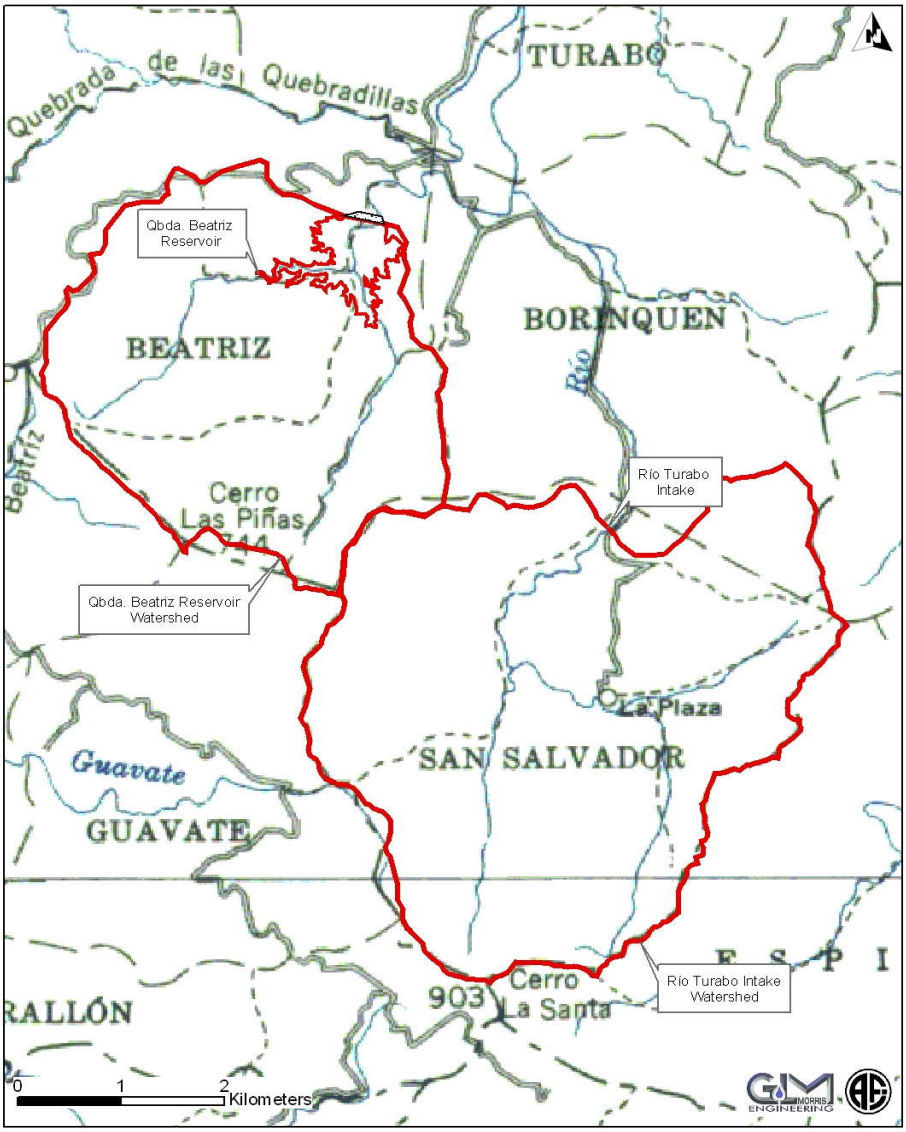
Nota al Lector:

Posterior a la emisión del presente estudio (**Estudio de Rendimiento Seguro**) 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.

Yield Analysis for Quebrada Beatriz Reservoir

Caguas, Puerto Rico



June 28, 2007

Prepared for:

Puerto Rico Aqueduct and Sewer Authority
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Yield Analysis for Quebrada Beatriz Offstream Reservoir

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June 28, 2007

1. INTRODUCTION

1.1. Project Description and Location

The Quebrada Beatriz damsite in Bo. Beatriz, Caguas, was identified in the Corps of Engineers Islandwide Water Supply Study (1977) and was also examined by Black & Veatch (1999) and the USGS (Gómez-Gómez et. al. 2001).

The Qbda. Beatriz reservoir is located between Río Turabo and Qbda. Las Quebradillas, making it possible to divert water by gravity from both of these streams into the reservoir in addition to the runoff from its own watershed. This diversion to increase yield was not examined by any of these prior studies; it was proposed by Gregory Morris Engineering (2005) and is analyzed in the present study.

A project location map is presented in Figure 1 showing the principal elements of the project including the Río Turabo intake and diversion pipeline, the Qbda. Beatriz dam and reservoir, the existing Caguas Sur filtration plant which would be enlarged, and the existing Qbda. de las Quebradillas gravity intake which would continue in service. As an alternative a new filter plant may be constructed, but this does not affect the yield analysis.

1.2. Scope and Purpose of Report

This report presents the water supply yield analysis for the Quebrada Beatriz reservoir . This report has been prepared as the basis for analyzing design alternatives for the reservoir, and selecting the final reservoir volume from the standpoint of water supply yield. The yield is determined for a variety of configurations considering the existing Quebrada Las Quebradillas intake, a proposed intake on Río Turabo, and inflow from Qbda. Beatriz to the proposed reservoir.

1.3. Limitations of the Analysis

This analysis has been undertaken based on historical streamflow data. It incorporates the assumption that hydrologic conditions in the future will be similar to the conditions experienced during the historical period covered by streamflow data. Although the dataset used in this analysis is relatively short, covering the period 2/1/1990 to 9/30/2003, it does cover the severe 1994-95 drought. Data beyond 2003 are not available for all gage stations. **Figure 2** shows the location of streamgage stations and watersheds used in the analysis.

1.4. Authorization

Preparation of this report was authorized by the Puerto Rico Infrastructure Financing Authority (AFI) as part of the Islandwide Analysis of Potential Reservoir Sites. Further analysis of this reservoir including modifications to this report were subsequently performed for the Puerto Rico Aqueduct and Sewer Authority.

2. STUDY APPROACH & METHODOLOGY

2.1. Conceptual Approach for Offstream Reservoir Yield Analysis

2.1.1. Onstream vs. Offstream Reservoirs

Reservoirs may be classified as either "onstream" or "offstream." Both configurations are compared in **Figure 3**. All reservoirs in Puerto Rico have been constructed onstream, with the exception of the new Fajardo and Río Blanco reservoirs. The Quebrada Beatriz offstream reservoir is to be supplied by an intake and diversion from Río Turabo.

Components of dams referred to in this report and important from the aspect of hydraulic analysis are illustrated in **Figure 4**. These components are the same for both onstream and offstream dams and reservoirs.

An offstream reservoir has important advantages in terms of greatly reduced sedimentation, reduced environmental impacts, and better water quality. In a conventional onstream reservoir all flows along the river enter the reservoir. During floods much water flows over the spillway at the same time that much sediment becomes trapped within the reservoir. In an offstream reservoir the flow rate of water entering the reservoir is limited by the capacity of the pipeline connecting the intake to the reservoir. Thus, very little flood-born sediment will enter the reservoir pool because of the limited capacity of the pipeline. It also offers the possibility to close the intake with a gate at the approach of a hurricane to further reduce sediment accumulation.

Yield analysis undertaken using data in Puerto Rico has shown that in moist areas of Puerto Rico the difference between the yield of an onstream and offstream reservoir on the same stream is small. Reservoir yield in moist areas of Puerto Rico is controlled more by the extreme intensity of infrequent drought events and limited storage volumes, rather than the ability to capture the flow from major floods. Thus, in moist areas firm yield is more closely related to reservoir volume than to whether it is onstream or offstream. Yield is also very sensitive to the magnitude of minimum instream flows that must be sustained.

2.1.2. Reservoir Firm Yield

The firm yield of reservoirs has been determined based on behavior simulations (McMahon and Mein, 1986) using a 1-day computational time step and historical streamgage records. Behavior simulations are performed by computing a daily water balance across the reservoir from historical inflow, estimated instream flow needs, flood

spills, changes in storage, and withdrawals per the specified operating rule. The water balance at Beatriz reservoir has been computed from the following parameters:

$$V_{t+1} = V_t + (\text{Inflows})_t - (\text{Spills})_t - (\text{Draft})_t - (\text{Instream Flow})_t - (\text{Net Evaporation})_t$$

Where, V = volume in the reservoir, Inflows = inflow from all intakes plus the watershed tributary to the dam, Spills = flood volume overflowing from the full reservoir, Draft = withdrawals for water supply, Instream Flow = minimum flows that must be released to the river, and Net Evaporation = net of rainfall and evaporation on the water surface. Time is indicated as t and t+1, using a time step of one day.

For this analysis the "firm yield" is defined as the uninterrupted rate of withdrawal from the reservoir that can be sustained 99% of the time, with water rationing on only 1% of the days. Rationing is implemented as a 25% reduction in reservoir withdrawals rationing begins when the reservoir level has dropped to 25% of the maximum active storage volume. During the rationing period filter plant production is constant at 75% of normal production; the filter plant is never shut down and the reservoir is never allowed to empty. The yield analysis has been run assuming a constant year-around rate of withdrawal, a reasonable assumption for Puerto Rico where water use does not have significant seasonal variation.

