation

P.T. Juwono, R. Asmaranto, A. Murdhianti

Abstract*: Ngancar Dam is located in Ngancar Village, Batuwarno Sub district, Wonogiri Regency Central Java Province. This dam was built in 1944-1946 and is classified as an old dam in Indonesia which has a function to meet the needs of 1300 ha of irrigation water. Ngancar Dam is a type of rock fill dam with a soil core, has a height of 19.40 m above the riverbed and 25.40 m above quarry. The length of the dam peak is 181.00 m and the width is 5.00 m while the reservoir volume at the normal water conditions is 1.64 million m^3. Because the Ngancar Dam has been operating for a long time then required the evaluation on the service age of the reservoir due to sedimentation so that it effects on the operating pattern and safety of the dam. Based on the results of hydrological analysis and reservoir bathymetry analysis obtained the information that the reservoir sedimentation rate equal to 4,266.08 m^3/year or 11.9 m^3/day and this requires mechanical and non-mechanical handling efforts to reduce the sedimentation rate.

Keywords*: Ngancar Dam, erosion rate, sedimentation, sediment delivery ratio.

I. INTRODUCTION

Ngancar reservoir is located in Wonogiri, Central Java, built in the colonial era around 1944 – 1946 [1]. Dam type is rock fill with soil core, the Ngancar dam also experiences erosion and sedimentation problems in the reservoir as well as other dams. Besides being caused by volcanic ash from volcanic eruptions, the main cause of reservoir sedimentation is due to human activities themselves. In many parts of the world, human behavior on nature has led many reservoirs lose the technical and economic functions of its storage in a short time [2]. The purpose of this study was to determine the effect of sedimentation on the service age of the Ngancar reservoir as well as sedimentation handling efforts to ensure water availability and food security in Wonogiri Regency.

II. LITERATURE REVIEW

A. Hydrological Analysis

Hydrological analysis of the Ngancar Dam is carried out to determine the impact arising from changes in hydrological parameters at the beginning of the design with the current conditions weather is it still within the safe limits. As for the hydrological analysis activities carried out among others:

a) Analysis of Design Rainfall
   Design rainfall is the largest annual rainfall with certain probabilities that might occur in an area, or rain with a possibility of certain return period [3]

b) Analysis of Design Flood
   Design flood is the amount of discharge that will be statistically equaled or exceeded once in a certain return period [4]

c) Analysis of Flood Routing

Flood routing is a way to determine flood flow modification[5]. Flood routing in reservoirs is needed to determine the maximum outflow discharge and maximum water height above the overflow/spillway threshold at the corresponding outflow discharge as a determination of the flood water level that occurs.

B. Estimation of Potential and Actual Erosion Rate

Potential erosion is the maximum erosion that may occur in a place with a perfectly deforested surface condition, so that the erosion process is only caused by natural factors (without human involvement or ground cover factors, such as plants and so on), namely climate, especially rainfall, internal soil characteristics and topographic soil conditions. Thus, potential erosion can be expressed as a double result among the factors of rainfall, soil erodibility and topography (slope and slope length). Estimation of potential erosion can be calculated using the following formula approach [6] [9]:

$$\mathbf{E\text{-}pot = R \times K \times LS \times A}$$

with :

E-pot = Potential erosion (ton/ha/year)
R = Erosivity indeks
K = Erodibility indeks
LS = Length and slope factor
A = Watershed Area (ha)

$$\mathbf{E\text{-}act = E\text{-}pot \times CP}$$

with :

E-act = Actual erosion in watershed (ton/ha/year)
E-pot = Potential erosion (ton/ha/year)
CP = Crop factor and soil preservation

C. Erosion Hazard Level (TBE)

Based on the calculation of the erosion rate factors above, the following is the calculation of the erosion value and the level of erosion hazard and the sedimentation rate of the Ngancar Reservoir catchment area. Next, determine the level of erosion hazard (TBE) compare the actual erosion (A) with tolerable erosion (T) with the following formula [10].

