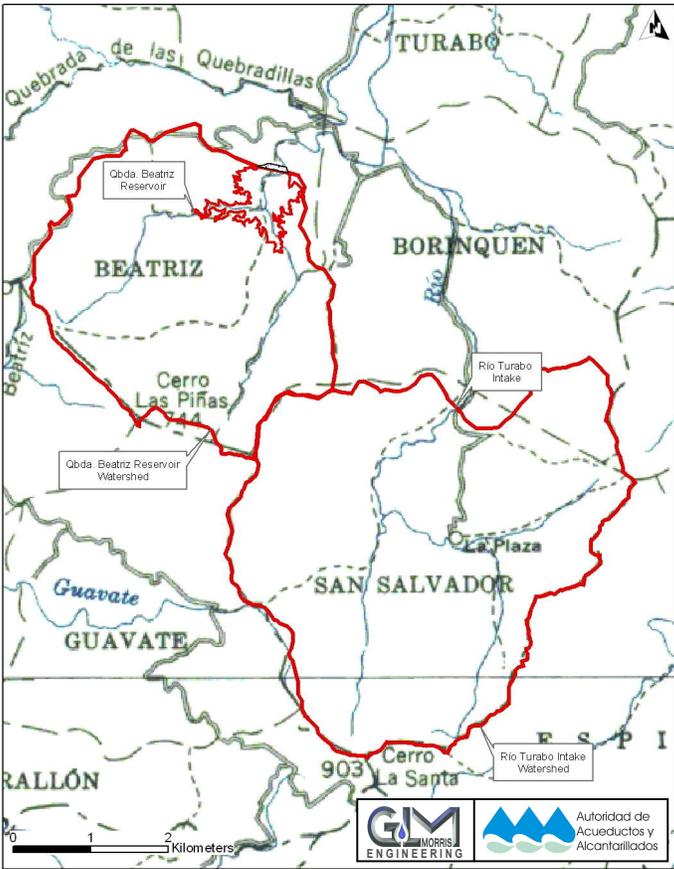


Nota al Lector:

Posterior a la emisión del presente estudio (**Estudio de Rendimiento de Sedimentos**) se modificó el Plano Conceptual del Proyecto Embalse Beatriz (el Proyecto). El Proyecto según redefinido propone la construcción de una nueva planta de filtración en vez de la ampliación de la planta de filtración Caguas Sur y define las áreas de disposición de sedimentos y área de amortiguamiento de la cortina de la represa. Estas áreas en conjunto ocupan aproximadamente 70 cuerdas adicionales al área de estudio original, las cuales fueron estudiadas separadamente. Además incluye dos alternativas de acceso a la nueva planta de filtración, actualmente en evaluación. Sin embargo, estas modificaciones no alteran los resultados del presente estudio.

Sedimentation Analysis for Beatriz Offstream Reservoir Caguas, Puerto Rico



June 28, 2007

Prepared for:

Puerto Rico Aqueduct and Sewer Authority
San Juan, Puerto Rico



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Sedimentation Analysis for Beatriz Offstream Reservoir

June 28, 2007

1. INTRODUCTION

1.1. Project Description and Location

The proposed project consists of a water supply reservoir created by a dam across Qbda. Beatriz and an intake on Río Turabo. The configuration of the reservoir in relation to sediment-producing watersheds and the streamgage stations used in the analysis is illustrated in **Figure 1**.

1.2. Scope and Purpose of Report

This report presents the pre-construction estimate of the rate of sediment accumulation and reservoir half-life. For more detailed background information on techniques for estimating sediment yield and reservoir sedimentation, please refer to Morris & Fan (1998).

1.3. Limitations of the Analysis

This analysis has been undertaken based on historical streamflow and sediment yield data. It incorporates the assumption that hydrologic conditions and land use in the future will be similar to the conditions experienced since, approximately, the 1970s. Actual sedimentation rates can be accelerated significantly if significant development occurs in the watershed upstream of the dam.

1.4. Authorization

Preparation of this report has been authorized by the Puerto Rico Infrastructure Financing Authority (AFI). It was subsequently updated for use by the Puerto Rico Aqueduct and Sewer Authority.

2. STUDY APPROACH & METHODOLOGY

2.1. Conceptual Approach

Beatriz reservoir is considered an “offstream reservoir” since most of the water that enters the reservoir will be diverted from Río Turabo via a river intake and pipeline. The conceptual difference between an “onstream” and an “offstream” reservoir are illustrated in **Figure 2**.

Sediment delivery from the Qbda. Beatriz watershed above the dam is given by the sediment yield from the watershed. However, sediment delivery from Río Turabo depends not only on the sediment yield of the watershed, but on the fraction of that sediment yield which is diverted into the reservoir via the river intake.

Most sediment is exported from the Turabo watershed by flood events, with discharges 30 to 300 times greater than the capacity of the intake pipeline to the reservoir. The offstream reservoir configuration greatly reduces the rate of sediment delivery to the reservoir during the major sediment-transporting events because most of the sediment-laden floodwaters from Río Turabo continue downstream and are not diverted into the reservoir.