All simulations include the continuous release of a minimum environmental flow at the new Río Turabo intake, as described in Section 2.1.4. At the dam the instream flow is released from the reservoir, but for the Río Turabo intake instream flow simply remains in the river. There is no difference from the standpoint of water budget computations.

Net evaporative losses have been computed based on the reservoir pool area and the daily record of evaporation and rainfall at Gurabo, as reported by NOAA and published on CD by EarthInfo, Inc. Pan evaporation is converted to lake evaporation by applying a factor of 0.80 to pan evaporation in accordance with studies compiled by Linacre (1994).

Simulations of each project configuration were run by trial and error using a solver algorithm to rapidly converge on the firm yield which produced water rationing on 1% of the simulation days. (The convergence criteria used was 1% ± 0.1%). Yield computations are initiated with an assumption of a full reservoir on the first day of the simulation. This a standard technique in yield analysis and is also a standard operating procedure for new reservoirs.

2.1.3. Run-of-River Firm Yield

The existing Caguas Sur filter plant has two run-of-river intakes. The original intake supplies the filter plant by gravity from Qbda. de las Quebradillas through the following

parallel pipes: two of 10″ diameter and one of 14″ diameter. This intake can deliver 4 mgd to the filter plant, when it is available in the river. There is also a pumped intake on Qbda. Beatriz at its confluence with Río Turabo. A rustic diversion channel also diverts flow into this intake from Río Turabo to augment low flows along Qbda. Beatriz.

Because they have no storage, the rate of withdrawal from existing run-of-river intakes is limited to the instantaneous flow rate in the stream. The firm yield from these existing intakes is computed by the ranking of daily streamflow data to determine the 99% flow exceedance (Q99) and without considering any instream flow requirements.

2.1.4. Environmental In-stream Flows

New or rehabilitated intakes are typically required to leave in the river a flow ranging from ½ Q99 to the full Q99. In practice the actual amount of instream flow is determined on a case-by-case basis by regulatory agencies.

The yield computed herein includes the effect of sustaining an instream flow below the diversion weir on Río Turabo equal to Q99 or the base streamflow, whichever is less. A minimum flow of Q99 is also provided below Qbda. Beatriz dam, using the flow value of 0.5 cfs as determined by periodic streamflow measurements and gage correlation studies by the USGS and reported as gage station 50053200, Qbda. Beatriz at Barrio Beatriz (Gómez-Gómez et. al., 2001). There is no instream flow requirement for the existing Quebrada de las Quebradillas intake, which is unaffected by this project, and no minimum flows along this stream are incorporated into the yield modeling.

For the system under analysis, the impact of increasing the environmental instream flow is to reduce the reservoir firm by essentially the same amount. Thus, a 1 mgd increase in instream flow produces approximately a 1 mgd decrease in firm yield.

2.1.5. System Configuration

Yield computations were performed for several alternative configurations as reported in the results section:

Existing Condition	Pre-project conditions (existing run-of-river yields)
Alternative #1	Beatriz dam only
Alternative #2	Beatriz dam plus variable flow intake up to 4 mgd on Qbda. de las Quebradillas delivering water to the reservoir
Alternatives #3 - #8	Beatriz dam plus variable flow intake up to 4 mgd on Qbda. de las Quebradillas delivering water to the reservoir, plus variable flow intake on Río Turabo delivering water to the

reservoir via pipeline or tunnel.

Alternatives #9 - #10	Yield for Beatriz reservoir, variable flow intake on Río Turabo which delivers to the reservoir via pipeline or tunnel. Qbda de las Quebradillas not used.

The maximum discharge of 4 mgd from the Qbda. de las Quebradillas intake corresponds to the capacity of the existing intake structure and pipelines. The discharge of Qbda. de las Quebradillas may be delivered directly to the filter plant or into the reservoir; the overall water balance and firm yield is identical under either alternative as long as the entire discharge available from this stream is used up to the limit of 4 mgd. Because this intake elevation (135 m) is lower than the reservoir pool, water from this source will need to be pumped.

The maximum flow rate along the pipeline or tunnel from Río Turabo intake to the reservoir is limited by hydraulic capacity, the available flow in the river and water level in the reservoir. Peak flow rates range from about 130 to 250 cfs (84 to 160 mgd) depending on the hydraulic configuration of the pipeline or tunnel.

Both the Qbda. de las Quebradillas intake and the Río Turabo intake will operate at variable flow rates, depending on the water available in the river and whether or not the reservoir is full. Flow from Qbda. de las Quebradillas can be delivered directly to the filter plant or directly to the reservoir, up to a maximum rate of 4 mgd. If delivered to the filter plant, withdrawal from the reservoir will vary from day to day, based on the difference between the amount of water delivered directly to the filter plant from the Quebradillas intake and the rate of water production in the filter plant. The total rate of water production at the filter plant is constant, but withdrawal rates from both the intake and the reservoir are variable. The intake and reservoir operate in parallel to supply the filter plant such that the sum of the water extracted from each is equal to the total filter plant flow.

The operating rule for the Río Turabo intake is to divert as much water as possible, after meeting instream flow needs, up to the hydraulic capacity of the pipeline. However, when the reservoir is full the Río Turabo intake should be closed so the reservoir will not spill.

Figure 5 illustrates the concept of using a reservoir and a river diversion operating in parallel. Given the discharge limitation at the Qbda. de las Quebradillas intake, this strategy produces a firm yield identical to that with the Qbda. de las Quebradillas intake delivering to the reservoir.

2.1.6. Raw Water Transmission Capacity and Hydraulic Profile

Transmission capacity through the Río Turabo pipeline supplying the reservoir has been computed based on the smaller of the head difference between the intake and the reservoir pool (to account for downstream submergence of the pipeline by the reservoir) or the physical slope of the pipeline. Hydraulic capacity has been computed by the Manning equation with a roughness value of n=0.012. This is considered a conservative value, since published n-values for a long concrete pipeline with smooth interior are in the range of 0.010 to 0.011 (Federal Highway Administration, 2005) corresponding to a long concrete pipe. The pipe should be designed so that its slope is constant along the pipeline length. Or, the pipe may include segments of variable slope to bypass obstructions, as long as the pipe stays below the computed hydraulic grade line for the condition with free outfall at the downstream end of the pipe.

For the tunnel alternative the same computational procedure has been used, but the n-value will depend on both the construction method and lining material, if any. Manning's n-values for various tunnel construction techniques are presented below (U.S. Army, 1997):

Drill and blast excavation, unlined	***n* = 0.038**
Tunnel boring machine excavation, unlined	**n = 0.018**
Lined with precast concrete segments	n = 0.016
Lined with cast-in-place concrete	n = 0.013
Lined with steel with mortar coat	n = 0.014
Lined with steel (diam > 3 m (10 ft))	n = 0.013
Lined with steel (diam < 3 m (10 ft))	n = 0.012

Based on the quality of rock and tunnel length, the least-cost tunnel construction technique cannot be definitely predicted at Beatriz since both drill and blast (D&B) methods as well as TBM (Tunnel Boring Machine) can be competitive in this situation. Accordingly, Manning n-values for both D&B and TBM tunnels have been used. The most economical construction diameter of a tunnel is anticipated to be in the vicinity of 8 to 10 feet (2.4 – 3.0 m). The tunnel will be approximately 3.1 km long, about half the length of the pipeline. Because of the higher hydraulic roughness, the drill & blast tunnel should have a minimum diameter of 2.75 m (9 feet), and the TBM tunnel will need a minimum diameter of 2.45 m (8 feet). Both tunnel alternatives have nearly identical hydraulic capacities at these diameters.

Because the tunnel alternatives provides more hydraulic capacity than a pipeline, use of a tunnel increases reservoir firm yield as compared to the pipeline and is the preferred alternative.

2.2. Streamflow Datasets

Streamflow datasets in Puerto Rico collected by the U. S. Geological Survey (USGS) are now of sufficient length, and cover periods of sufficient drought intensity, to rely on historical data as a direct measure of intake and reservoir yield. Furthermore, in a comparative analysis of historical streamflows and synthetically generated streamflow datasets for eastern Puerto Rico (Fajardo gage station), it was found that the historical datasets contained drought events more severe than approximately 90% of the synthetic datasets.

The dataset used in the analysis includes the period from February 1990 through September 2002 and includes the 1994-95 drought, which is the most severe drought since the 1967-68 event. Gages on Río Gurabo and Río Loíza indicate the 1967-68 event was more severe than the 1994-95 event. Streamflow records dating from the early 1960s and rainfall records from earlier in the 20th century indicate that the 1967-68 and 1993-94 drought were probably the most severe of the past 100-years. Data are available from the following streamgage stations (see Figure 2).