Revised Manuscript Received on June 30, 2020.
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TBE = A/T

T = (ESD/RL) + LPT x BD x 10

With:

A = Actual erosion (ton/ha/year)

T = Tolerable erosion (ton/ha/year).

ESD = the equivalent depth namely the product of the effective soil depth with the depth factor value (mm)

RL = Service age of the soil (400 year)

LPT = Soil Formation Rate (2 mm)

BD = Bulk Density (gr/cc)

D. Sediment Delivery Ratio (SDR)

Soil that experiences erosion in a watershed will be carried into the river body, which is then known as sediment. Sediments carried into the river are only part of the eroded soil and some will settle at somewhere. The amount of sediment transported into the river against the amount of erosion that occurs in the watershed is called the Sediment Delivery Ratio (SDR) [8]. SDR values that close to 1 (one) mean that all soil particles transported by erosion enter the river as a whole. This can occur in watersheds that have a small area, do not have flat areas but have steep slopes, have a lot of fine grains transported, high drainage density, and in general do not have the nature to precipitate the sediment. From the results of empirical research several SDR equations have been published as follows [6] [7].

D = Y/ T

with:

D = Sediment Delivery Ratio (SDR)

Y = sediment results obtained at the watershed outlet

T = total erosion derived from the catchment area (including gully erosion, sheet erosion and rill erosion) which takes place at the upper part of the outlet.

Various methods of determining SDR can be seen in table 1, but in this study the Boyce method (1975) will be used, where:

SDR = $0.41\ A^{-0.3}$

with:

A = watershed area

Table 1. Several studies which stated the relationship of SDR and watershed characteristics

Research	Study Location	Equation
1.Mutchler and Bowie (1975)	Pigeon Roost Creek, Miss..,USA	SDR = 0.488-0.006 A + 0.010 Q_{wa}
2. Boyce (1975)		SDR = 0.41 $A^{-0.3}$
3. Mou and Meng (1980)	Dali River Basin, Shaanxi China	SDR = 1.29 + 1.37 Ln Rc – 0.025 Ln A
4. Auerswald (1992)	Bavarian Watersheds	SDR = -0.02 + 0.358 $A^{-0.2}$
5. Suripin	Upper Solo	Log SDR = 2,31+3.07 Log Rb + 0.41Log S-1.26 Log (F_L + Fw)

▪ Source: Yupi, 2006.

III. RESULT AND DISCUSSION

A. Rainfall and Flood Design

From the results of the latest contour map analysis and identification of the reservoir catchment boundary equal to 7.2 km^2. Then the calculation result of design flood discharge, obtained the PMF flood discharge 272.18 m^3/sec, details are presented in Table 2. Based on these results it is known that there was an increase in flood discharge with data from 1992 namely a difference of = 83,15 - 45,70 = 37,45 m^3/sec at 100 year Return Period, while in the PMF there was an insignificant difference of 272,18 - 271,83 = 0,35 m^3/sec. The analysis results of the design rainfall and flood using the latest hydrological data recorded at the Ngancar Rain Station in Selopuro Village, Batuwarno Sub district Wonogiri Regency are as follows:

Table 2. Comparison of Design Flood

Tr	R (mm)		Q (m^3/sec)	
	Previous (1992)	*Latest (2019)*	*Previous (1992)*	*Latest (2019)*
100	158.77	120.58	45.70	83.15
1000	200.62	123.90	66.23	85.45
½ PMF	268	196.87	135.92	136.09
PMF	**536**	**393.73**	**271.83**	**272.18**