The rate of sediment accumulation also depends on the fraction of the delivered sediment which remains trapped in the reservoir, termed the trap efficiency. The trap efficiency will be close to 100% at this site.

Sediment yield from Qbda. de las Quebradillas is not considered because this intake delivers water directly to the filtration plant; it does not enter the reservoir.

The sediment entering the reservoir has been computed based on a simulation analysis with a one-day time step using the entire period of streamflow record available at the USGS Río Turabo gage station.

Because reservoir operations are seriously impaired by a 50% volume loss due to sedimentation (if not sooner), we have computed this “half-life” as the time-horizon parameter for reporting the sedimentation rate.

2.2. Available Gage Station Data

Sediment yield computations for this report are based on the two gage stations presented in Table 1, where they are compared to the damsite characteristics. The USGS gage at Río Turabo (gage 50053025) is located several hundred meters below the proposed intake and represents an excellent dataset for the analysis of that river. However, there is no gage station along Qbda. Beatriz. Therefore, we have performed the sedimentation analysis using fluvial sediment data from both Río Turabo and Río

Caguitas to simulate sediment yield from Qbda. Beatriz. This strategy has been used because Qbda. Beatriz is located north of Río Turabo (in the direction of Río Caguitas), yet its lower elevation and lower rainfall is more similar to the Río Caguitas gage than Río Turabo (see Table 1).

Table 1: Characteristics of Gage Stations Compared to Dam Site.

USGS Gage Station	Annual Rain (mm)	Gage Elev. (m)	Watershed Area (km ²)	Period of Record <u>a/</u>	
				Discharge	Susp. Sediment
Turabo abv. Borinquen (50053025)	2360	150	18.3	2/90 - 9/02	10/90 - 9/01
Caguitas at A. Buenas (50055100)	1780	125	13.7	2/90 - 9/02	2/90 - 9/01
Beatriz dam site	1930	120	11.7	--	--

a/ Record period used for the analysis.

b/ Mean annual rainfall in tributary watershed by isoheytal map.

At both gage stations unpublished data were obtained from the USGS which reported daily values of discharge and suspended sediment load. We divided the load by the discharge to obtain mean daily concentration which was plotted as a function of mean daily flow to create concentration-discharge rating curves.

There are no measured bed load sediment discharge data for Puerto Rico, although sand-size material will be collected in suspended sediment samplers once discharge become significant. The Río Turabo intake is being designed to exclude bed material, so estimation of bed material load along that river is irrelevant to the analysis. However, all bed material from Qbda. Beatriz will be trapped in the reservoir. Qbda. Beatriz has gravel to cobble size bed material (Rosgen C3 to C4 class). Field visits over an interval of several years revealed stable geomorphic conditions along this stream, and the bed material load appears to be very small in relation to the suspended solid load. We have estimated bed material load to be equal to 5% of the suspended solid load based on Strand and Pemberton (1987).

Although the gage record is relatively short, it does cover the most severe drought period in the region since 1968, which occurred in the 1994-95 period. It also covered large storms such as Hortense and Georges, important from the standpoint of computing sediment yields and balancing the effect of the low-yield drought period. Consequently, the hydrologic coverage is judged to be representative of long-term conditions.

2.3. Methodology

A hydrologic and hydraulic simulation model with a one-day time step has been prepared to analyze daily reservoir behavior and yield. The simulation analysis was performed for the period of record at the Turabo gage. This model includes computation of the suspended sediment concentration in each stream from a two power equations each having the following form:

$$\text{Conc.} = a Q^b$$

The values “a” and “b” are empirically-derived coefficient values, suspended sediment concentration is given in mg/L, and discharge “Q” was computed normalized to the mean daily flow computed over the period of record (i.e. Q/Q_{mean}). The normalized flow values were used to facilitate application of the rating equation from one location to a discharge series at a different location.

Suspended sediment rating curves were prepared for each of the analyzed streams. The Río Turabo rating curve was applied to the Río Turabo streamflow dataset. Two separate simulations were used to apply both the Río Turabo and the Río Caguitas rating curves to the Qbda. Beatriz dataset as a sensitivity analysis.

The flow entering the reservoir from both Río Turabo and from Qbda. Beatriz are both variable, and the sediment load delivered to the reservoir from each stream was computed as the product of mean daily flow and concentration. Peak flow along Qbda. Beatriz is equal to the flood flows along this stream, but peaks from Río Turabo are limited to less than about 100 cfs by the capacity of the intake and 54” diameter pipeline.

The trap efficiency of the sediment delivered from the Río Turabo will be 100%, since the reservoir should not have inflow from that river if it is discharging over its spillway. Also, Río Turabo enters the reservoir distant from the intake to the filter plant, minimizing the sediment discharge through that intake.

