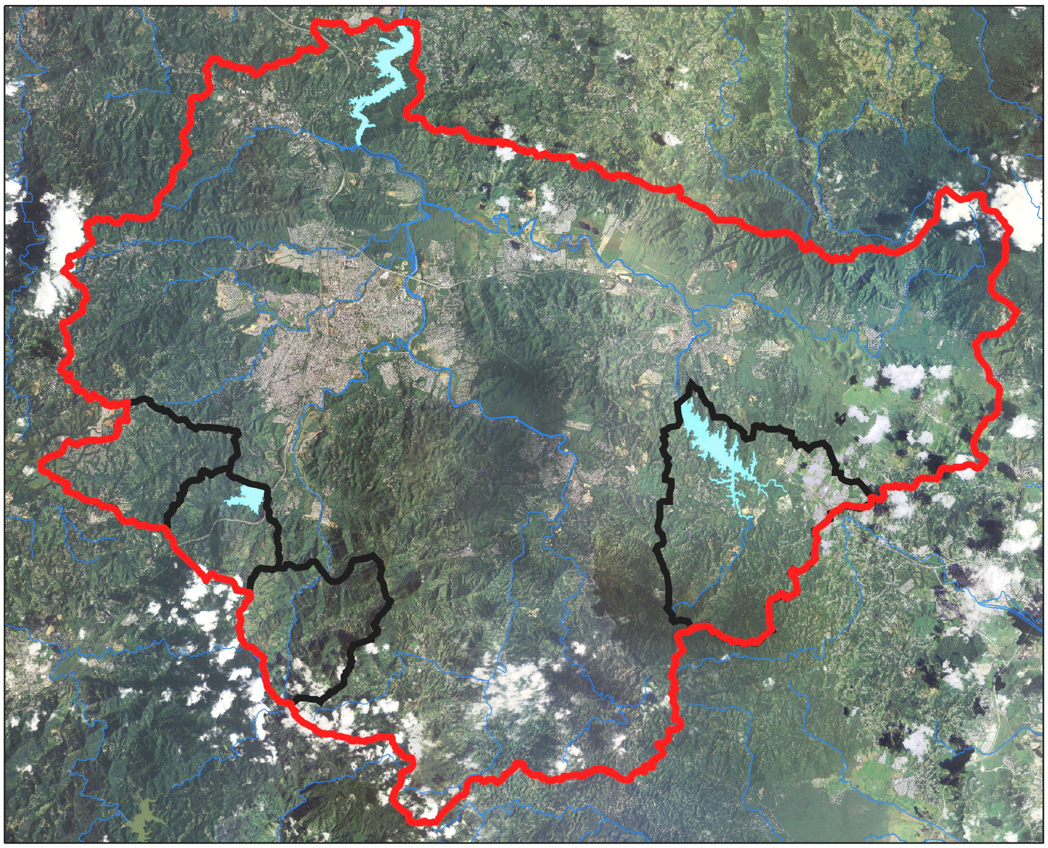
Cumulative Impact of Proposed Beatriz and Valenciano Reservoirs on Carraízo Reservoir Firm Yield



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1. INTRODUCTION

1.1. Study Purpose and Location

This study analyzes the impact of constructing two proposed new reservoirs, Valenciano and Beatriz, on the firm yield of the existing Carraízo (Loíza) reservoir. All reservoirs are single-purpose municipal water supply reservoirs located in the Loíza watershed, and the two proposed reservoirs are to be located upstream of Carraízo, which is the principal source of water supply to San Juan. The location of the three reservoirs is shown in the location map (Figure 1). There are no other reservoirs in the Loíza watershed.

This analysis: (1) determines the firm yield for Carraízo reservoir, (2) generates streamflow data for each of the two upstream reservoirs operating at their firm yield, and (3) determines the probable impact of the two upstream reservoirs on the firm yield at Carraízo.

1.2. Limitations

This analysis has been undertaken using the best hydrologic and operational data available. However, drought events vary in severity, and there are also inaccuracies inherent in hydrologic data. These limitations, which are inherent in any yield analysis, should be considered when interpreting the results.