Gage	Station Name	Period of Record
50053025	Río Turabo abv Borinquen	1/1/1990 - 2/6/2005
50055100	Río Caguitas nr Aguas Buenas	2/1/1990 - 9/30/2003

Streamgages are not located at the proposed or existing intake sites. This makes it necessary to use streamgage data from one location for estimating daily flows at another location. This is accomplished by multiplying the gaged daily streamflow values at an existing or "index" gage site by a gage factor. This was performed by computing the mean annual flow at both the USGS gage station (the index site) and the point of the proposed waster supply intakes by a regional regression equation developed from streamflow data at 26 long-term USGS gage stations in Puerto Rico with minimal influence by upstream reservoirs, large water supply intakes, and groundwater interactions. An equation was also developed to estimate the minimum flow (Q99). These equations were developed in the DNER "Water Plan for Puerto Rico" (2006) and has the following form:

$$Qmean = 0.0030\ A^{0.87}\ P^{1.61} \qquad \text{Equation \#1}$$

$$Q99 = 8.0 \times 10^{-8}\ A^{1.011}\ P^{3.327} \qquad \text{Equation \#2}$$

Where, Q = mean discharge in cfs, A = watershed area in square miles, and P = mean annual precipitation in inches per year from the Isoheytal Map of Puerto Rico (DNER, 2006). Parameter values are given in **Table 1**.

The last two columns of **Table 1** show the index gage used to simulate streamflow at each ungaged location, and the corresponding gage adjustment factor. Gage adjustment factors have been computed comparing the yield at both locations using the same methodology, the regional regression equation. The ungaged Qbda. Beatriz and Qbda. de las Quebradillas watersheds fall between the gaged Río Turabo and Río Caguitas watersheds. For the Qbda. de las Quebradillas watershed the Río Caguitas streamgage has been used as the index gage as it is the closest gage to that watershed, and for Qbda. Beatriz the Río Turabo gage is used since Qbda. Beatriz is immediately adjacent to the Turabo watershed. The gage adjustment factor is also shown for the use of Río Caguitas as the index gage for Qbda. Beatriz.

Table 1: Parameter Values for Computation of Yields by Regional Equation.

Watershed	Area (mi^2)	Precip. (in/yr)	Mean Flow (cfs)	Index Gage	Gage Adjustment
USGS Gages Used as Index Stations:					
Río Turabo gage 50053025	7.14	93	24.5	Turabo	1.00
Río Caguitas gage 50055100	5.30	68	11.4	Caguitas	1.00
Ungaged Locations:					
Turabo Intake	7.05	93	24.2	Turabo	0.99
Beatriz at Dam	4.50	74	11.3	Turabo	0.46
Quebradillas Intake	6.36	66	12.8	Caguitas	1.20
Pumped Q. Beatriz intake a/	5.64	73	13.5	NA	NA

a/ Pumped intake on Qbda. Beatriz at confluence with Río Turabo, to be abandoned when dam is constructed.

2.3. Long Term Changes in Hydrology

The yield analysis has been performed under the assumption that the period covered by historical streamflow data at the longest-record gages in Puerto Rico (1960-2002) will be representative of 21st century conditions. If droughts become more frequent or more severe, yields will be lower than predicted. At this point we have no data which can be used to reliably predict changes in future rainfall and runoff patterns. Although climate modeling suggests that dry summers may become drier in the Caribbean by mid-century due to global warming (Neelin et. al. 2006), no data or procedures are currently available for developing modified rainfall-runoff scenarios in Puerto Rico.

Long-term rainfall data from U.S. Weather Bureau rain gage stations were analyzed by creation of a mass curve to determine if any increase or decrease total annual rainfall could be observed. A mass curve is simply a cumulative sum of the rainfall over the period of record, and if the long-term rainfall is essentially constant this line will be approximately straight, with deviations for wet and dry years. However, an increase in rainfall will cause the curve to bend upward, whereas a trend of decreasing rainfall will cause the curve to bend down. The created mass curves are presented in **Figure 6.**

The mass curve analyses performed for five rain gages across the island did not reveal any significant deviation in the precipitation regime for the past 50 years. All the developed mass curves show monotonically increasing rainfall accumulations. Linear relationships with no breaks in slope are evident for the entire data periods of the studied gages. This indicates that there has been no long-term change in the cumulative precipitation amounts recorded at the studied gage stations for the past 50 years.

Land use changes will also alter runoff patterns. Because the proposed reservoir receives runoff from watersheds having a relatively small percentage of impervious area, and limited potential for urban expansion, this effect is not anticipated to be significant.

2.4. Minimum Instream Flows

The Q99 value at Río Turabo was based on the gage station data and was determined as 4.36 cfs (2.8 mgd) based on streamflow data at USGS gage 50053025.

The Q99 value for Qbda. Beatriz at the damsite was reported as 0.5 cfs by Gómez-Gómez et. al. (2001) based on 8 low-flow measurements and correlation to gage station 50053025 (Río Tuabo above Borinquen).

The Q99 discharge at the existing PRASA intake was computed for Qbda. de las Quebradillas as 1.7 cfs by application of the gage adjustment factor to the USGS gage on Río Caguitas (gage 50055100).

2.5. Firm Yield of Existing Filter Plant

The Caguas Sur filter plant has two intakes, a gravity intake on Qbda. de las Quebradillas and a pumped intake on Qbda. Beatriz immediately above its confluence with Río Turabo. The total firm yield from these two intakes is 2.2 cfs (about 1.5 mgd).

A non-engineered earthen channel has been dug which can also divert flow from Río Turabo into the Qbda. Beatriz pumped intake, thereby augmenting yield to reportedly sustain about 4 mgd during drought. There is no intake structure in Río Turabo.

2.6. Reservoir Geometry

Reservoir geometry is presented in the form of storage vs. elevation curve in **Figure 7**, based on the data in **Table 2**. Volume was computed from photogrammetric survey with a contour interval of 2 m, and includes a net additional volume of 400,000 m^3 within the live storage zone anticipated by excavation of embankment fill material from below the normal pool elevation and above the dead storage pool, and placed downstream of the reservoir axis.

Table 2: Post-construction Pool Geometry, Beatriz Offstream Reservoir.

Stage (m)	Area (hectares)	Cumulative Volume (Mm^3)
117	0.00	0.00
120	0.76	0.01
125	6.40	0.16
130	11.66	0.61
135	18.26	1.35
140	24.73	2.42
145	33.87	3.88
150	47.20	6.30
155	62.60	9.03
160	75.43	12.48

2.7. Siting Alternatives Considered

The Río Turabo intake location was determined based on the full reservoir level, the pipeline slope required to divert water into the reservoir, the presence of a site on the river with a suitable geomorphic configuration, and maximization of the watershed area tributary to the intake. The reservoir pool was placed at the highest elevation possible to maximize storage and thus firm yield. The normal pool level of 153.1 was selected as a trade-off among factors including topographic limitations of the reservoir site, the Río Turabo intake elevation, and the PMF flood surcharge (flood pool is approximately 2 to 3 m higher than the normal pool, depending on the spillway configuration). It is desired to place the intake at the highest elevation possible to maximize hydraulic head and potentially reduce pipeline diameter, and at the lowest elevation possible to maximize the contributing watershed area and minimize pipeline length. It is also important that the intake location have a stable geomorphic configuration (e.g. rock) to minimize long-term operational problems due to sediment accumulation or scour.

As a result of considering all trade-offs, the proposed intake on Río Turabo has been located immediately downstream of its confluence with an unnamed tributary. This site can be reached through PR-765, 250 meters upstream of the entrance to Felipito Flores community. This area is frequented by recreational bathers, which must be considered in the intake final design.

3. RESULTS

3.1. Storage-Yield Relationship

Several different configurations were tested in the simulation model to evaluate the effect of Río Turabo raw water pipeline diameter and the Qbda de las Quebradillas intake on the firm yield. The configurations tested include the without-project scenario as well as several project configurations, as summarized in **Table 3**. This table shows the yield for the selected pool elevation of 153.1 m, which produces a total volume of 8.0 Mm^3, and a live pool volume of 7.4 Mm^3 used the simulations, leaving 0.6 Mm^3 for the dead pool below elevation 130 m. The rationing pool corresponding to 25% of the live volume, not the dead pool.

The tunnel will not be pressurized and it is probable that the tunnel will induce ground water flow into the reservoir, thereby somewhat increasing the yield above that shown in Table 3. This flow cannot be predicted from the available data and is ignored in yield computations.

The top of the dead pool elevation is defined by the level of the low-level outlet, and represents the lowest level at which water can be withdrawn from the reservoir. The top of dead pool elevation has been set at 130 m in this yield analysis, but it may be increased slightly with little impact on firm yield. This impact on yield may be quantified by the storage-yield curve for the selected alternative.

Table 3: Firm Yield for Alternative Conveyance Configurations.

Scenario	Description	Firm Yield (mgd) a/
Existing Condition	Existing run of river pumped intake on Qbda. Beatriz and gravity intake on Qbda. de las Quebradillas, no instream flow requirement.	1.5 b/
Río Turabo	Río Turabo run-of-river yield at proposed intake	2.8 b/
1	Beatriz reservoir only	5.7
2	Beatriz + Quebradillas 4 mgd max	8.5
3	Beatriz + Turabo 48" + Quebradillas 4 mgd max	13.1
4	**Beatriz + Turabo 54" + Quebradillas 4 mgd max**	**13.5**
5	Beatriz + Turabo 60" + Quebradillas 4 mgd max	13.7
6	Beatriz + Turabo 66" + Quebradillas 4 mgd max	13.8
7	**Beatriz + Turabo D&B Tunnel 108″ + Quebradillas 4 mgd max**	**14.0 c/**
8	**Beatriz+Turabo TBM Tunnel 96″ dia.+Quebradillas 4 mgd max**	**14.0 c/**
9	Beatriz + Turabo 54″ (without Quebradillas intake)	11.0
10	Beatriz + Turabo D&B Tunnel 108″ (without Quebradillas intake)	11.6

a/ All reservoir simulations maintain minimum instream flow of Q99 below Beatriz dam and Río Turabo intake. Quebradillas intake is unchanged and operates, as at present, with at a maximum flow rate of 4 mgd with no instream release requirement.

b/ Q99 values for Qbda. Beatriz (0.5 cfs) translated downstream to the existing pump station (0.6 cfs) and Q99 at Qbda. de las Quebradillas intake (1.7 cfs) per Section 2.4. 2.3 cfs = 1.5 mgd.

c/ D&B = drill & blast tunnel 108″ dia, TBM = tunnel boring machine tunnel 96″ diameter.