Because there will be reservoir spills due to flood inflow from the Beatriz watershed, the trapping of sediment from the Beatriz watershed has been adjusted based on the trap efficiency, which was computed by the Brune (1953) curve relationship (**Figure 3**). This Relates the percentage of the inflowing sediment load that is trapped in the reservoir to the capacity:inflow (C/I) ratio. For Beatriz the capacity inflow ratio is computed as:

$$\text{Reservoir Capacity} = 8.0 \text{ Mm}^3$$

$$\text{Mean Annual Inflow from Beatriz} = 8.2 \text{ Mm}^3$$

$$\text{C/I ratio} = 0.98$$

The total reservoir capacity of 8.0 Mm³ has been used for computing the C/I ratio, but the dead storage pool has been excluded from the yield computations and simulation modeling. From the Brune curve about 95% of the inflowing sediment load will be trapped. There will be a small decline in the C/I ratio and trap efficiency over time as sediment accumulates, but this effect will not be significant over the next 50 years.

2.4. Mass to Volume Conversion

To compute the rate of volume loss due to sedimentation it is necessary to convert the sediment mass into sediment volume. We used the conversion of 1 metric ton of dry sediment per cubic meter (1 t/m³), based on the anticipated nature of the deposits and field collected during initial sedimentation studies at Carraízo reservoir.

3. RESULTS

3.1. Rating Curves

The sediment rating curves for the two gage stations, along with their equations, are presented in Figure 4 and Figure 5. In these figures mean daily concentration is graphed against the normalized mean daily discharge. Thus, a value of 10 corresponds to a flow equal to 10 times the long-term mean daily discharge for the stream. The long-term mean is computed as total discharge divided by the number of days of record, and the daily means are as reported by the USGS. Coefficient values for the rating equations in both streams were adjusted until the actual and predicted loads matched within 0.5%, while also insuring that actual load matched predicted loads over the full range of discharge values.

3.2. Sediment Yield Simulations

Two simulations were performed, each with different rating curves. In both simulations #1 the Río Turabo sediment rating curve was used for that gage station, but two alternative sediment rating curves were tested at Qbda. Beatriz. These simulation results are summarized as follow:

<u>Simulation</u>	<u>Location</u>	<u>Sediment Rating Curve Used</u>	
		<u>Río Turabo</u>	<u>Qbda. Beatriz</u>
#1	Table 2	Río Turabo	Río Turabo
#2	Table 3	Río Turabo	Río Caguitas

The Río Turabo discharge series was used to simulate inflow from Qbda. Beatriz in both simulations; only the rating equation was modified. Both simulations were performed for the project configuration which produces the highest yield and sedimentation rate, which is the option using the tunnel to convey water from Río Turabo to the reservoir.

Table 2: Summary of Sediment Load Simulation #1.

Parameter	Beatriz (#1)	Turabo (#2)	Total
Watershed area, km ²	11.7	18.3	30.0
Total suspended sed. load in river, t/yr	10,635	22,889	33,524
Watershed susp. Sediment yield, t/km ² /yr	909	1,251	
Suspended load entering reservoir, t/yr	10,635	4,458	15,094
Percent of load entering reservoir	100%	19.5%	
Trap efficiency	95%	100%	
Suspended load trapped in reservoir, t/yr	10,104	4,458	14,562
Bed Load, % of suspended sediment load	5%	0%	
Bed load contribution, t/yr	532	0	532
Annual total load trapped in reservoir, t/yr	10,635	4,458	15,094
Annual load trapped by source, %	70%	30%	100%
Reservoir Initial Volume, Mm ³			8.00
Annual storage loss, % of initial volume			0.19%
100-year storage loss, Mm ³			1.51
Half-life, years			265

Table 3: Summary of Sediment Load Simulation #2.

Parameter	Beatriz (#1)	Turabo (#2)	Total
Watershed area, km ²	11.7	18.3	30.0
Total suspended sed. load in river, t/yr	8,657	22,889	31,546
Watershed susp. Sediment yield, t/km ² /yr	740	1,251	
Suspended load entering reservoir, t/yr	8,657	4,458	13,115
Percent of load entering reservoir	100%	19.5%	
Trap efficiency	95%	100%	
Suspended load trapped in reservoir, t/yr	8,224	4,458	12,682
Bed Load, % of suspended sediment load	5%	0%	
Bed load contribution, t/yr	433	0	433
Annual total load trapped in reservoir, t/yr	8,657	4,458	13,115
Annual load trapped by source, %	66%	34%	100%
Reservoir Initial Volume, Mm ³			8.00
Annual storage loss, % of initial volume			0.16%
100-year storage loss, Mm ³			1.31
Half-life, years			305

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Sedimentation Rate

The simulations indicate that the Beatriz reservoir will accumulate approximately 14,000 m³/year of sediment (range of 13,000 to 15,000 per the two simulations), producing a half-life of between about 265 and 305 years.

The major source of sediment supply is the Qbda. Beatriz watershed, constituting about 66 to 70 percent of the total load. Because high-concentration flood flows along Río Turabo are not diverted into the reservoir, less than 20% of the total sediment load from this river enters the reservoir. Thus, even though Río Turabo transports much more sediment than Qbda. Beatriz, it contributes less than 25% of the sediment load to the reservoir while Qbda. Beatriz contributes the remainder.

4.2. Reduction in Firm Yield by Sedimentation

The yield simulations have assumed a dead storage pool of 0.6 Mm³, which is equivalent to approximately 43 years of sediment accumulation. During the subsequent 57 years an additional 0.8 Mm³ of live storage will become sedimented, reducing live storage. This

will reduce firm yield by 0.3 mgd (from 14.0 mgd to 13.7 mgd). Thus, after 100 years of sedimentation the reservoir's firm yield will have been reduced by only 2%.