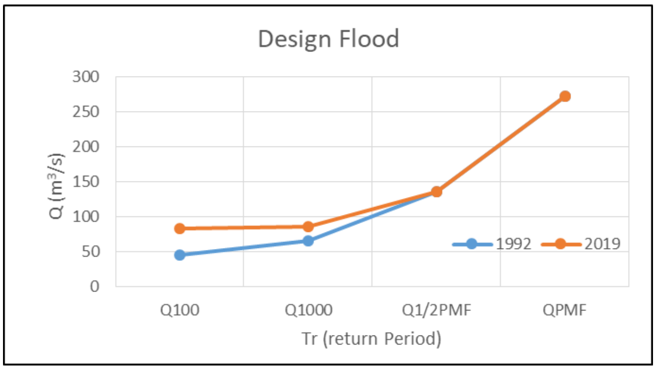
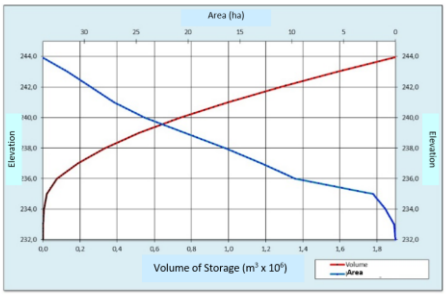


Fig 1. Changes in the design floods in 1992 and 2019

B. Reservoir Capacity

Based on the results of the latest bathymetry measurements, it is known that the reservoir storage volume at the crest spillway elevation is 1.64 x 10^6 m^3 (Table 3). Whereas based on the results of a previous study in 1992 (PT. Indrakarya) the reservoir storage volume was = 2.05 x 10^6 m^3; this shows that there was a reduction in sediment amounted to 0.411 million m^3, in a period of 25 years or occurred sediment deposition equal to 16.44 m^3/year.

The curved graph of the Ngancar Reservoir Capacity from the results of the latest bathymetry measurements are as follows.



Elevation	Area (m^2)	Volume (m^3)
232	-	-
233	1,417	472
234	9,666	5,400
235	21,679	20,674
236	96,682	75,388
237	129,157	187,916
238	164,184	334,237
239	203,133	517,550
240	241,850	739,760
241	271,343	996,215
242	293,673	1,278,649
243	316,083	1,583,458
244	341,965	1,912,397
245	352,958	2,259,843
246	367,226	2,619,911
247	381,702	2,994,351
248	394,467	3,382,418
249	407,363	3,783,315
250	417,681	4,195,826

Fig 2. Reservoir Storage capacity of Ngancar Dam based on the latest measurement results

Table 3 shows the technical data of the dam and some changes in the measurement tie points, including the effect on the elevation and volume of reservoir reservoirs.

Table 3. Comparison of Elevation and storage condition in 1992 and the present if used New BenchMark TTG 1161

	NGANCAR DAM			
	Elevation (m)		Storage Volume	
condition	**Previous (1992)**	**Latest (2019)**	**Previous (1992)**	**Latest (2019)**
Elevation of Crest Spillway	+248.50	+243.20	2.051×10^6 m^3	$1.640 \times 10^6\ m^3$
HWL	+249.5	+243.98	2.87×10^6 m^3	$1.912 \times 10^6\ m^3$
El. of Parapet Peak	No parapet	With parapet + 245.50		
Note : The elevation difference is due to the 2019 Measurement using the benchmark 1161 Global Fixed Point (TTG), which is located in Boto Village, Baturetno Sub district, Wonogiri Regency				

Tabel 4. Flood design vs return periode

Tr	Q (m^3/sec)					
	Previous (1992)			***Latest (2019)***		
	Q_{inflow}	$Q_{outflow}$	***Elev. (m)***	Q_{inflow}	$Q_{outflow}$	***Elev. (m)***
100	45.70	13.64	249.04	83.15	46.98	243.94
1000	66.23	21.62	249.16	85.45	48.48	243.96
½ PMF	135.92	48.16	249.49	136.09	80.98	244.29
PMF	271.83	111.48	250.09	272.18	173.66	245.01

Table 4 explains the relationship between flood discharge and flood return period. Based on the results of flood routing analysis obtained the flood water level elevation above the overflow/spillway is El. +245.01 so that not occurred overtopping because parapet is installed at the peak of the dam with parapet at +245.50 elevation, with the remaining free board is 0.491 m, less than that required for the minimum free board for free spillway (no sluice) namely equal to 0.75 m