The storage-yield curve for the tunnel alternative (the recommended configuration) is presented in **Figure 8.** The curve for the pipeline alternative will be slightly lower but will have the same overall shape. The storage-yield relationships for the 54″ pipeline configuration and the tunnel alternative are also shown in **Table 4.**

Table 4: Firm Yield (mgd) as a Function of Live Storage Volume.

Live Storage (Mm^3)	54″ dia. Pipeline	Tunnel a/
1	7.9	7.8
2	9.4	9.5
3	10.5	10.6
4	11.6	11.7
5	12.4	12.7
6	12.9	13.4
7	13.3	13.9
8	13.7	14.3

a/ Results are essentially identical for either the 108″ D&B tunnel or the 96″ TBM tunnel.

3.2. Recommended Configuration

The recommended conveyance configurations from **Table 3** will consist of either the 54″ pipeline (Alternative #4), a 108″ diameter tunnel excavated by drill and blast methods (Alternative #7), or a 96″ diameter tunnel excavated by tunnel boring machine (Alternative #8). For all conveyance systems the upstream water surface elevation at the Río Turabo intake should allow full flow with a water surface elevation not lower than 159 m, and the downstream centerline elevation of the discharge into the reservoir should be set not higher than 148 m.

The recommended reservoir capacity is 7.4 Mm^3 of live pool, which can be achieved by a normal pool elevation of 153.1 m and setting the bottom of the live pool at 130 m.

The existing Qbda. de las Quebradillas intake should be maintained as a variable rate intake with a maximum flow rate of 4 mgd. It may operate by either gravity or by pump station. It may deliver water directly to the reservoir, or water may be withdrawn from the Quebradillas pipeline and delivered directly to the filter plant before this water actually reaches the reservoir. The firm yield is identical for either case.

A behavior diagram illustrating the daily variation in water storage over the simulation period for the Río Turabo tunnel alternative is presented in **Figure 9**. The behavior for the pipeline alternative is almost identical.

3.3. Firm Yield Reduction by Sedimentation

The firm yield estimate excludes the 0.6 Mm^3 dead pool volume, which is equivalent to about 50 years of sediment volume. Live storage will be reduced to 6 Mm^3 after approximately 80 additional years of sedimentation. Thus, with reference to Table 4, after 130 years of operation, sedimentation will have reduced firm yield by between 0.4 and 0.5 mgd, depending on whether the pipeline or tunnel is used. This represents less than a 4% reduction in firm yield over the next 130 years without any dredging. In the case of the tunnel alternative, firm yield would still be above 13 mgd 130 years in the future if current climatic conditions persist.

3.4. Instream Flow

The sequence of daily flows below the proposed Río Turabo intake are illustrated for pre-and post-project conditions in **Figure 10**. The exceedance curve for mean daily flows comparing the pre-project and post-project conditions are presented in **Figure 11.**

The pre-project Q99 discharge for Río Turabo at the intake is 0.123 m^3/s (4.36 cfs). No graph is shown for Qbda. Beatriz as there is no gage record for this stream.

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FIGURES

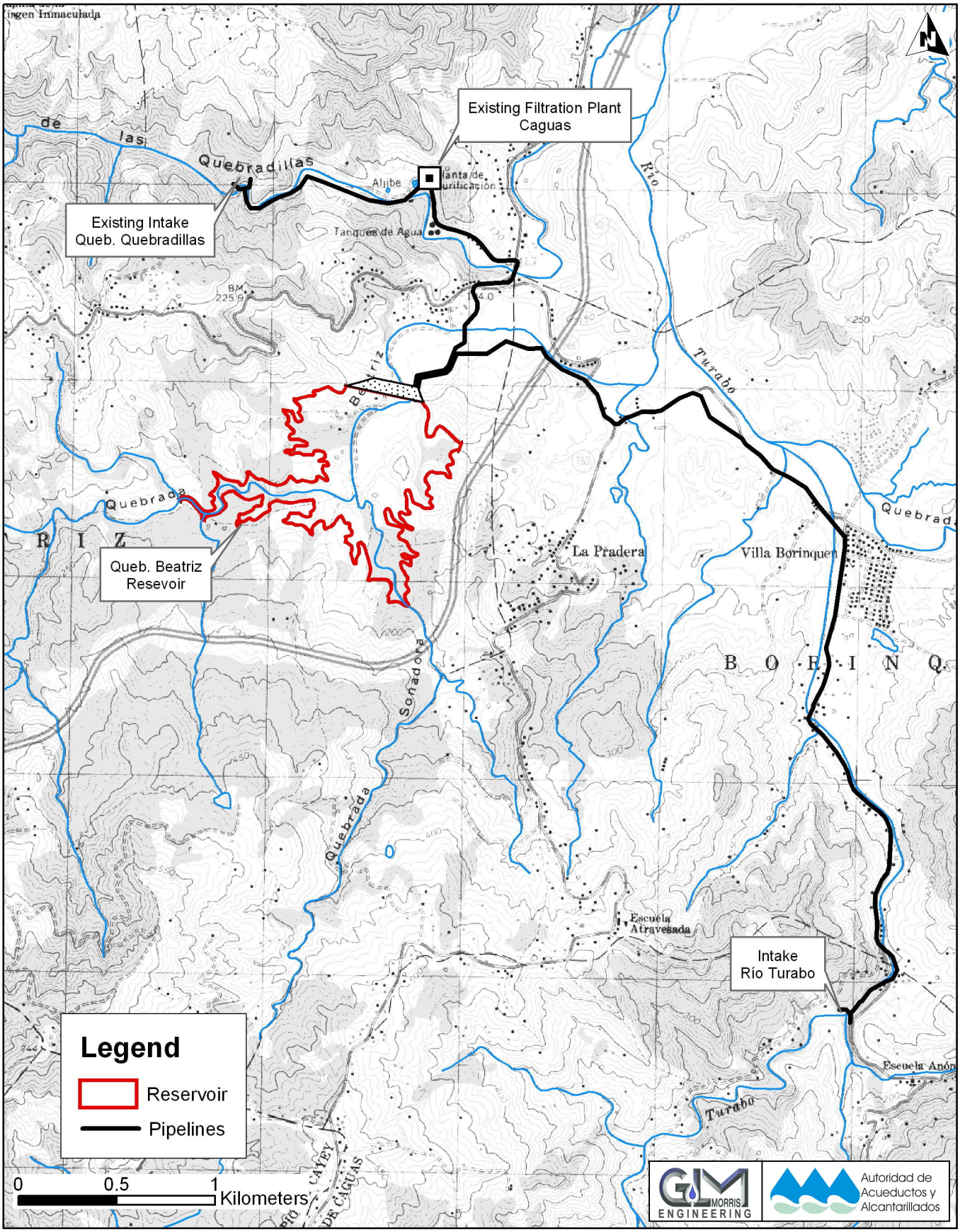

Figure 1: Location of the proposed Quebrada Beatriz reservoir site, water supply pipelines and intakes.