The rate of sediment accumulation at Beatriz is 1.4 Mm³ per 100 years, which is a very low rate and which can be handled by a relatively small-scale dredging operation once every century.

By means of comparison, to maintain the current capacity of Carraízo dam under the present operating rule would require dredging of about 30 Mm³ each century, which is 21 times greater than the dredging volume required at Beatriz. The rate of volume loss at Carraízo and Beatriz reservoirs is compared in Figure 6.

4.3. Sediment Management Recommendations

Four sediment management activities are recommended at the Beatriz reservoir.

1. **Reservoir Surveys.** A post-impoundment bathymetric survey should be performed, and surveys should be performed thereafter at intervals of approximately 25 years to check the rate and pattern of sediment accumulation. Given that most of the inflowing sediment will consist of fines, we anticipate that sediment will tend to fill the reservoir from the bottom up without formation of a delta. These surveys will indicate the true rate of sedimentation, which may differ from the predicted rates, especially if land use or climate changes occur.

The initial (25-year) sedimentation survey will over-estimate the long-term sedimentation rate, unless it is adjusted to account for future sediment consolidation.

2. **Land Use Control.** Observations along the stream and the existing land use in the watershed indicate that sediment yield from the Beatriz watershed is not high compared to other areas in Puerto Rico. However, the future sedimentation rate could be greatly accelerated (doubled) by uncontrolled development in this watershed. The steep slopes and limited road access have inhibited urban development to date, and will likely continue to inhibit urban development in the future.

Approximately 75% of the sediment entering Beatriz reservoir will come from the watershed above the dam. With an area of nearly 12 km², the Beatriz watershed is too large to be purchased for the purpose of land use control. Most of this watershed is currently in forest and with limited road access. The rate of sedimentation within the Beatriz reservoir will be very sensitive to earth movement activities within this watershed. To maximize protection of the

reservoir we recommend that no additional road construction be undertaken in the watershed, development activity should be strictly limited, and any development that may be undertaken should have stringent erosion controls.

3. **Closure of Río Turabo Intake.** The Río Turabo intake may be closed in advance of large storms such as hurricanes with the highest sediment concentration and with the maximum possibility of delivering debris. This will have only a small impact of sediment loading, but is recommended as a precautionary measure to reduce the potential for obstruction with debris. The exception to this rule would be following a dry period when the reservoir level is low and there is a need for all the available water supply.
4. **Dredging.** Sediment removal by dredging may be considered after about 100 years (when firm yield drops to 13.7 mgd) or 150 years (when yield drops to about 13.4 mgd), and thereafter repeated at intervals of approximately 50 to 100 years. Approximately 0.7 to 1.4 Mm³ should be removed at each dredging, resulting in a dredging rate of 1.4 Mm³/100 years to maintain a stable reservoir capacity. The area recommended for acquisition immediately below the dam may be used for temporary storage of dredged sediment, which may be hauled to a fill area to make the site available for the next dredging activity.

5. REFERENCES

Brune, G.M. 1953. "Trap Efficiency of Reservoirs," Trans. Am. Geophysical Union, 34(3): 407-418.

Morris, G.L. and Fan Jiahua. 1997, Reservoir Sedimentation Handbook. McGraw-Hill Book Co., New York.

Strand, R. I. and Pemberton, E.L. 1987. "Reservoir Sedimentation." Appendix-A in: *Design of Small Dams*. U.S. Bureau of Reclamation, Denver.