C. Land Erosion Analysis

Erosivity (R)

Erosivity is a characteristic of low intensity rain rarely causing erosion, but heavy or short periods of heavy rain can cause large surface runoff and soil loss. According to Utomo (1994) the nature of rainfall that affects erosivity is seen as the kinetic energy of raindrops that hit the soil surface [6]. In this study the rain erosivity index is calculated based on the Bols (1978) equation because it is in accordance with the data in the field [6] [7]:

$$R = \frac{EI_{30}}{100}$$

With:

EI_{30} = $6.12\ (RAIN)^{1.21} \cdot (DAYS)^{-0.47} \cdot (H_{24}Max)^{0.53}$

R = annual average rain erosivity

RAIN = annual averagae rainfall (cm)

DAYS = number of Rainy Days on average per year

H_{24}Max = the maximum average rainfall in 24 hours per month for a period of one year (cm)

From the calculation results obtained an average monthly rain erosivity of = 183.2 with the highest erosivity in 2003 equal to 310.42 and the lowest in 2002 amounted to 90.85.

Erodibility (K)

According to Utomo (1994) the definition of soil erodibility is the ease of soil to be eroded [6]. Erodibility of land is given the symbol *K*. The sensitivity of a soil to erosion or the value of erodibility of a soil is determined by: (1) soil resistance to external damage; (2) the ability of the soil to absorb water (infiltration and percolation). Soil resistance determines whether easy or not the soil mass is destroyed by water (either rainwater or surface runoff), while infiltration and percolation determine the volume of surface runoff to erode and transport the destroyed of soil mass. The more easily the mass of the soil is destroyed, the higher the value of erodibility. The more difficult the soil absorbs water, the greater the surface runoff, the greater the mass of soil that is eroded and transported, so the erodibility *(K)* value is also greater. Determination of *K* value can be obtained by a calculation, (Wischmeier, 1975) connects the physical properties of soil with soil loss using the following equation;

$$K = \frac{2.1 \times 10^{-4} (12 - OM) M^{1.14} + 3.25 (S - 2) + 2.5 (P - 3)}{100}$$

Where:

K = soil erodibility

OM = percent organic element or (organic C x 1.72)

S = soil structure classification code (granular, platy, massive, etc.)

P = soil permeability

M = percentage of particle size (% dust + very fine sand) × (100 - % clay)

Table 5. Erodibility Value of Ngancar Watershed Soil Type

Soil Type	**Erodibility Value (K)**	**Area (ha)**
Grumusol	0.21	167.147
Latosol	0.12	553.061

Source: Analysis Results

Table 5 shows that the Ngancar watershed is dominated by Grumusol soil types with an erodibility value of 0.21 and an area of 167.15 ha, and Latosol soil types with erodibility value of 0.12 with an area of 553.06 ha.

Length and Slope (LS)

Calculating the slope length factor (L) becomes a very complicated problem when applying pixel-based geographic information system (GIS) in erosion calculations using the USLE method. Erosion calculation using USLE method uses slope length data from field observations and it is impossible to calculate the entire slope length for each slope shape in the catchment. In contrast to the slope factor (S) which can be obtained easily from GIS data. According Blanco and Nadaoka (2006) GIS applications require Digital Elevation Model (DEM) data to produce a more specific depiction of LS factors in each pixel. n its development, there are several formulas for determining the value of DEM-based LS factors in GIS which take into account the heterogeneity of the slope and prioritize the direction and accumulation of flow in its [11]. The assumption used is the LS factor value will be different between the upper and lower slopes. LS value will be greater at the place of accumulation of flow occurred than at the upper slope even though it has the same slope length and slope.