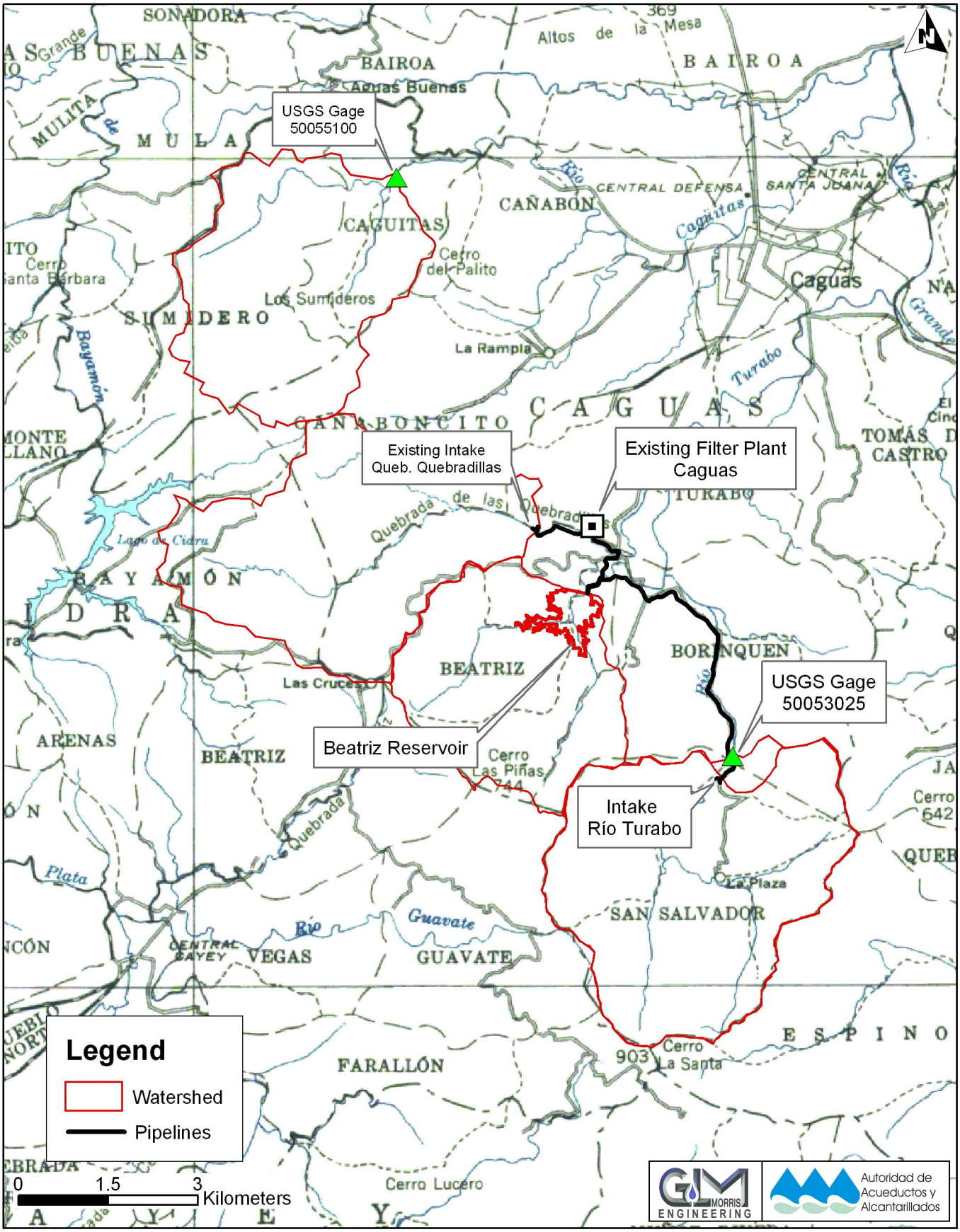

Figure 2: Location of streamgage stations and watershed limits used in the analysis of Quebrada Beatriz reservoir.

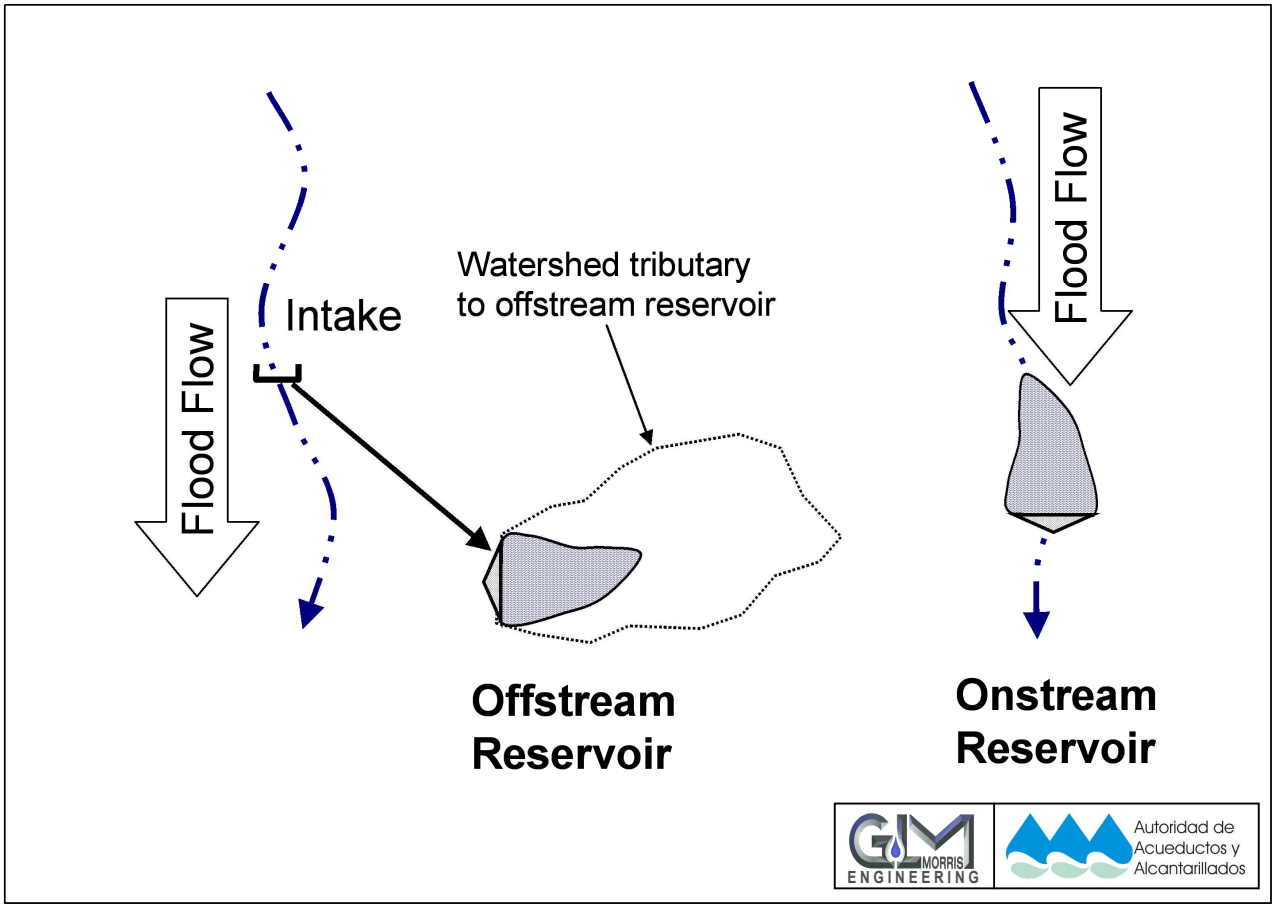

Figure 3: Conceptual difference between an onstream reservoir and an offstream reservoir.

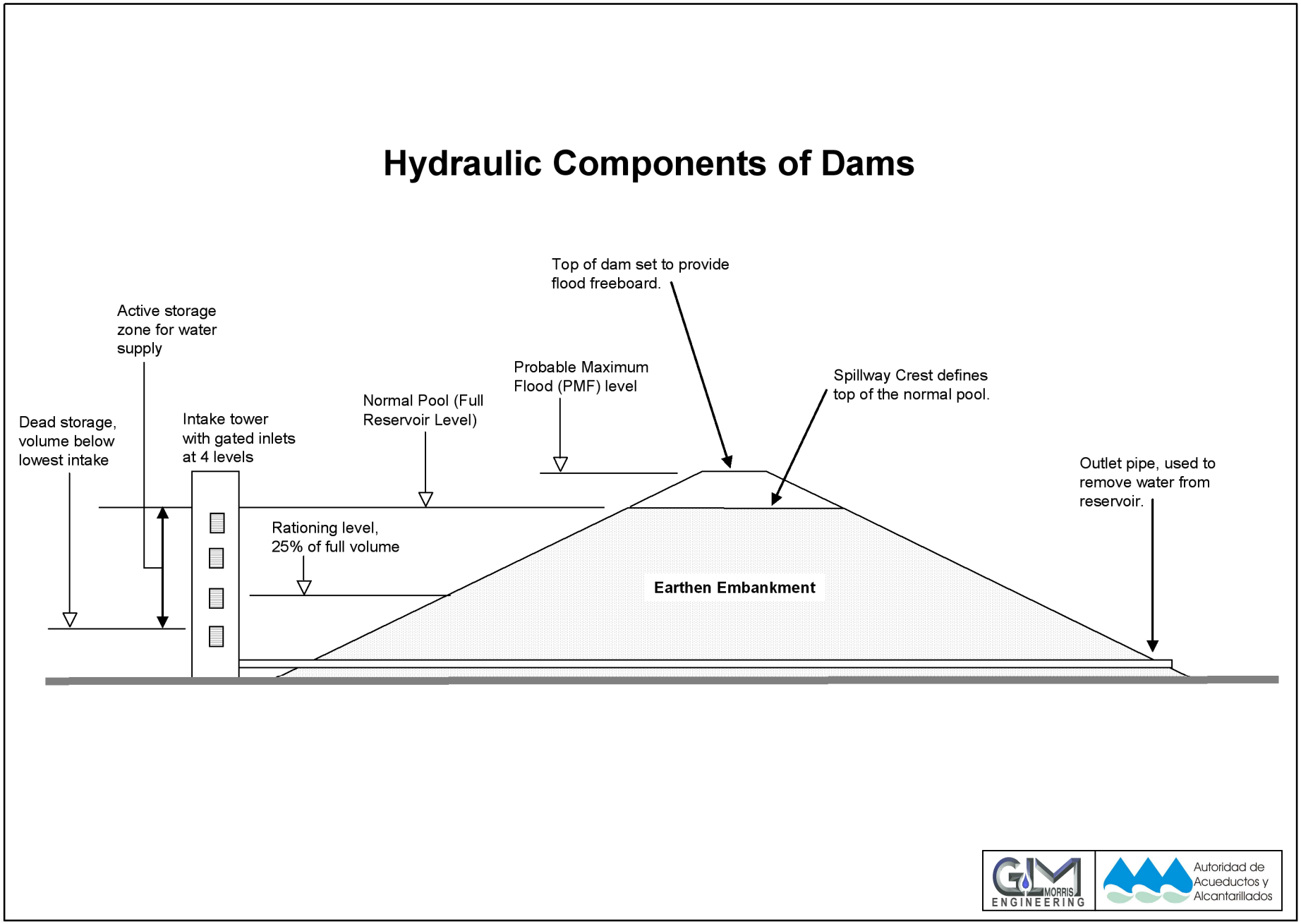

Figure 4: Hydraulic components of dams.