FIGURES

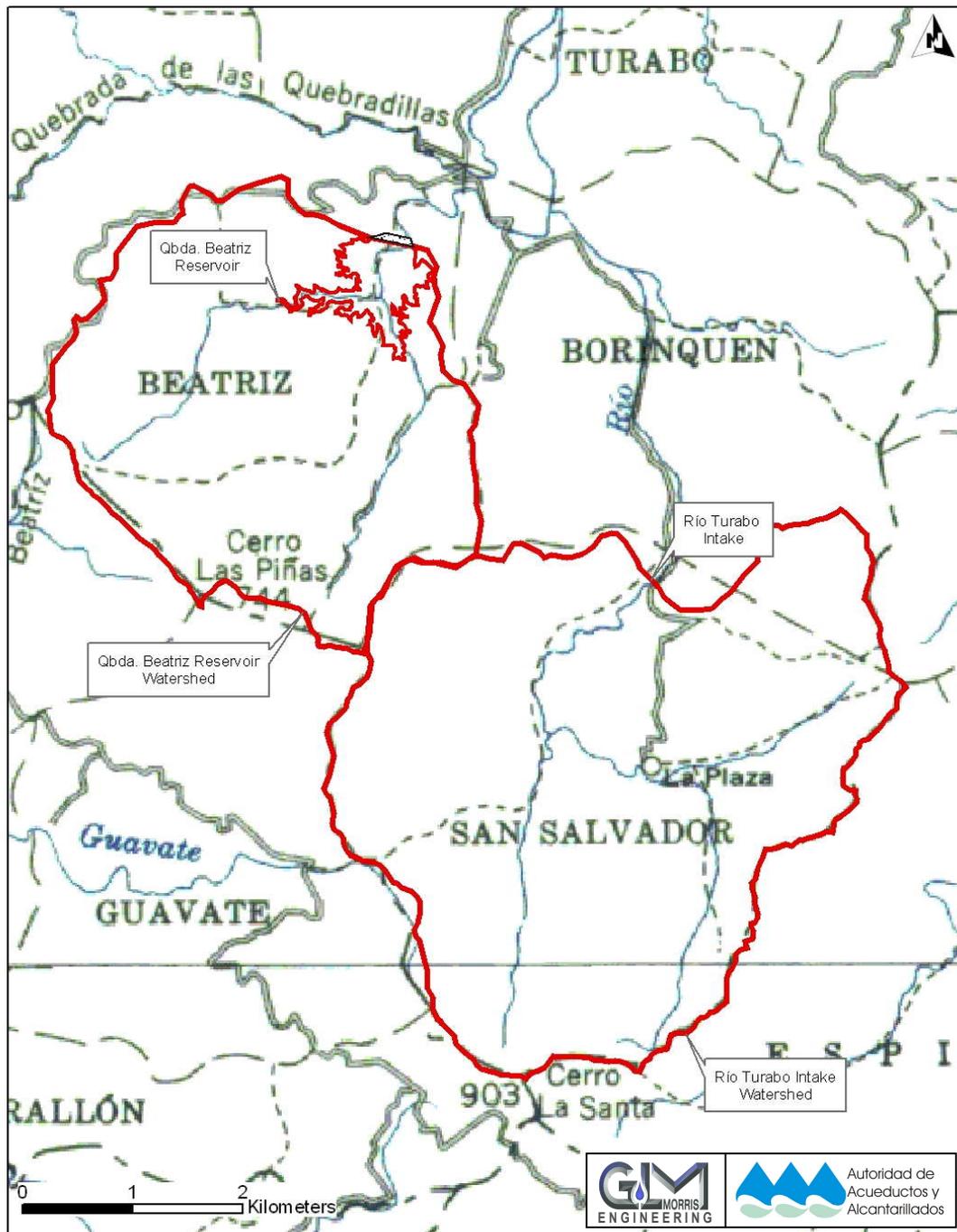


Figure 1: Location map showing the dam on Q. Beatriz, the intake on R. Turabo, and the watersheds tributary to each.