The guideline used to calculate LS is Modeling Soil Detachment with USLE 3d using GIS. The results of the analysis of LS calculations using the raster calculator as follows:

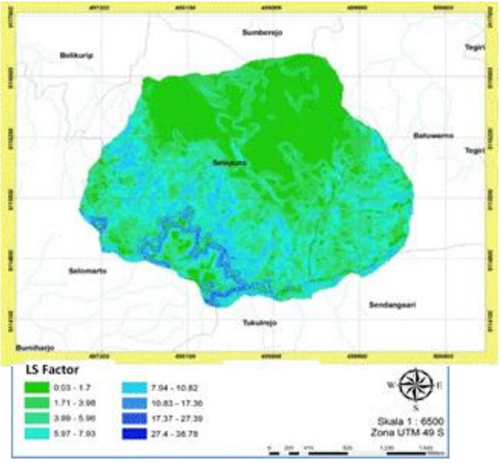


Fig 3. LS values in the Ngancar Reservoir Catchment Area

Cover Crop Factors

The CP value in the catchment area of the Ngancar reservoir is dominated by mixed dry land agricultural crops with a CP value of = 0.43 [6][7].

Land Erosion Rate

Erosion rate (A) calculation is conducted using geoprocessing-overlay vector map techniques namely conducting overlays the erosivity polygons (R), erodibility (K), slope (LS) and plant factors (CP), or A = R.K.LS.CP. The calculation result is the ratio of erosion in tons / ha / year as follows:

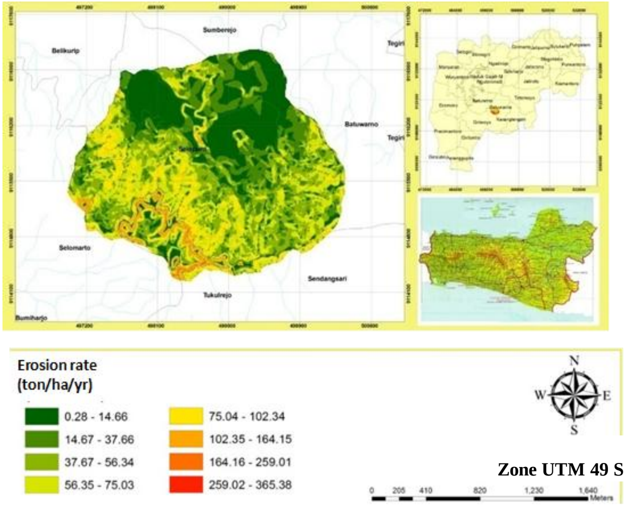


Fig 4. Erosion rate of Ngancar Dam Watershed

The results of erosion analysis in the Ngancar Reservoir Catchment Area indicate that, the level of erosion hazard is dominated by light and moderate categories. This shows that land management in this region is still relatively good, which is characterized by minimal erosion. However, thing that need to be aware is at moderate erosion levels. Land management in this category needs to be treated with caution, especially on rather steep slopes to very steep slopes.

Table 6. Analysis of erosion rate for each slope

slope	Slope class	area	area	Erosion rate		Erosion	Allowable Erosion Value	TBE	Level TBE
		(ha)	*(Km2)*	*(ton/ha/yr)*	*(mm/yr.)*	*(ton/yr)*			
8-15%	B	259.08	2.59	56.79	618.69	14712.54	47.56	1.19	Moderate
8-15%	B	12.87	0.13	56.79	30.73	730.85	47.56	1.19	Moderate
15-25%	C	415.58	4.16	32.91	575.10	13675.83	47.56	0.69	Light
25-40%	D	32.67	0.33	74.70	102.64	2440.74	47.56	1.57	Moderate

Category	Slope Class	area		SDR	Unit Weight	Sediment Rate			Total Sediment
		(ha)	*(km^2)*		*Soil (gr/cc)*	*(ton/ha/year)*	*(m^3/year)*	*(m3/day)*	*(ton/year}*
8-15%	B	259.08	2.59	0.31	2.38	17.50	1906.47	5.22	4533.57
8-15%	B	12.87	0.13	0.76	2.38	43.07	233.09	0.64	554.29
15-25%	C	415.58	4.16	0.27	2.38	8.80	1537.90	4.21	3657.13
25-40%	D	32.67	0.33	0.57	2.38	48.24	588.62	1.61	1399.73

The results of sedimentation analysis in the Ngancar Reservoir Catchment Area show that the estimation of total sediment rate entering the Ngancar Dam inlet is 10,144.73 tons/year or 4,266.08 m^3/year or 11.9 m^3/year.

