Estimation of Bank Erosion Due to Reservoir Operation in Cascade (Case Study: Citarum Cascade Reservoir)

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Abstract. Sedimentation is such a crucial issue to be noted once the accumulated sediment begins to fill the reservoir dead storage, this will then influence the long-term reservoir operation. The sediment accumulated requires a serious attention for it may influence the storage capacity and other reservoir management of activities. The continuous inflow of sediment to the reservoir will decrease the capacity of reservoir storage, the reservoir value in use, and the useful age of reservoir. Because of that, the rate of the sediment needs to be delayed as possible. In this research, the delay of the sediment rate is considered based on the rate of flow of landslide of the reservoir slope. The rate of flow of the sliding slope can be minimized by way of each reservoir autonomous efforts. This effort can be performed through; the regulation of fluctuating rate of reservoir surface current that does not cause suddenly drawdown and upraising as well. The research model is compiled using the searching technique of Non Linear Programming (NLP).
The rate of bank erosion for the reservoir variates from 0.0009 to 0.0048 MCM/year, which is no sigrificant value to threaten the life time of reservoir.
Mean while the rate of watershed sediment has a significant value, i.e: 3,02 MCM/year for Saguling that causes to fullfill the storage capacity in 40 next years (from years 2008).

Keywords: *rate of the sediment; long-term reservoir operation; capacity of reservoir storage; non linear programming; suddenly; drawdown; upraising; life time.*

1 Introduction

According to Sloff (1991) [1], erosion is a phenomenon of land or part of the land sliding from one place to another by the cause of natural media, water. Erosion is actually a naturally common phenomenon (natural erosion), and a geological process that may cause the gradual changing of mountain's height, coastline, or delta in the lowland. However if the process occurs in a very rapid way (accelerated erosion), then the happening of land loss occurs faster than its

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own formation. This accelerated erosion is commonly caused by nature, yet what may be frightening cause is that from the human's activity.

Erosion and sedimentation are such natural phenomenon in the equilibrium of energy element. In the matter of land erosion, the rate of higher sedimentation that fills in to the reservoir is unavoidable, but it may be delayed.

Mean time, the pattern and the number of sediment are such significant issues once the accumulated sediment begins to fill dead storage reservoir, this will then affect the long term reservoir operation. Accumulated sediment in the reservoir requires serious attention for it may influence the storage capacity and other reservoir management of activities [2].

Seen from the sources, the sediment rate in the reservoir originates from 2 (two) respects:

1. Sediment debt originating from watershed (river flow current), and
2. Rate of flow of landslide of the reservoir slope.

Sediment flow rate regulation from watershed relates to watershed regulation performed integrally with government program and related institution. Whereas the landslide regulation of the reservoir slopes flow rate is the authority of each reservoir. The effort performed in minimizing sediment for the cause of the reservoir slope sliding is on regulating of fluctuation rate of reservoir water surface that emerges nothing:

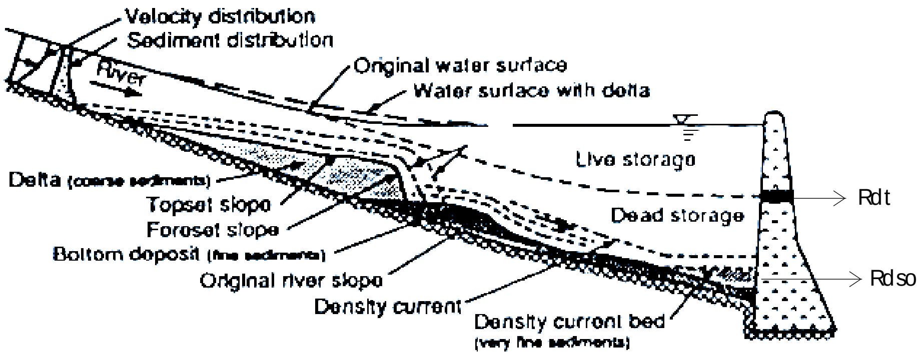
1. Suddenly drawdown; and
2. Upraising.

Regarding the matters above, the researcher conducts further analysis considering sedimentation in the reservoir for the cause of local phenomena of suddenly drawdown and upraising.

2 Erosion and Sedimentation Reservoir Process

The accumulated sediment in the reservoir will precipitate after particular period during the reservoir operation. In the reservoir system, sediment transport is produced from the erosion process happening in watershed, river, and coastline surrounding the reservoir.

Once the river flow decreases, the rough material (coarse) stacks on the blocked water and stacks on the reservoir upper course. The bed load moves by the wave of water. For more detail, the process of sediment deposition in a reservoir is illustrated in Figure 1.



Rdt = Release for water demand in mantly time. Rdso = Release for sediment outflow

Figure 1 Deposited Forming Deltas in a Reservoir [3].

The smooth particle moves further into the reservoir. The survey of reservoir sediment is performed using echo sounding equipments periodically every 4 to 5 years to determine the basic topography and reservoir storage volume. Though the sediment moves and fills the dead storage, this will affect the long-term reservoir operation.