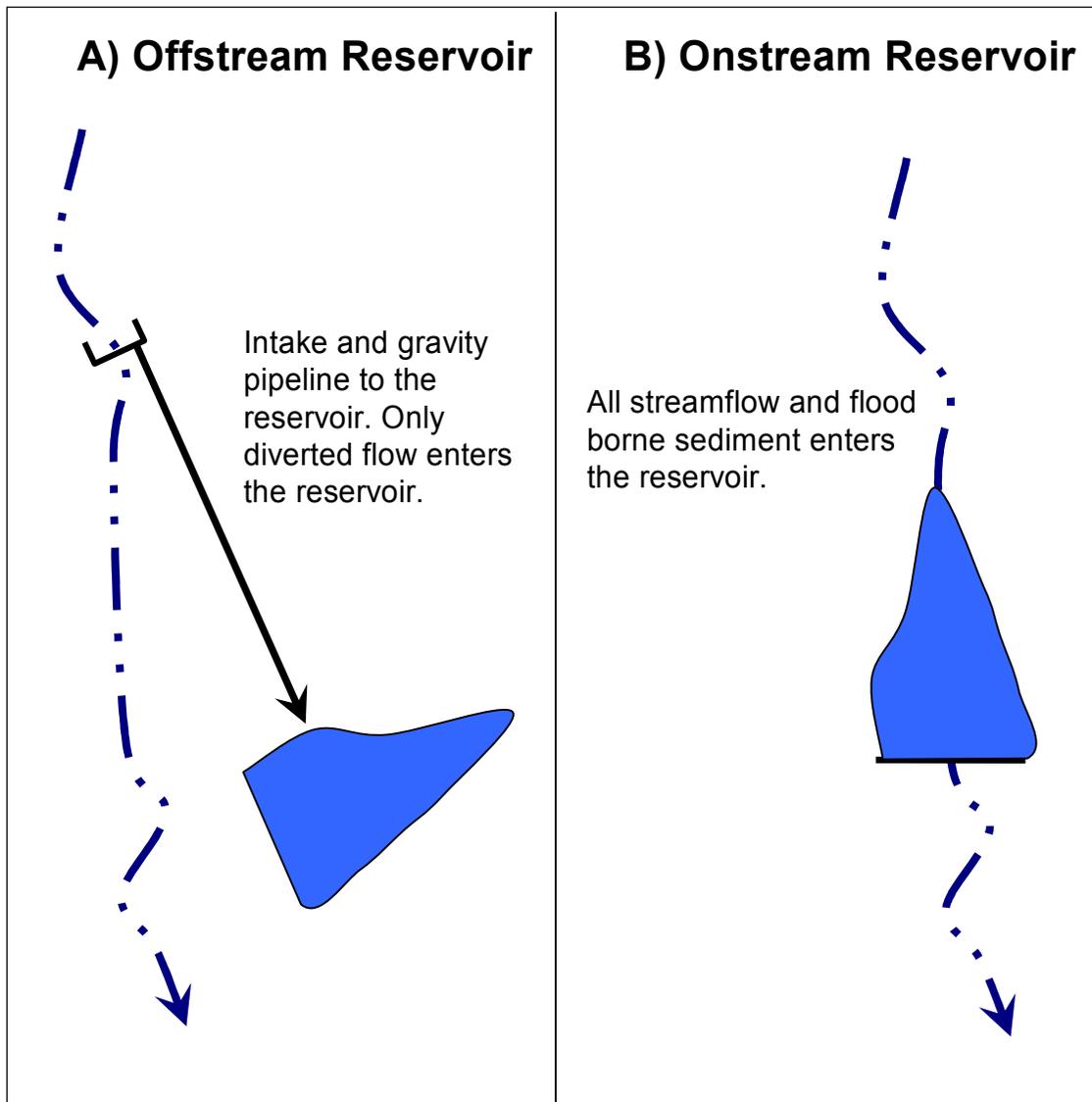


Figure 2: Conceptual difference between an onstream reservoir and an offstream reservoir. During sediment-laden flood events most of the flood flow and its sediment load runs along the river and past the intake to the offstream reservoir. In contrast, the entire volume of flood borne sediment is delivered to the onstream reservoir.

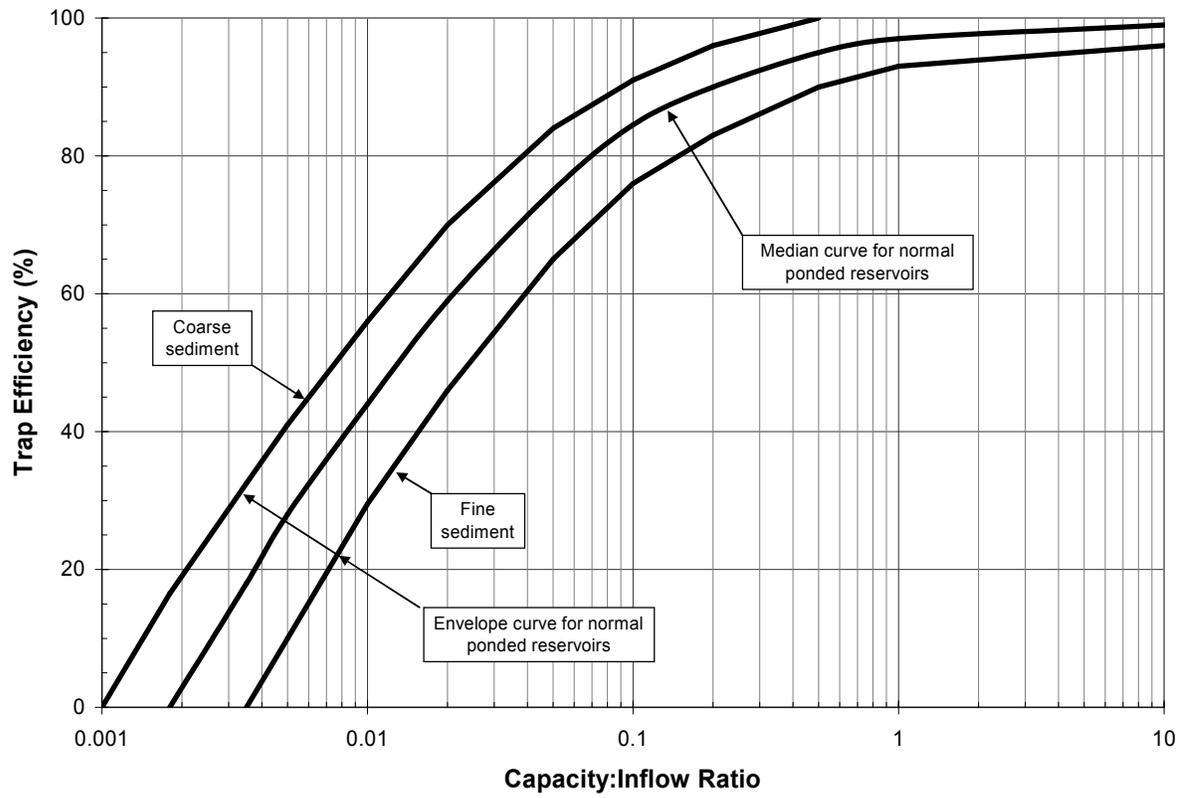


Figure 3: Relationship developed by Brune (1953) relating the percentage of inflowing sediment trapped in a reservoir to the capacity:inflow ratio.