1.3. Authorization

This study has been authorized by CSA Engineers, as project managers representing the Puerto Rico Aqueduct and Sewer Authority.

2. STUDY CONCEPTS

2.1. Definition of 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 is computed from the following parameters:

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

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, and Instream Flow = minimum flows that must be released to the river. In a conventional reservoir this flow is released at the dam, but for the intake supplying the offstream reservoir this flow simply remains in the river. There is no difference from the standpoint of water budget computations. Time is indicated as t and t+1, using a time step of one day. Because rainfall equals or exceeds evaporation, the net losses to evaporation are approximately zero and are not counted.

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. 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.

Rationing is implemented as a 25% reduction in rate of withdrawal (draft), and this flow is sustained on all rationing days. In all simulations rationing begins when the reservoir level has dropped to 25% of the active storage volume. All simulations include the continuous release of a minimum environmental flow, including rationing days.

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.

2.2. Upstream Reservoir Impacts on Firm Yield

Construction of new reservoirs in the Loíza watershed upstream of the existing Carraízo reservoir will increase the total amount of storage volume and thus will increase the firm yield for the entire watershed. However, the net effect of upstream reservoirs on the firm yield at Carraízo reservoir will depend on the fate of the upstream extracted water. For example, if 100% of the water extracted from upstream reservoirs is pumped into another watershed, or is evaporated, then the return flow to streams which enter Carraízo will be zero. Under this scenario the firm yield at Carraízo will diminish. However, if 100% of the water extracted from the upstream reservoirs is returned to the streams and flows into Carraízo following municipal use and treatment, then the firm yield at Carraízo will actually be increased due to the upstream reservoirs. This occurs because, under this scenario, water released from storage at the upstream reservoirs during drought would be delivered to Carraízo via treated wastewater effluent, thereby increasing reservoir inflow during the drought period. Thus, Carraízo benefits directly from the upstream storage.

The actual amount of return flow from the upstream reservoirs will fall between the two extremes of 0% and 100% considered in these two scenarios, and at some intermediate value there will be a net effect of zero on Carraízo yield.

Under a third scenario, a new reservoir may replace water supplies which are currently being imported from another region. To the extent that the new reservoirs produce water which is delivered to new users, then it can contribute to an increase in wastewater flow which will eventually enter Carraízo. However, to the extent that the new reservoirs replace water which is being imported from outside of the region, there is no net increase in regional wastewater flows, and an imported source of water is being eliminated from the area tributary to Carraízo.

The flow of treated wastewater which enters Carraízo can also be increased by extension of the sanitary sewer network to include unsewered areas, since a substantial part of the flow from septic tanks is probably captured and transpired by plants. This may also occur independent of new reservoir construction.

2.3. Return Flow Estimate

The following values of return flow have been used in determining the volume of wastewater delivered to customers that is returned to the wastewater treatment plant:

88% of residential water deliveries and 100% of non-residential water deliveries. Infiltration has been computed on a per-customer basis as given in **Table 1**.

Table 1: Infiltration Rates Used in Calculations (CSA 2007a).

Municipality	Infiltration (gal/customer/day) a/
Caguas	44.55
Gurabo	46.65
Juncos	45.30
San Lorenzo	45.15

a/ Computed based on number of residential customers.

Projected wastewater flows are summarized in **Table 2**. This corresponds to the total increase in wastewater flow resulting from both the extension in sewerage collection systems into previously unsewered areas plus new construction.

Table 2 also shows the wastewater flow increase from 1993 to 2025. This represents the increase since the 1994 drought which was used for calibration of the gage adjustment factor for streamflow entering Carraízo reservoir. This will be explained in more detail in Section 3.6.

Table 2: Projected Wastewater Flows Plus Sewer Infiltration Tributary to Carraízo (mgd).