3 Potential of Suddenly Drawdown and Upraising

Suddenly drawdown is the lowering level of water surface that happens rapidly on the slope surface. Slope stability analysis on the suddenly drawdown is meant to maintain the slope of reservoir from the sliding of slope material formation. Commonly, the disrepair of land stacking occurs for the sliding of some groundmass along the curved surface. Rapid declining on a reservoir after filling may cause critical condition on the front surface if the stacks do not dry immediately.

Any disrepair on the reservoir slope formed from the clay material as the result of suddenly drawdown occurs for the pressure excess of water pore does not meet appropriate time to dissipate. By the time reservoir is filled with full of water, the pore pressure is high, the inside part of the reservoir gains water pressure to the surface so that the weight decreases. However, by the time the reservoir water surface with drawn suddenly, the water inside the pores disappear very slow that the water existing in the pores. In the wet condition, the pores weight higher for the water pressure to the surface no longer exists. This circumstance causes inequality in the pressure condition and there is potential retrogressive erosions on the reservoir bank as the result of draw down operation for the rapid upraising that may cause groundmass may cause groundmass eroded along the reservoir slope. Figure 2 and Figure 3 illustrate local phenomenon of suddenly drawdown and upraising.

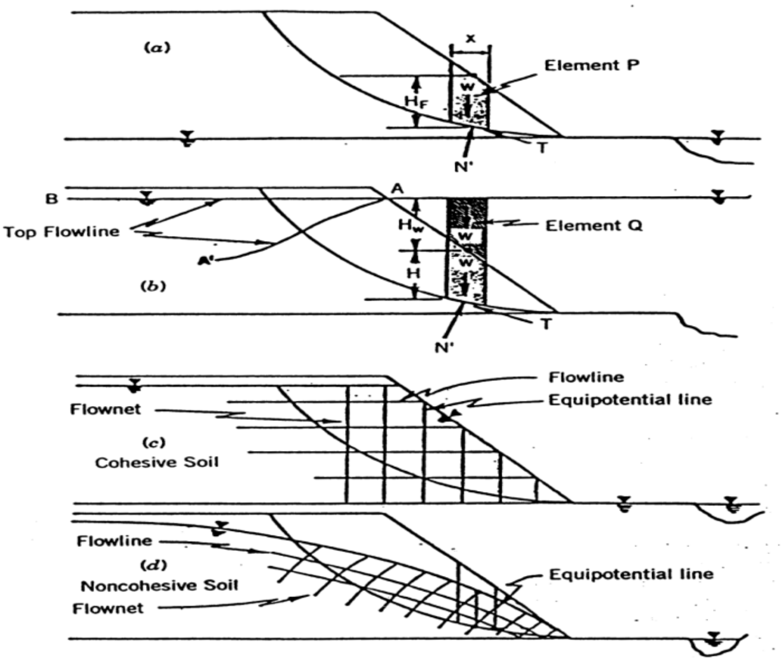


Figure 2 Development of Suddenly Drawdown (a) Low Water Level (b) High Water Level (c) Suddenly drawdown on cohesive soil (d) suddenly drawdown on non-cohesive soil [4].

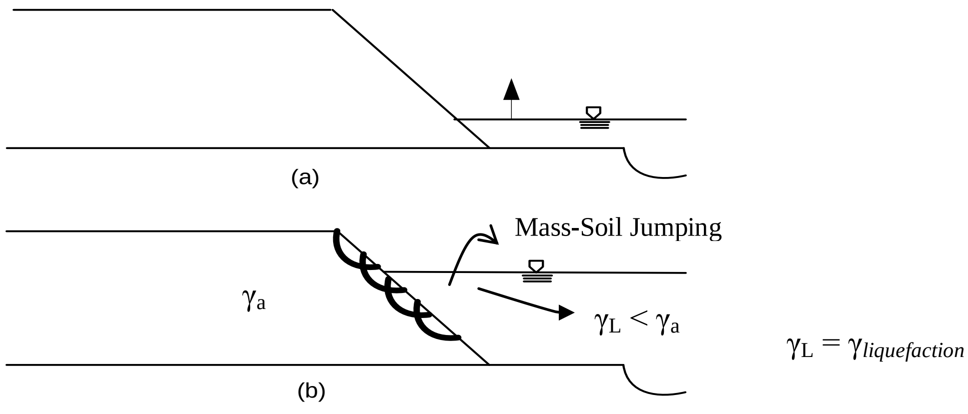


Figure 3 Condition of Upraising.

3.1 Case Study in Citarum Cascade Reservoir System, West Jawa

The reservoirs of Saguling, Cirata, and Djuanda operate in series or cascade, known as Citarum Cascade Reservoir System. There is "equilibrium pattern of Citarum cascade reservoir" applies in the operation of Citarum Cascade Reservoir. This is to prevent the percentage of effective storage distribution volume in every end of the months from the three reservoirs so the distribution is in equal portion. As a cascade reservoir, in its operation, Saguling reservoir (the most upper course reservoir in location) release will be an inflow for Cirata Reservoir (the middle course reservoir in location), and the release of Cirata reservoir will be an inflow for Djuanda reservoir (the lowest course reservoir in location).