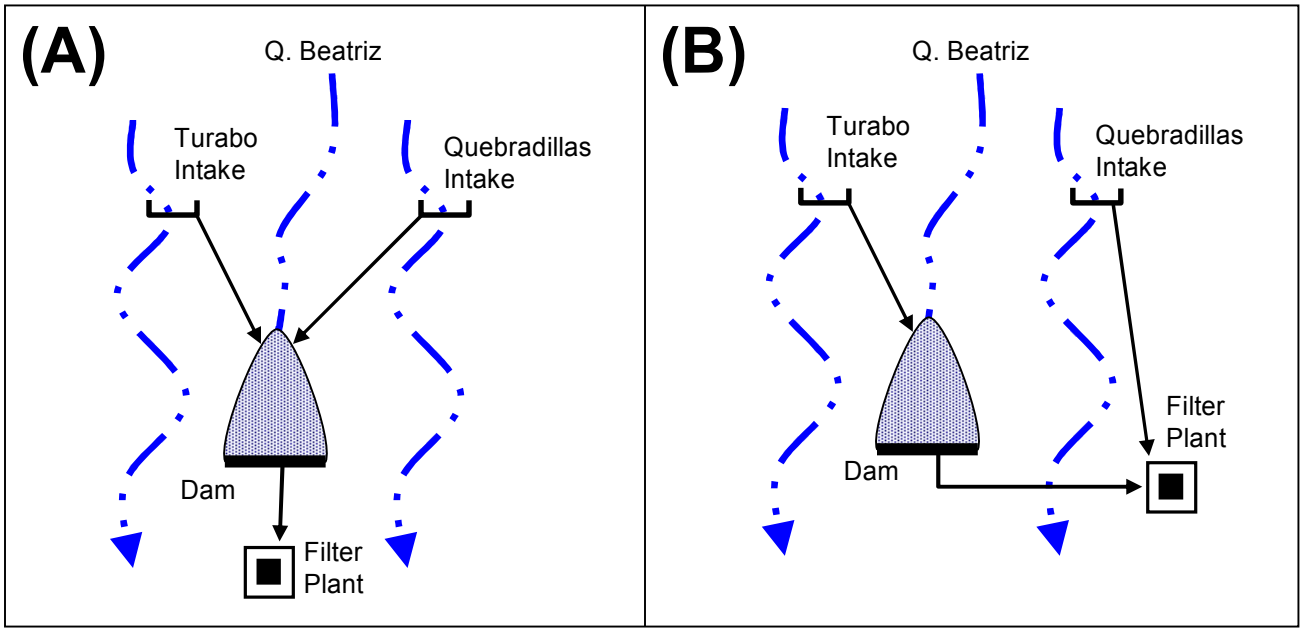

Figure 5: Alternative water supply configurations. (A) Both offstream intakes operate at variable rates and deliver water directly to the reservoir. The reservoir delivers water to the filter plant at a constant rate. (B) Existing Q. de las Quebradillas intake delivers water to the filter plant at a variable rate, and the reservoir also delivers at a variable rate, such that the sum of the two sources is a constant inflow rate. The overall water balance and firm yield are identical for both configurations.

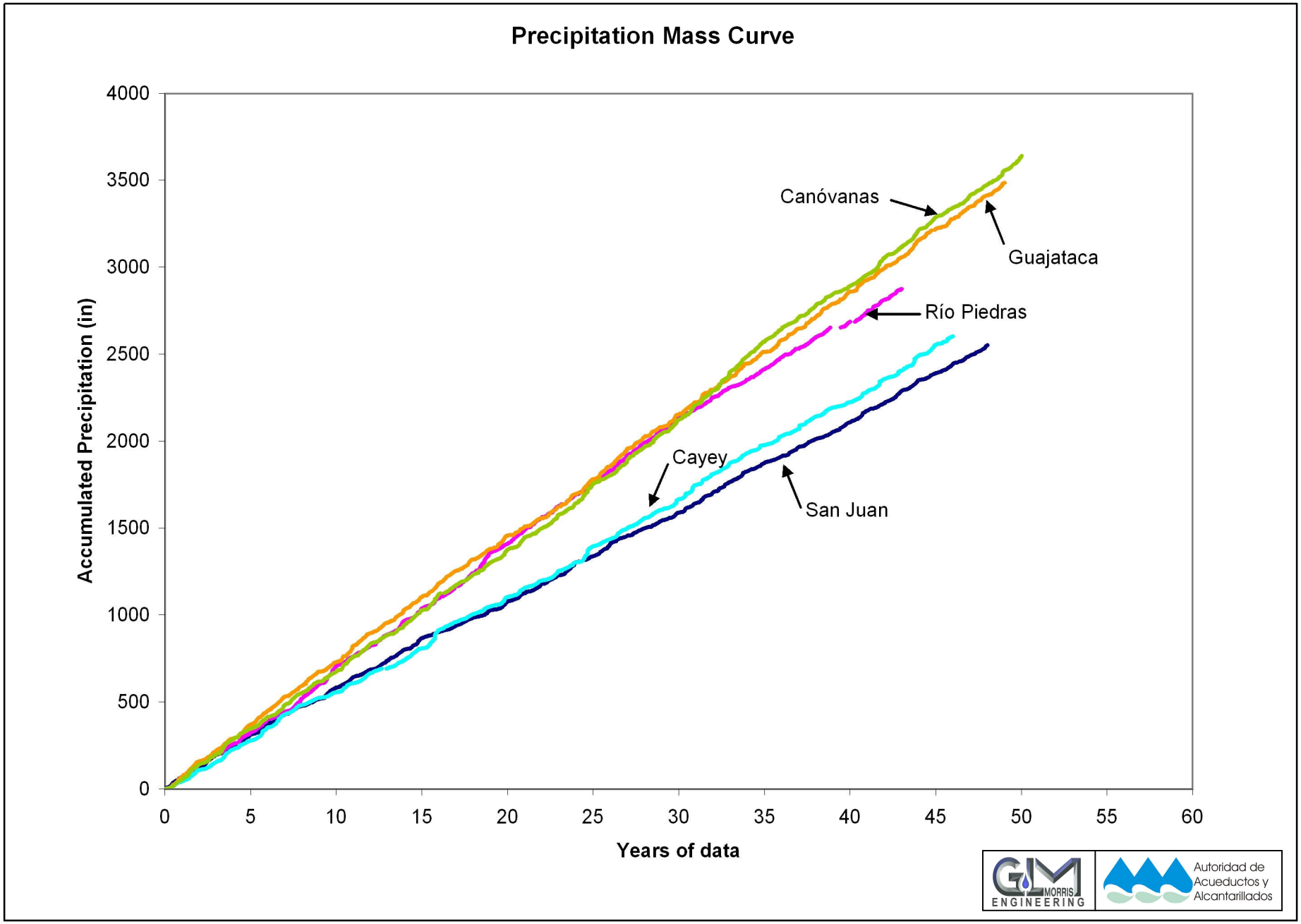

Figure 6: Mass curve analysis performed for 5 rain gages across the island indicating that there is no long-term trend of increasing or decreasing rainfall.