Based on the results of field and laboratory investigations of sediment samples that have settled in reservoirs, it is known that the composition of sediment material is as follows: Fine sand (18%), Silt (44.56%), and clay (49.44%).

Analysis of reservoir useful life

Above already explained, that the measurement results of reservoir storage volume using elevation of the latest spillway peak with TTG (global fixed point) namely the latest spillway elevation + 243.2 is 1.649 million m^3, while based on the results of previous studies of PT Indra Karya in 1944 on the elevation of the crest spillway with local datum obtained an elevation of crest + 248.7 with the value of reservoir storage volume amounted to 2.258x10^6 m^3 and a study in 1992 with the same datum obtained a storage volume of 2.051x10^6 m^3.

This shows the sedimentation rate or reduction in reservoir volume by 0.402x 10^6 m^3 over a period of 24 years or identical to the sediment rate of 16.75 m^3/year without considering the volume of sediment that has been taken / dredged removed from the reservoir. By taking the reference from the sedimentation rate calculation of the SDR calculation results obtained a total erosion rate of 4,266.08 m^3/year.

So that the useful life/service age of the Ngancar reservoir is the volume of remaining dead storage (at the time of design; 0.5x10^6 m^3 - 0.402x10^6 m^3) = 98.000 m^3 divided 4,266.08 m^3/year = 23 year assuming that all sediments will settle at the dead storage. However, if based on the latest measurement results, it can be seen that the base of the intake gate at +235 elevation and based on the storage capacity is 20,700 m^3, then the remaining dam life is 5 years if the sediment rate amounted to 4,266.08 m^3/year entering all collected in the dead storage. This shows that erosion and sedimentation in the Ngancar Reservoir need to be a concern for stake holders to improve the management of the catchment area considering that the construction of new reservoirs requires a lot of cost. In addition need to be conducted the study on the erosion of river banks and landslides, especially in weathered limestone formations In addition need to be conducted the study on the erosion of river banks and landslides, especially in weathered limestone formations

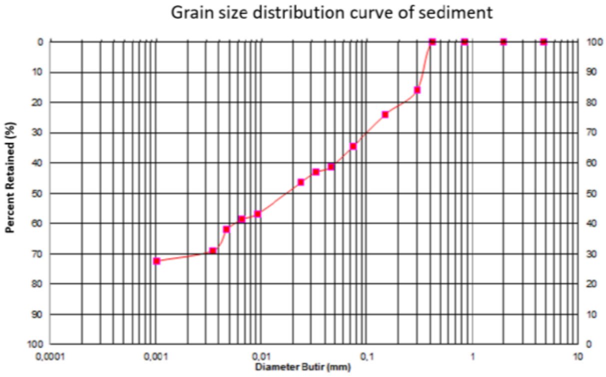


Fig 5. Grain size Distribution Curves of Sediment Samples in the Ngancar Reservoir Intake

Water requirements for irrigation water supply

The existence of Ngancar Reservoir is to supply 1300 ha of irrigation water needs so that a minimum availability of water needed is 1.2 liters/sec/ha x 1300 = 4.32 m^3/s, especially in MT/Planting Season I and MT//Planting Season II. If continuous flooding/inundation is carried out on irrigation fields for 3 consecutive months of the planting season, then needed a water volume of = 1.12 x 10^6 m^3, so that the presence of an effective storage must be maintained above this value by paying attention to sedimentation in the reservoir. Operation pattern of the opening of intake gate is as follows:

Table 7. Recommendations for operating of the intake gate under current storage conditions

Operation of the Opening Gate of the Ngancar Intake

Tpye	Conduit
Dimension (b)	1,5 m
Gate Type	Sorong
Number of Gate	1 Buah
Elevation of bottom	235.00 m
NWL	243.00 m

Rumus:

$$Q = K \mu a b \sqrt{2g h_1}$$

Keterangan:

Q =	Discharge
K =	Factor
μ =	Discharge coefficient
a =	Gate Opening
h =	Water Depth in front of the Gate

Elevation MA	H air (m)	Gate Opening Height (cm)															FULLY OPENED
		0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
		Debit Q (m^3/dt)															
235,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
235,50	0,50	0,00	0,28	0,56	0,85	1,13	1,41	1,69	1,97	2,26	2,54	2,82	3,10	3,38	3,66	3,95	4,23
236,00	1,00	0,00	0,40	0,80	1,20	1,59	1,99	2,39	2,79	3,19	3,59	3,99	4,39	4,78	5,18	5,58	5,98
236,50	1,50	0,00	0,49	0,98	1,46	1,95	2,44	2,93	3,42	3,91	4,39	4,88	5,37	5,86	6,35	6,84	7,32
237,00	2,00	0,00	0,56	1,13	1,69	2,26	2,82	3,38	3,95	4,51	5,07	5,64	6,20	6,77	7,33	7,89	8,46
237,50	2,50	0,00	0,63	1,26	1,89	2,52	3,15	3,78	4,41	5,04	5,67	6,30	6,93	7,56	8,19	8,82	9,45
238,00	3,00	0,00	0,69	1,38	2,07	2,76	3,45	4,14	4,83	5,52	6,21	6,90	7,60	8,29	8,98	9,67	10,36
238,50	3,50	0,00	0,75	1,49	2,24	2,98	3,73	4,47	5,22	5,97	6,71	7,46	8,20	8,95	9,70	10,44	11,19
239,00	4,00	0,00	0,80	1,59	2,39	3,19	3,99	4,78	5,58	6,38	7,18	7,97	8,77	9,57	10,36	11,16	11,96
239,50	4,50	0,00	0,85	1,69	2,54	3,38	4,23	5,07	5,92	6,77	7,61	8,46	9,30	10,15	10,99	11,84	12,68
240,00	5,00	0,00	0,89	1,78	2,67	3,57	4,46	5,35	6,24	7,13	8,02	8,91	9,81	10,70	11,59	12,48	13,37
240,50	5,50	0,00	0,93	1,87	2,80	3,74	4,67	5,61	6,54	7,48	8,41	9,35	10,28	11,22	12,15	13,09	14,02
241,00	6,00	0,00	0,98	1,95	2,93	3,91	4,88	5,86	6,84	7,81	8,79	9,76	10,74	11,72	12,69	13,67	14,65
241,50	6,50	0,00	1,02	2,03	3,05	4,07	5,08	6,10	7,11	8,13	9,15	10,16	11,18	12,20	13,21	14,23	15,25
242,00	7,00	0,00	1,05	2,11	3,16	4,22	5,27	6,33	7,38	8,44	9,49	10,55	11,60	12,66	13,71	14,77	15,82
242,50	7,50	0,00	1,09	2,18	3,28	4,37	5,46	6,55	7,64	8,73	9,83	10,92	12,01	13,10	14,19	15,28	16,38
243,00	8,00	0,00	1,13	2,26	3,38	4,51	5,64	6,77	7,89	9,02	10,15	11,28	12,40	13,53	14,66	15,79	16,91