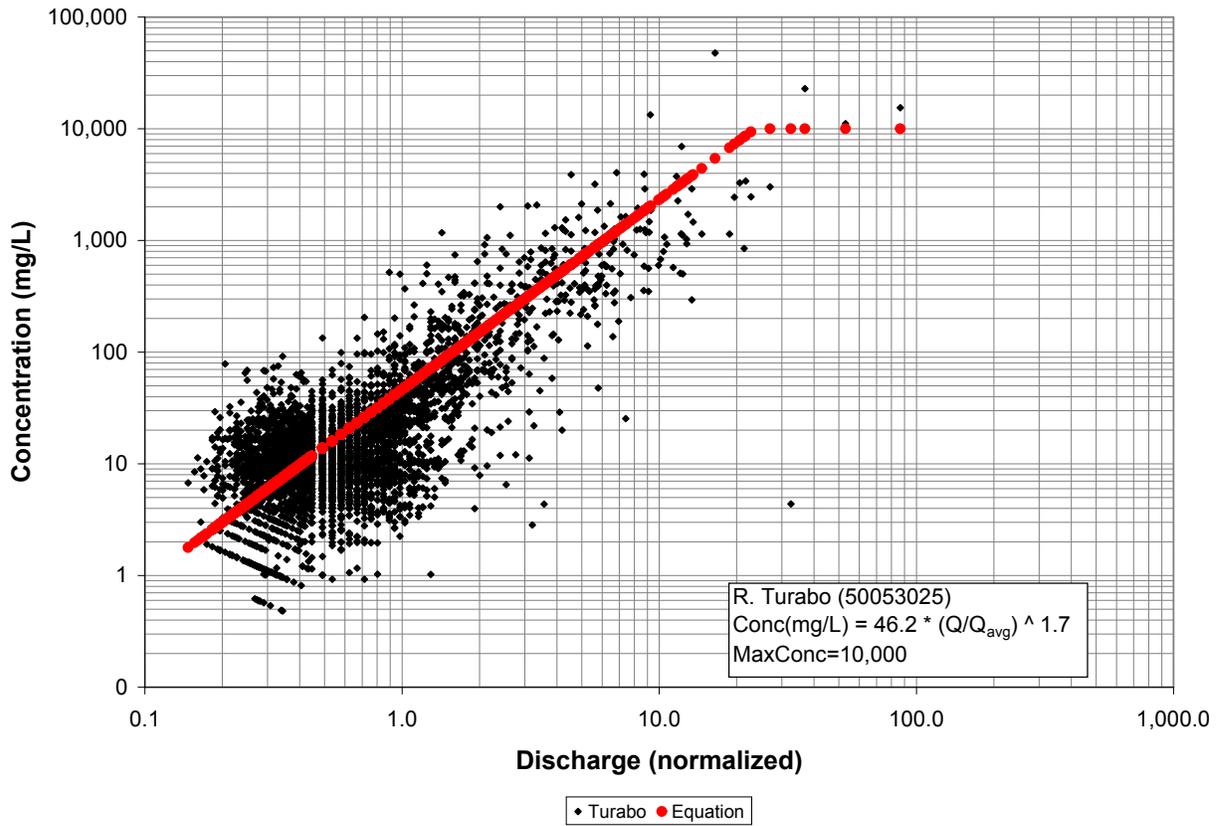


Figure 4 : Suspended sediment rating curve for Río Turabo gage station

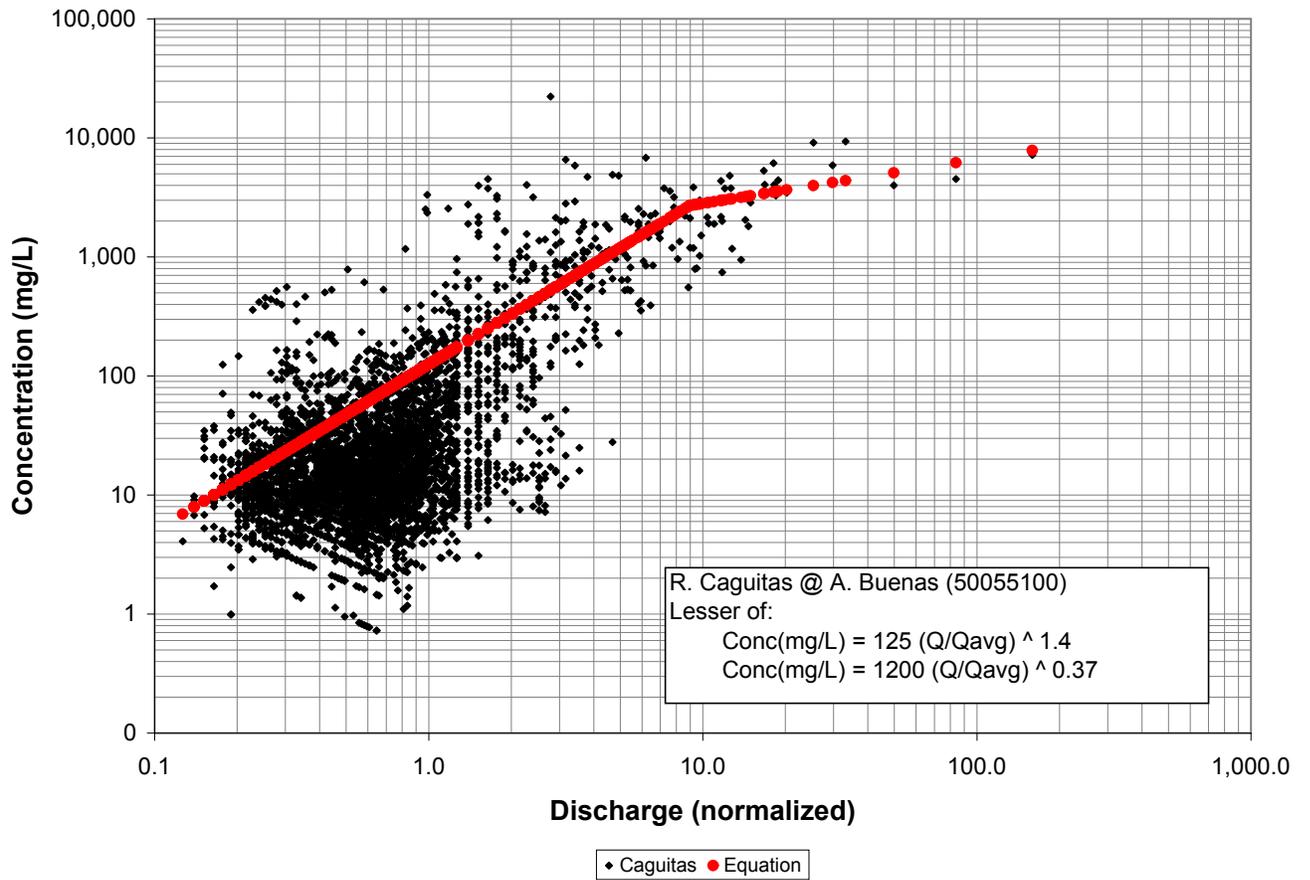


Figure 5 : Suspended sediment