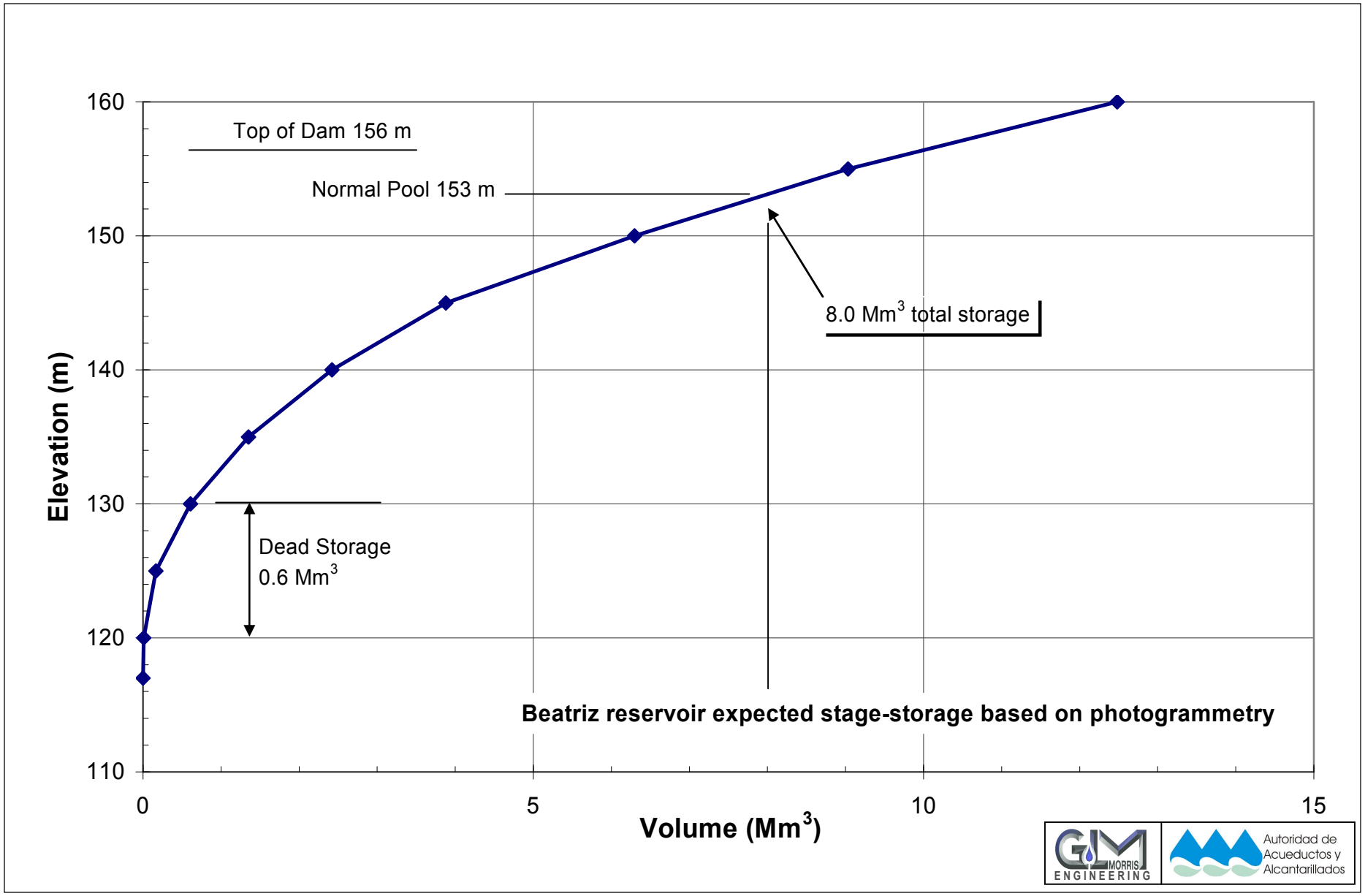

Figure 7: Stage-volume relationship for Beatriz reservoir site, based on photogrammetric survey plus 400,000 m^3 of net volume increase within the live storage zone anticipated from excavation of embankment fill material from below the normal pool level.

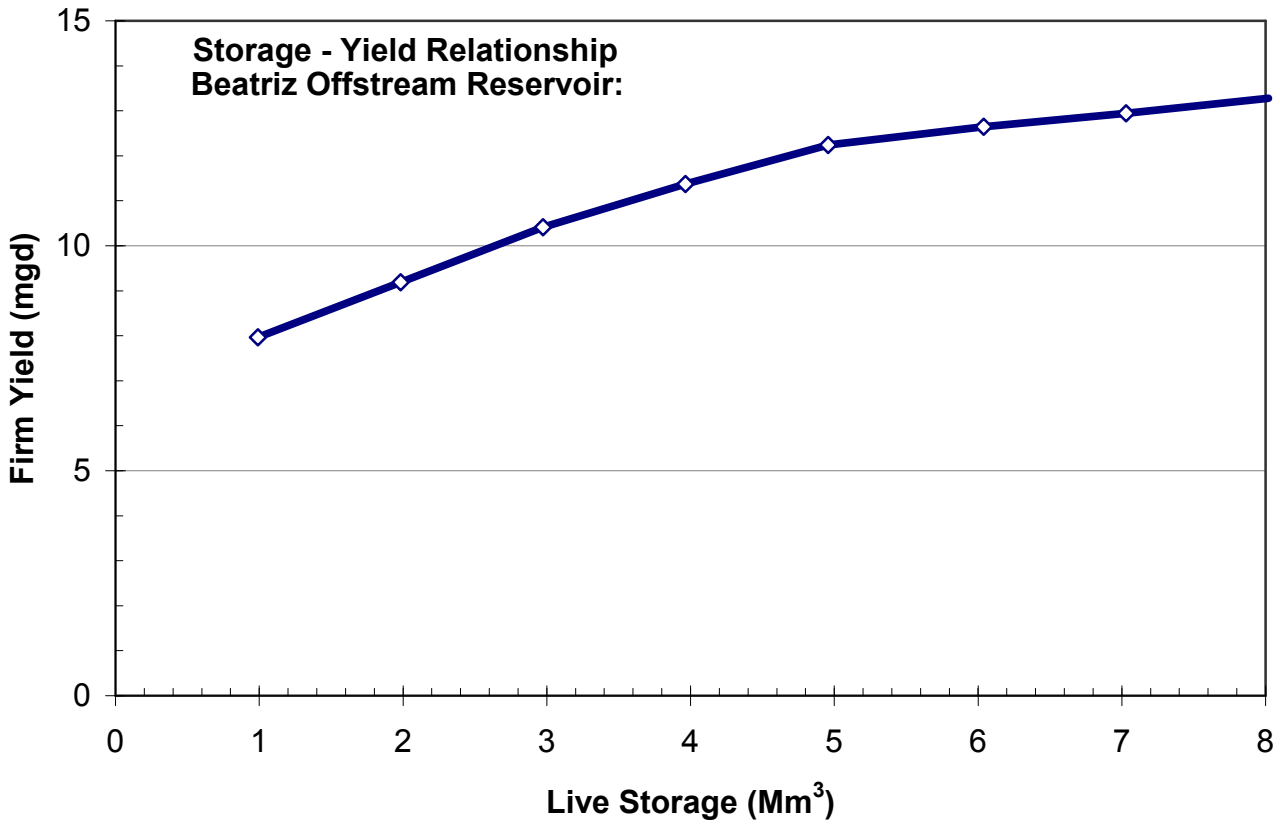

Figure 8: Yield as a function of storage for Beatriz offstream reservoir.

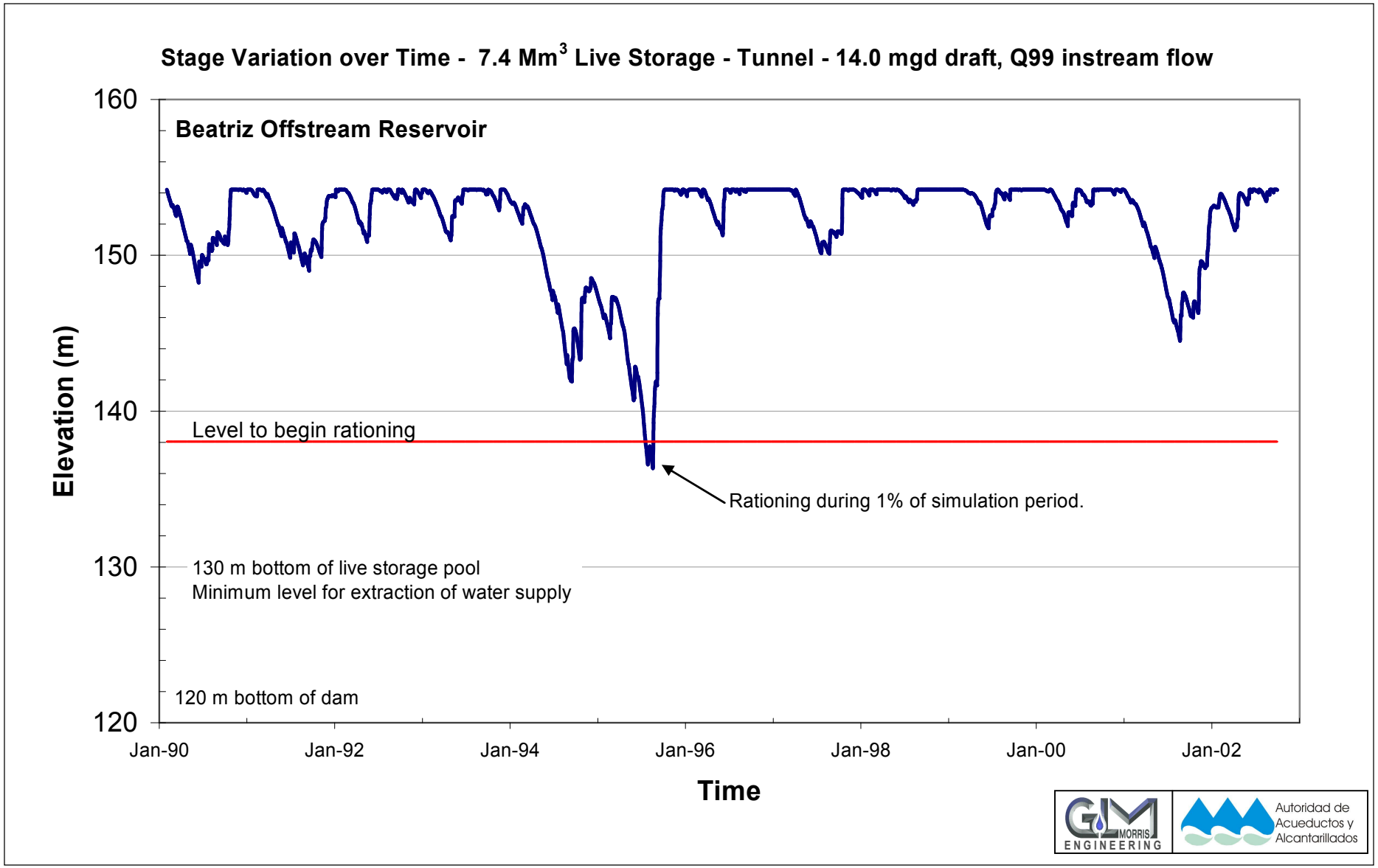

Figure 9: Behavior diagram for Q. Beatriz reservoir showing the variation in water level over time for the firm yield condition. Drought conditions during 1994-1995 define the critical design conditions for this reservoir.