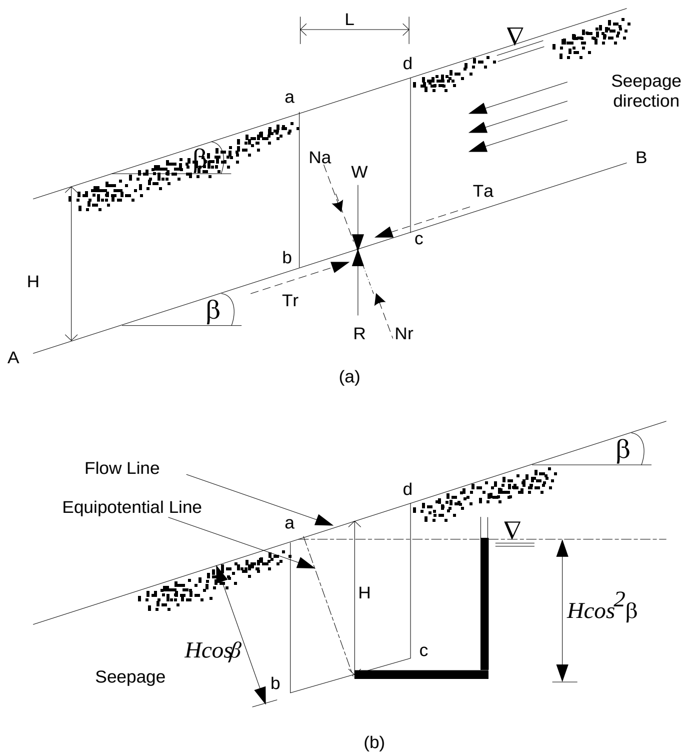


Figure 4 Slope Stability with the Existence of Water Influences.

Saguling Reservoir inflow is such unregulated inflow for it directly emanates from Nanjung. Nevertheless, there is a possibility of higher inflow from the upper course. The higher inflow will allow for upraising on the slope of Saguling Reservoir and be maintained to have higher effective head to meet energy target (hydro power). As well as Cirata reservoir. Therefore, this will give a small chance to Saguling Reservoir for the happening of suddenly draw down to release higher discharge.

On the other hand, Djuanda Reservoir inflow is such a regulated inflow for the majority kind of release originating from Cirata Reservoir. This reservoir is proposed to meet water supply and irrigation. Therefore, the possibilities of the happening of higher inflow from its upper course are small especially during dry period and tend to release more water to meet the demand. Therefore, those three reservoir operation will generate suddenly and rapid drawdown for balancing between inflow and demand. The Figure 4 indicates the effect of suddenly drawdown due to the soil particle on the top layer of the reservoir bank to be eroded because of attractive force of surface drawdown [5].

3.2 Formula of the Slope Stability

Shear stress of soil can be written:

$$\tau_f = c + \sigma' \tan\phi \tag{1}$$

where:

τ_f = Shear Stress (N/m^2)

c = Cohesion of Soil (N/m^2)

σ' = Effective Normal Stress (N/m^2)

φ = Internal Angle Friction (degree)

To determine the safety points to soil erosion along the plane AB, pay attention on the slope *abcd*. The forces working on the vertical surface *ab* and *cd* are in the same size and in the opposite direction. Weight of slope element in wide unit:

$$W = \gamma_{sat} L H \tag{2}$$

where:

W = Weight of soil element (N/m^3)

γ_{sat} = Unit weight of saturated soil (N/m^3)

L = Length of the soil element (m)

H = Head of soil element (m)

Components W in erect and row toward *AB* area:

$$N_a = W cos\beta = \gamma_{sat} LH cos\beta \text{, and} \quad (3)$$

$$T_a = W sin\beta = \gamma_{sat} LH sin\beta \quad (4)$$

where:

N_a = Normal Force (N)

T_a = Tangential Force (N)

R = Reaction Force (N)

β = Angle of slope (degree)

Reaction from weight *W* is equal to *R*. With the result that:

$$N_r = R cos\beta = W cos\beta = \gamma_{sat} LH cos\beta \quad (5)$$

$$T_r = R sin\beta = W sin\beta = \gamma_{sat} LH sin\beta \quad (6)$$

where:

N_r = Normal resultant (N)

T_r = Tangential resultant (N)

R = Reaction force (N)

Total normal stress and shear stress on base of slope element:

Total normal stress: $$\sigma = \frac{N_r}{\left(\frac{L}{cos\beta}\right)} = \gamma_{sat} H cos^2\beta \quad (7)$$

Shear stress: $$\tau = \frac{T_r}{\left(\frac{L}{cos\beta}\right)} = \gamma_{sat} H cos\beta cos\beta \quad (8)$$

The opposite of shear stress on base denoted by index *d* of slope element:

$$\tau_d = c_d + \sigma' \tan\phi_d = c_d + (\sigma - u) \tan\phi_d \quad (9)$$

$$u = \gamma_w H cos^2\beta \quad (10)$$

where:

u = pore water pressure (N/m^2)

γ_w = Unit weight of water (N/m^3)