rating curve for Río Caguitas gage station

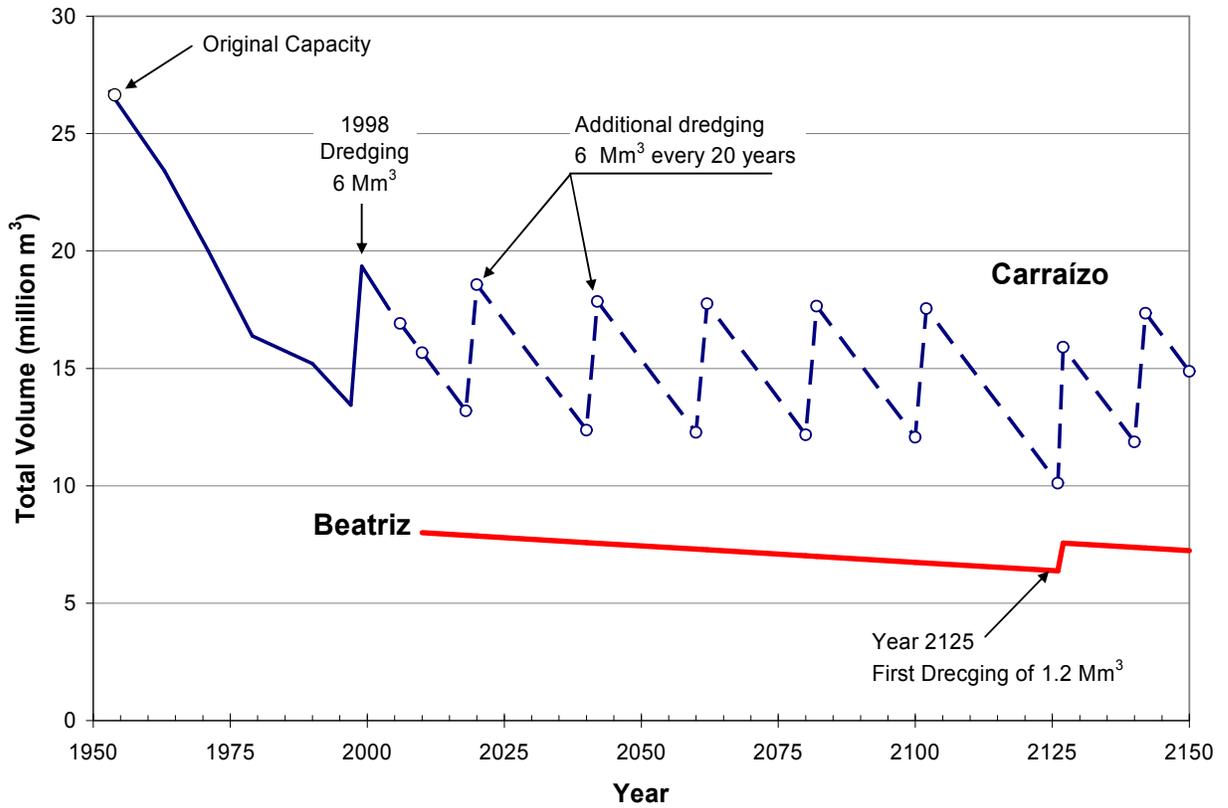


Figure 6 : Comparison of rate of storage loss and dredging requirements, Carraízo and Beatriz reservoirs.