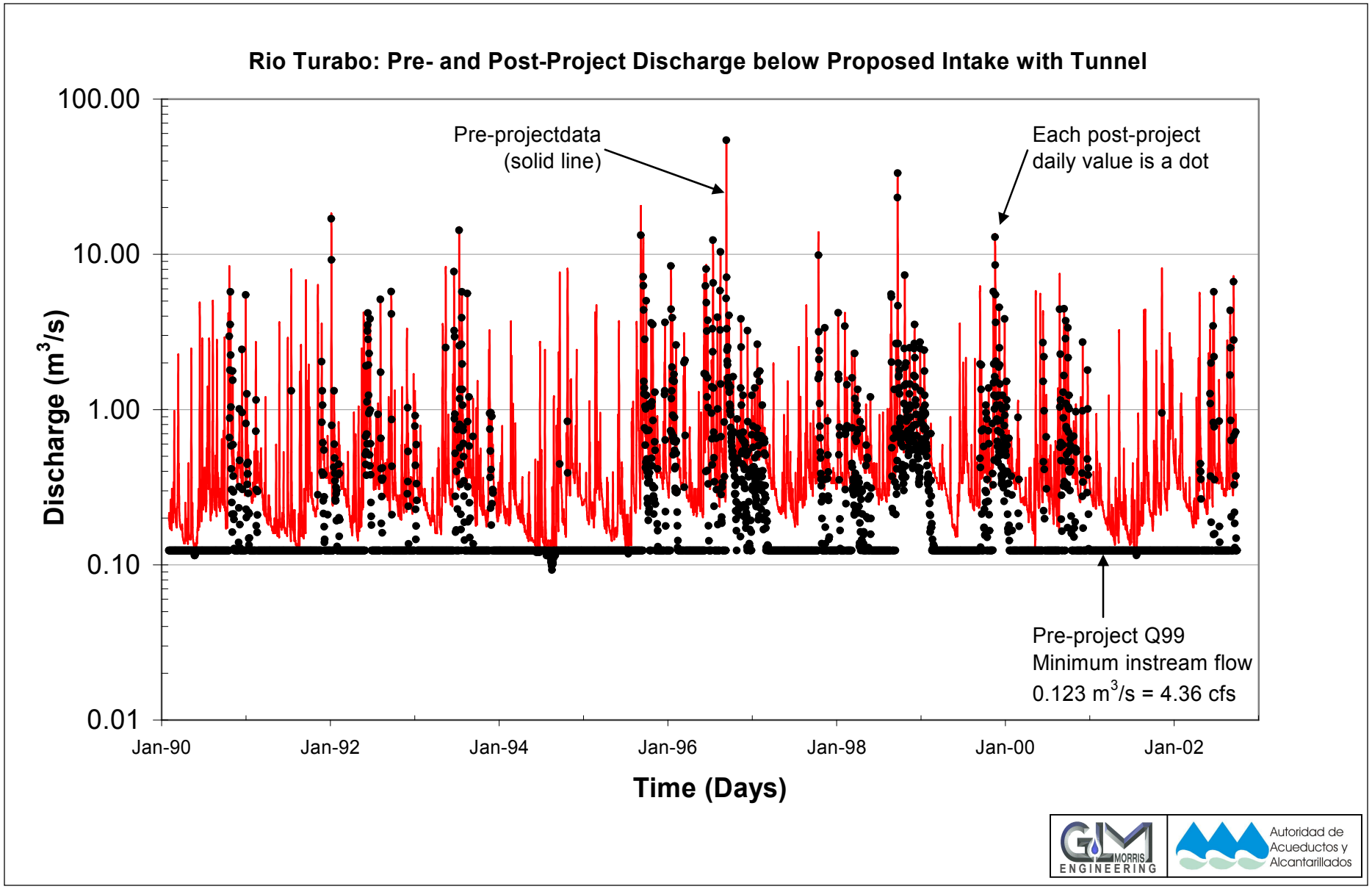

Figure 10: Mean daily stream flow in Río Turabo below the proposed intake for pre- and post-project conditions, by daily simulation of the historical streamflow dat aset.

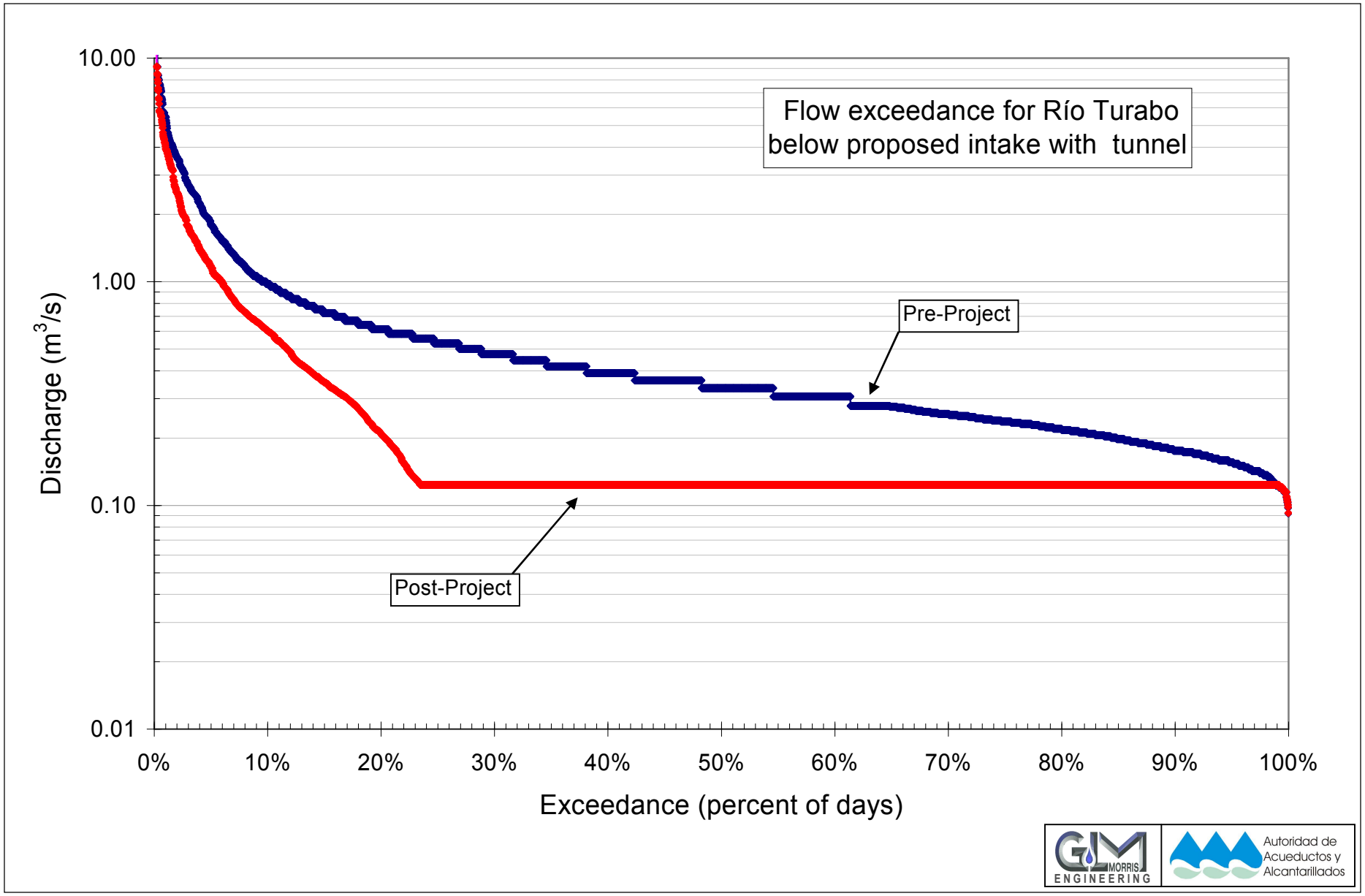

Figure 11: Instream mean daily flow, exceedance curve for Río Turabo below proposed intake, pre- and post-project conditions.