Substitute σ in formula (7) and *u* in formula (10) to (9), we can find:

$$\tau_d = c_d + (\gamma_{sat} H \cos^2\beta - \gamma_w H \cos^2\beta) \tan\phi_d = c_d + \gamma\, H \cos^2\beta \tan\phi_d \quad (12)$$

$$\gamma_{sat} H \cos\beta . \sin\beta = c_d + \gamma' H \cos^2\beta \tan\phi_d \quad (13)$$

or:

$$\frac{c_d}{\gamma_{sat} H} = \cos^2\beta \left(\tan\beta - \frac{\gamma'}{\gamma_{sat}} \tan\phi_d \right) \quad (14)$$

where:

γ' = Effective unit weight of soil (N/m^3)

Safety number to the soil force can be defined with substitute:

$\tan\phi_d = \frac{\tan\phi}{F_s}$ and $c_d = \frac{c}{F_s}$ to formula (14):

$$F_s = \frac{c}{\gamma_{sat} H \cos^2\beta . \tan\beta} + \frac{\gamma'}{\gamma_{sat}} \frac{\tan\phi}{\tan\beta} \quad (15)$$

where:

F_s = Safety factor of the slope

3.3 Permeability and Water Level Data

The land on the three reservoirs (Saguling, Cirata, and Djuanda) is un-uniformed land, and is the kind between clay-silt-sand. From the data of detailed design report of Cirata Reservoir [6], the land around Cirata Reservoir has average permeability coefficient 1,14 x 10^{-5} meter/second. With the opinion that Saguling and Djuanda Reservoirs are in the same watershed, then the soil permeability coefficient around Saguling and Djuanda is thought to be same as that of the Cirata's. The decreasing water inside the soil is as big as the value of the average permeability coefficient.

The fluctuation of water level on history Citarum Cascade reservoir history operation in year 2003 is as Table 1.

Table 1 Citarum Cascade Reservoir water level history in year 2003.

	Saguling	**Cirata**	**Djuanda**
Maximum decrease of level (m)	631,33 to 628,04	209,95 to 207,22	91,46 to 88,19
Maximum decrease per month (m/month)	3,29*	1,73*	3,27*
Maximum increase of level (m)	628,65 to 633,40	208,38 to 211,38	86,73 to 90,01
Maximum increase per month (m/month)	4,75**	3,00**	3,28**

(*) = potential of suddenly drawdown
(**) = potential of upraising

Suddenly drawdown analysis from permeability coefficient toward maximum decreasing water level of reservoir operation:

1. Saguling reservoir = 3,29 meter/month = 1,27 x 10^{-6} meter/second < k = 1,14 x 10^{-5} meter/ second (safe toward suddenly drawdown)
2. Cirata reservoir = 1,73 meter/month = 6,67 x 10^{-7} meter/second < k = 1,14 x 10^{-5} meter/second (safe toward suddenly drawdown)
3. Djuanda reservoir = 3,27 meter/month = 1,26 x 10^{-6} meter/second < k = 1,14 x 10^{-5} meter/ second (safe toward suddenly drawdown)

where:

k = permeability coefficient (meter/second)

Erosion of reservoir slope analysis from critical depth of slope:

Specific density of sediment, ρ_s = 1700 kg/m^3.

Specific weight of sediment, $\gamma = \rho_s . g = \frac{1700 \text{ x } 9,81}{1000} = 16,67 \text{ kN/m}^3 = \gamma_{sat}$

γ_w = 9,81 kN/m^3.

$\gamma' = \gamma_{sat} - \gamma_w = 16,67 - 9,81 = 6,86 \text{ kN/m}^3$.

To define critical depth of slope, then F_s = 1.

3.3.1 Saguling and Cirata Slope

Soil cohésive: c = 4 ton/m^2 = 4 x 9,81 = 39,24 kN/m^2

With unconsolidated and undrained soil, internal friction angle $\phi = 0^o$; slope angle of Saguling and Cirata reservoir $\beta = 23^o$

$$F_s = \frac{c}{\gamma_{sat} H_{cr} \cos^2 \beta . tan\beta} + \frac{\gamma'}{\gamma_{sat}} \frac{\tan\phi}{\tan\beta}$$

$$1 = \frac{39,24}{16,67 \ x \ H_{cr} \ (\cos 23^o)^2 .tan23^o} + \frac{6,86}{16,67} \frac{tan0^O}{tan23^O}$$

$$1 = \frac{6,44}{H_{cr}} + 0$$

H_{cr} = **6,44** meter

where:

I = Unity for equilibrium stability of slope

H_{cr} = critical depth of slope

3.3.2 Djuanda Slope

Soil cohesion 0,17 kg/cm^2 = 0,17x 9,81 x10^{-3}x10^4 = 16,68 kN/m^2

With unconsolidated and undrained soil, internal friction angle $\phi = 0^o$

Angle slope of Djuanda reservoir = 11^0

$$1 = \frac{16,68}{16,67 \ x \ H_{cr} \ (cos11^0)^2 .tan11^0} + \frac{6,86}{16,67} \frac{tan0^0}{tan11^0}$$

$$1 = \frac{5,34}{H_{cr}} + 0$$

H_{cr} = **5,34** meter

4 Sediment Accumulation from Suddenly Drawdown and Upraising

Process of erosion of reservoir slope is illustrated in Figure 5.