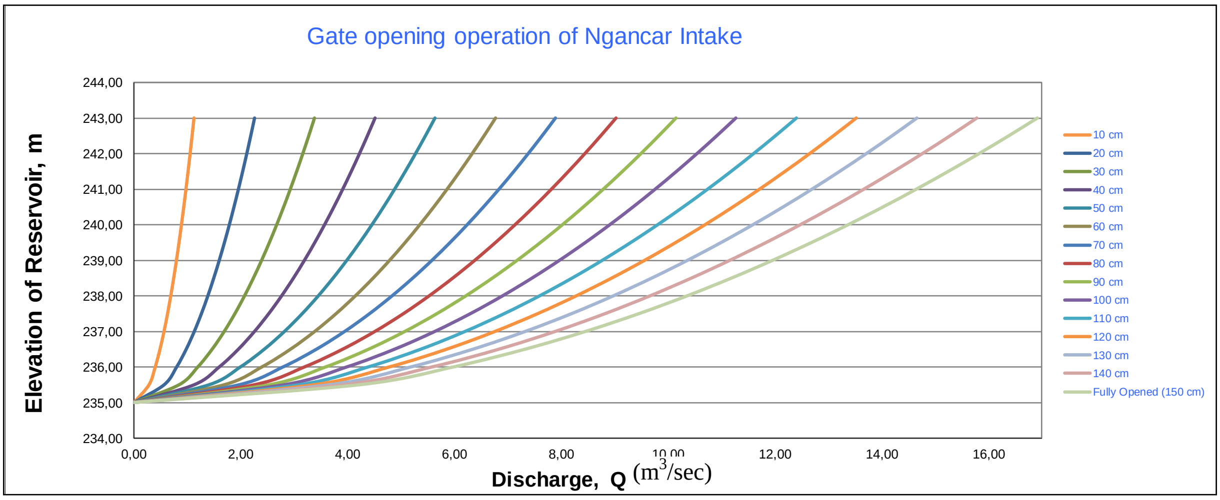


Fig 6. Design of the operating pattern of the intake gate on the Ngancar Dam

IV. CONCLUSION

Based on the results of the hydrological analysis and stability that have been done, the following conclusions are obtained:

a. Characteristics of sediments that settle in the Ngancar Reservoir are dominated by Clay (49.44%), Silt (44.56%) and Fine Sand (18%) with an average Specific Gravity (GS) equal to 2.338. Based on the characteristics of the sediment suspected came from erosion of agricultural land, where some inundation areas around the reservoir are also used dry land farming so that accelerate the rate of erosion,

b. From the calculation of sediment rate using the SDR (sediment delivery ratio) method obtained the amount of sediment is 10,144.73 tons/year or identical with 4,266.08 m^3/year or 11.9 m^3/day. The largest erosion rate occurred in the slope class of 8-15%, namely equal to 5087.86 tons/year. This result proves that on the land slope which is relatively gentle also produce quite large sediments, this is because land allotment for dry plant cultivation dominates. Based on the analysis of the reduction in the reservoir effective storage at the present day and erosion estimation through the SDR method, obtained the useful life of the Ngancar reservoir is around 23 years. However, if based on measurement results that the intake base at +235 elevation with dead storage capacity is 20.700 m^3. Then with a sediment rate of 4,266.08 m^3/year it is assumed that all of entering collected at the dead storage, obtained the remaining age of the dam amounted to 5 years.

c. To ensure food security in the Wonogiri region, specifically water supply for irrigation needs of 1300 ha then needed an effort of water availability in the Ngancar reservoir amounted to1.2 liters/sec/ha so that needed a minimum availability of water amounted to 1.2 liters/sec/ha x 1300 = 4.32 m^3/sec, especially in MT/Planting Season I and MT//Planting Season II. If continuous flooding/inundation is carried out on irrigation fields for 3 consecutive months of the planting season, then needed a water volume of = 1.12 x10^6 m^3, so that the existence of an effective storage must be maintained above this value by paying attention to sedimentation in the reservoir.

ACKNOWLEDGMENTS

Thanks to the Universitas Brawijaya for providing research funding research with contract numbers: 22/UN10.F07/PN/2019, also thanks to Bengawan Solo River Basin Agency especially the operation and maintenance work unit that has supported the writing process of this research.

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