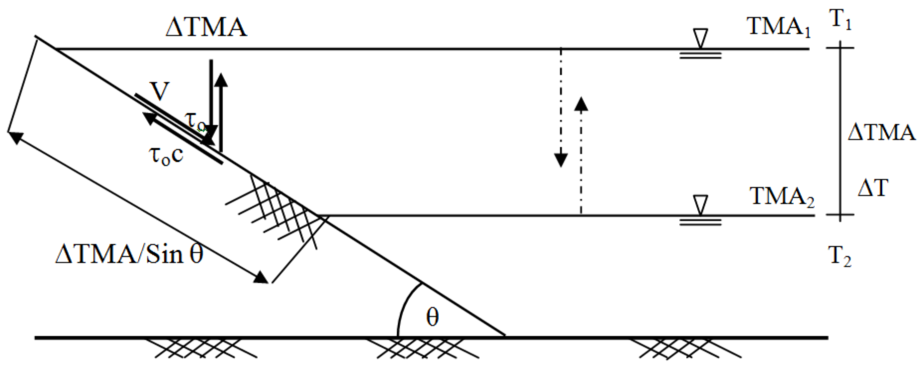


Figure 5 Process of Erosion of Reservoir Slope.

To calculate rate of sediment from erosion of reservoir slope, use formulas:

Du Boys formula [7]:

$$q_b = A(\tau_o - \tau_{oc}) \tag{16}$$

and

$$\tau_o = \gamma_w R S \tag{17}$$

Manning formula [8]:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{18}$$

and

$$R = \left(\frac{V n}{S^{1/2}}\right)^{\frac{3}{2}} \tag{19}$$

where:

A = Du Boy's constant

q_b = Sediment rate per meter (ton/s/m)

τ_o = Shear stress (kg/m^2 or lb/ft^2)

τ_{oc} = Critical shear stress of grain soil (kg/m^2)

γ_w = Unit volume of water(kg/m^3 or lb/ft^3)

R = Radius hydraulic (m or ft)

S = Gradient of slope

Considering the Figure 5, the velocity of water surface on the slope.

$$v = \frac{\Delta TMA / Sin\theta}{\Delta T} \quad (20)$$

$$\Delta TMA = TMA_1 - TMA_2 \quad (21)$$

and

$$\Delta T = T_1 - T_2 \quad (22)$$

where:

TMA_1 = Initial water level position (m)

TMA_2 = Final water level position (m)

T_1 = Time on TMA_1 (month)

T_2 = Time on TMA_2 (month)

Variation A and dan τ_{oc} with sediment's size in Table 2.

Table 2 Variation A and dan τ_{oc} with Sediment's Size.

D (mm)	1/8	1/4	1/2	1	2	4
A/γ_s (ft^6/lb^2s)	0,81	0,48	0,29	0,17	0,10	0,06
τ_{oc} (lb/ft^2)	0,016	0,017	0,022	0,032	0,051	0,090

Rate of sediment from erosion of reservoir slope:

$$Q_b = q_b \, . \, p \, . \, \Delta T \quad (23)$$

$$\text{or } V_b = Q_b / \gamma_s \quad (24)$$

where:
Q_b = Total sediment (ton)
q_b = Sediment rate per meter (ton/s/m)
p = perimeter of reservoir (m)
ΔT = Time release annual operation (month)
V_b = Volume of sediment annual (m^3)
γ_s = Unit weight of sediment (ton/m^3)

The long-term calculation will generate accumulated sediment resulted from the reservoir slope erosion.

After gaining the sediment inflow, then finding the cumulative value is the next step. The sediment cumulative value will reduce reservoir capacity and eventually influences the energy production and energy firm as well. If the energy and the energy firm are no longer able to fulfill the *demand*, the reservoir is no longer effective. The following formula shows the changing of reservoir storage volume as the result of accumulated sediment [9].

$$V_{t+1} \leq V_{max} - (V_{sed} + S_t + I_{s_t}) \tag{25}$$

where:

V_{t+1} : Initial reservoir volume month t+1; (MCM)

Sto_{max} : Maximum reservoir capacity; (MCM)

V_{sed} : Cummulative volume of sediment month t-1; (MCM)

S_t : Reservoir slope erosion; (MCM)

In_{st} : Sediment inflow month t. (MCM)

MCM : Million Cubic Meter.

5 Results and Discussion

Accumulated sediment of slope erosion caused by fluctuating water surface resulted from Citarum cascade reservoir is illustrated in Figure 6.

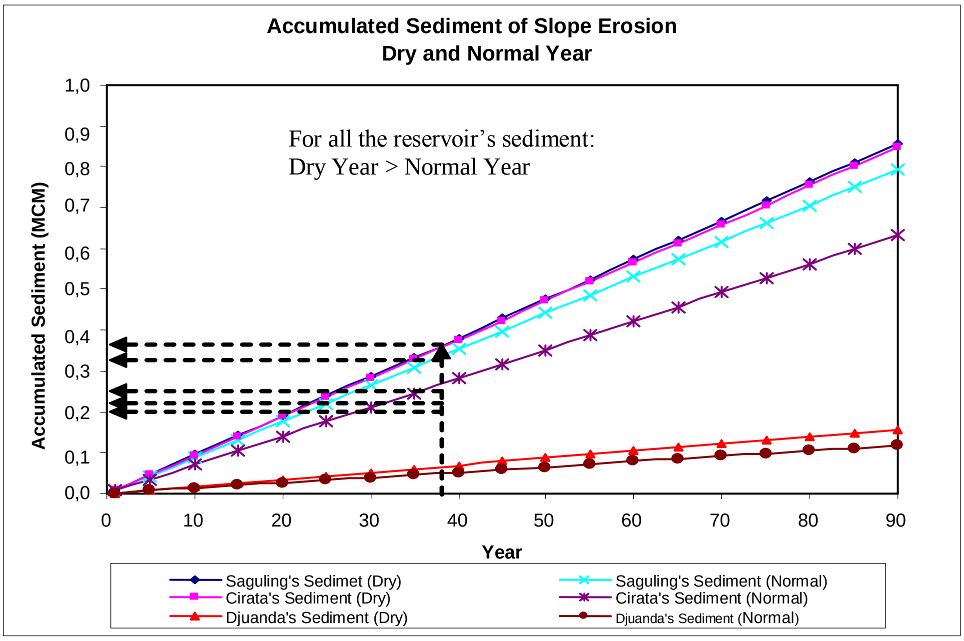
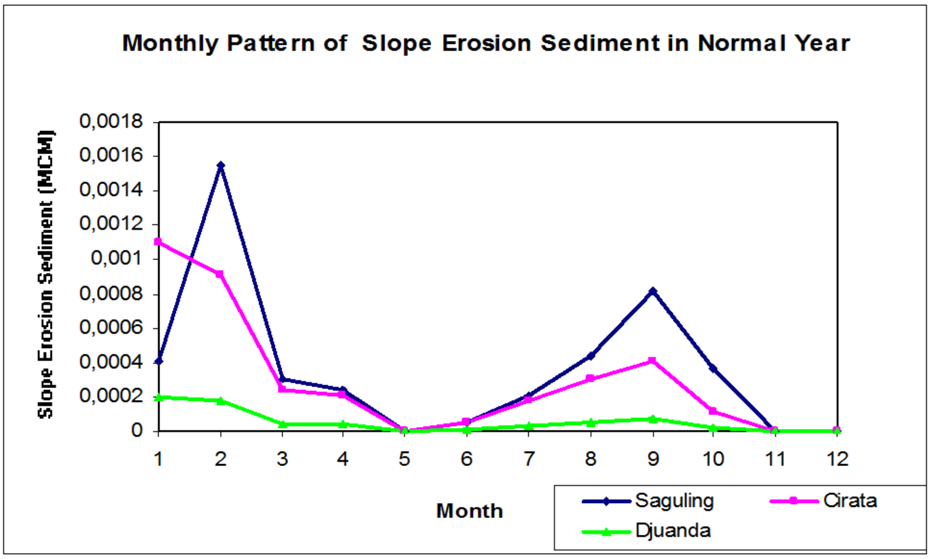


Figure 6 Accumulated Sediment of Slope Erosion.

The rate of bank erosion for three resevoirs is found as follows:

- Saguling resevoir = 0,0048 MCM/year
- Cirata reservoir = 0,0047 MCM/year
- Juanda reservoir = 0,0009 MCM/Year



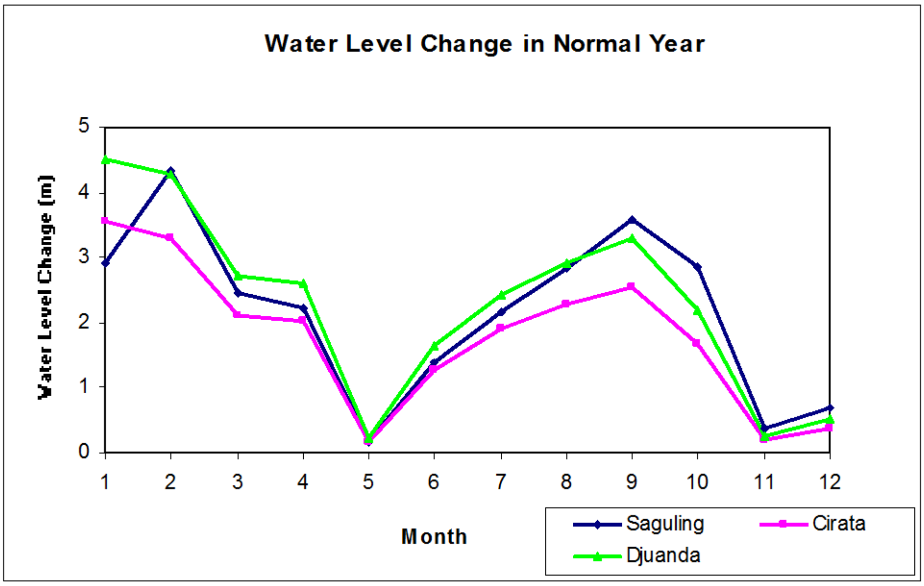


Figure 7 Monthly pattern of slope erosion sediment and water level change in normal year.

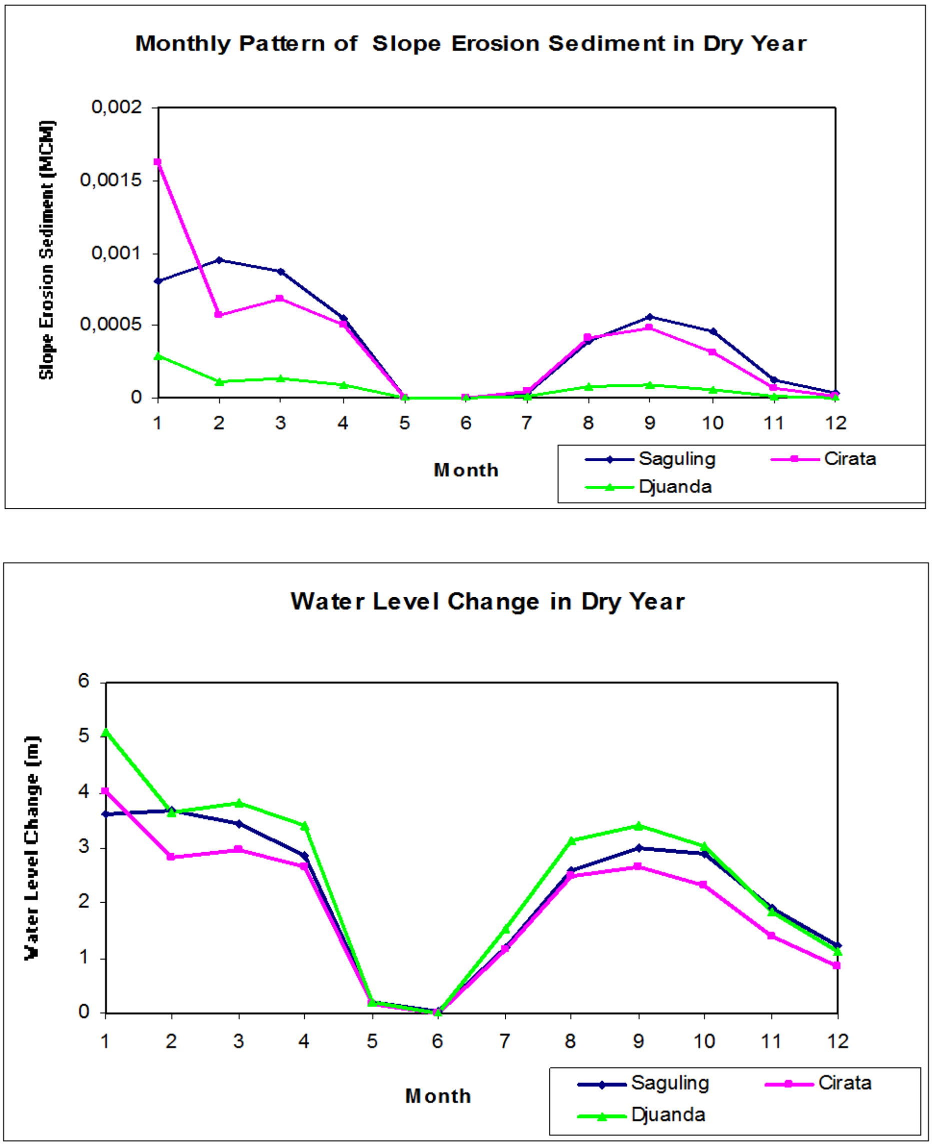


Figure 8 Monthly Pattern of Slope Erosion Sediment and Water Level Change in Dry Year.

Based on the accumulated sediment of reservoir slope erosion, the accumulated sediment can be described as follow:

- Slope sediment depends on the different height of water surface during its operation, the width of reservoir slope experiencing different height of water surface, and the angle of reservoir's slope.
- Seen from the different height of water surface, Djuanda reservoir also experiences greater different height of water surface than the other reservoirs. This correlates with the interest of Djuanda reservoir to fulfill its needs of water in its lower course. Physically, Djuanda has the biggest wetted area than Cirata and Saguling. However, Djuanda has sloped slightly.
- For the three reservoirs in the dry year, the accumulated sediments get higher than that in the normal year. For in the dry year, a relatively fluctuating height of water surface occurs. This condition has something to do with the reservoir *inflow* that is relatively small during the dry year, and the interest of the reservoir to comply the needs of water.

Figure 7 and Figure 8 illustrate the monthly pattern of slope erosion sediment and the water level changes in dry and normal year operations.

The rate of bank erosion in the monthly period is different from January to December.

The maximum rate of bank erosion accours in January – February wich are 0.0016 MCM for saguling reservoir, 0.0011 MCM for Cirata reservoir and 0.0002 MCM for Juanda reservoir.

Mean while, the minimum rate of bank erosion occurs in May, which is less than 0.0001 MCM.

Based on the monthly sediment pattern of slope erosion, the changes can be described as follows:

- In monthly period, the slope erosion sediment in the normal and dry year comes close to the pattern of height changes of water surface.
- In the normal and dry year, Djuanda reservoir experiences lower rate of flow of slope sediment monthly, then Cirata, and then Saguling. It is indeed so, Djuanda Reservoir has the biggest wetted area than the other reservoirs as it also experiences different height of water surface than the other reservoirs. However, with slope slightly of Djuanda, the result that rate of sediment from erosion of Djuanda reservoir slope is lower.
- In the dry year, from the beginning of operation to March, the slope sediment for the three reservoirs is relatively high. This is because the reservoirs initiate to save water for the oncoming dry months. The height of the water surface occurs quite often.

- Once it gets in to dry months (June-October) the occurrence of slope sediment for the three reservoirs is high enough. This correlates with the interests of Djuanda reservoir to comply its needs of water in its lower course so that the two reservoirs below it must release relatively greater water during the dry months.
- The occurrence of a relatively fluctuating of different height of water surface in the dry year takes place for the reservoir *inflow* is relatively small in the dry year.
- In the early operation of normal year to April, the slope sediment for the three reservoirs is relatively high. For in the reservoir early operation in normal year, the reservoir releases greater water. This is allowable since in the dry months (June-October), the *inflow* is in its propriety to meet the demand in the months.

Accumulated sediment from watershed and slope erosion on Saguling, Djuanda, and Cirata reservoirs to the 90th year can be illustrated in Figure 9.

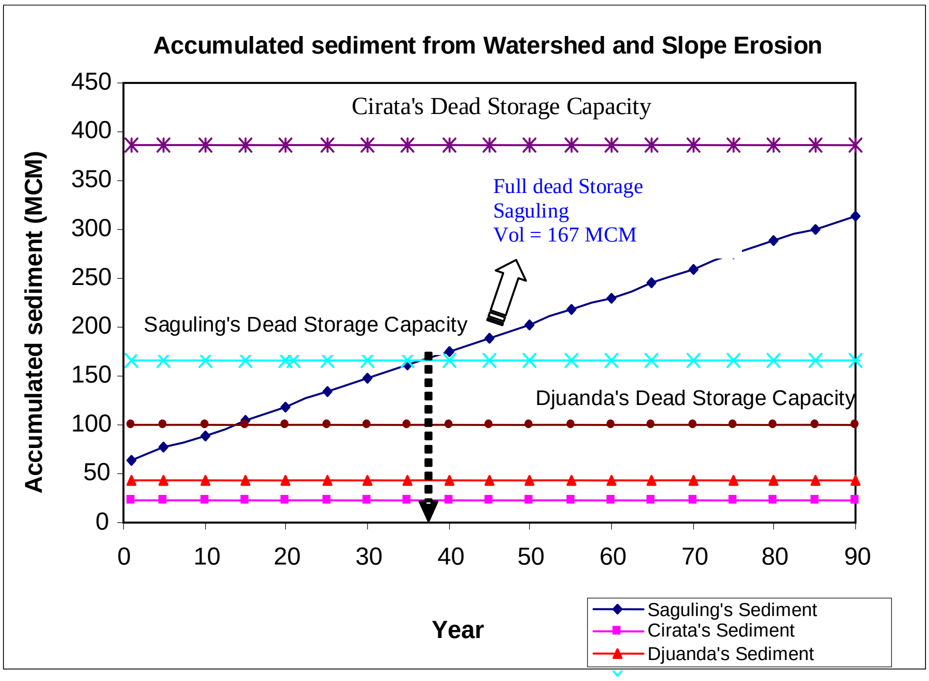


Figure 9 Accumulated Sediment from Watershed and Slope Erosion.

The total sediment due to bank and watershed erosion shows that Saguling resevoir has greater rate (3.02 MCM/year) then that for the Cirata (0.0017

MCM), and for the Juanda (0.0028 MCM). The most of watershed sediment is trapped in upstream resevoir i.e: Saguling resevoir.

6 Conclusion

Slope sediment has different pattern from that of the watershed sediment. Watershed sediment depends on only the *inflow* condition that goes into the reservoir. Whereas slope sediment not only depends on the *inflow* but it also depends on the *rule curve* of the reservoir operation and the physical condition of the reservoir. That the watershed accumulated sediment for Cirata and Djuanda Reservoirs is far smaller than that of the Saguling's. In the opposite way, slope sediment for Cirata and Djuanda reservoirs is greater than that for the Saguling.

The rate of bank erosion for three resevoirs which variates from 0.0009 to 0.0048 MCM/year has no significant value to fullfill the dead storage capacity of sediment.

The rate of watershed dediment for Saguling resevoir has significant value (3.02 MCM/year) which causes to fullfill the dead storage capacity (170 MCM) for the 40 next.years

Due to the watershed sediments which is trapped in the Saguling resevoir, the Cirata and Juanda dead storage will have life time more longer than that Saguling.

Watershed accumulated sediment in the reservoirs contributes effects to the operation of Citarum Cascade Reservoir. In the opposite condition, the operation of Citarum Cascade Reservoir causes the occurrence of accumulated sediment from the reservoir slope erosion. The accumulated sediment from watershed and slope will provide negative impacts to the long-term reservoir operation. By fully loaded the dead storage (particularly on Saguling reservoir located in the very upper course), the reservoir operation is under interferences. This is because the decreasing volume of reservoir effective storage. This circumstance may create greater conflicts of interest in Citarum Cascade Reservoir.

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