	Year			
Municipality	1993 b/	2000	2010	2025
Caguas a/	7.54	11.3	13.1	14.7
Gurabo b/	1.03	1.4	1.8	2.4
Juncos b/	0.84	1.5	2.1	2.5
San Lorenzo b/	0.65	1.1	1.4	1.5
Infiltration	3.04	2.6	5.5	6.2
Total	13.10	17.9	23.9	27.3

a/ Projected wastewater volume based on population and water use projection provided in the P-EIS for Beatriz Reservoir (GME, 2007).
b/ Data and projections provided by CSA (2007a)

3. METHODOLOGY

3.1. Analysis Overview

The analysis has been performed with the two long-term gage stations in the Loíza basin above Carraízo reservoir, supplemented by data from gage stations with shorter records on streams supplying Beatriz and Valenciano reservoirs. These shorter gage records include the 1994-95 drought but which do not include the more severe 1967-78 drought.

Firm yield at Carraízo was determined by the long-term dataset for the Gurabo and Loíza gage stations and the computed gage factor. The shorter-term datasets (1990 – 2003) were the only datasets available for all three reservoirs, and were used to make the following determinations:

- A constant value of the gage factor relating flow at the Gurabo and Loíza gages to reservoir inflow was determined by calibration. The 1967-68 drought could not be used for this purpose due to lack of data on reservoir level and pumping rates from the reservoir.
- Compute the yield at Carraízo for the post-1990 period (the 1994-95 drought).
- Compute the sensitivity of yield at Carraízo to changes in the percentages of return-flow from the upstream reservoirs during the post-1990 period.
- Determine the percentage of return-flow which produces a zero impact on yield at Carraízo during the post-1990 period.

There have been no significant drought events following the 1990-2003 study period.

3.2. Reservoir Characteristics

Characteristics of the analyzed reservoirs are summarized in Table 3. Reservoir volumes cited herein are always active or "live" volumes; the dead pool is not included. The Carraízo volume corresponds to 2007 and the new reservoir volumes correspond to the condition following construction. The Capacity:Inflow (C:I) ratio refers to the ratio of live volume to mean annual inflow and is a measure of a reservoir's capacity in relation to its tributary inflow. At Beatriz, an offstream reservoir, the tributary inflow is taken as the discharge from the watershed above the dam plus the watersheds above the two intakes (proposed Río Turabo intake and existing Qbda. de las Quebradillas intake).

Simulations are run for zero downstream release at Carraízo dam and for Q99 below Qbda. Beatriz dam, below Río Turabo intake to Beatriz, and below Valenciano dam.

Table 3: Summary Characteristics of Studied Reservoirs.

Name	Volume (Mm^3)	Watershed Area (km^2)	Mean Annual Inflow (Mm^3)	C:I Ratio
Carraízo	16.3 a/	537.87 b/	318	0.05
Beatriz	7.0	45.51	37.9 c/	0.18
Valenciano d/	11.7	38.25	40.1	0.29

a/ 2007 volume extrapolated from Soler-López and Gómez-Gómez, 2005.
b/ Includes watersheds of the two proposed upstream reservoirs.
c/ Based on total flow tributary to dam plus flow at Río Turabo intake plus flow at Qbda de las Quebradillas intake, which will be delivered directly to the filter plant but which contributes to reservoir yield.
d/ P-EIS for Valenciano dam (CSA, 2007b).

3.3. Data Sources

The gage stations used in the analysis are listed in **Table 3** and are shown in **Figure 2.** The gages for the long-term analysis are Loíza and Gurabo, each with continuous datasets starting in 1959. We also obtained operating records for the Sergio Cuevas filter plant which is supplied by Carraízo reservoir.

Table 4: USGS Stream Gage Stations Used in the Analysis.

Gage Station	Watershed Area (km^2)	Period of Record
Rio Loíza below dam (50059050)	541.3	12/25/1986 – 4/4/2007
Rio Gurabo at Gurabo (50057000)	155.9	10/1/1959 - 4/4/2007
Río Loíza at Caguas (50055000)	232.6	11/17/1959 – 4/4/2007
Río Valenciano nr Valenciano (50056400)	42.5	1/28/1971 - 4/4/2007
Río Turabo abv Borinquen (50053025)	18.5	10/1/1989 - 4/4/2007
Río Cagüitas nr Aguas Buenas (50055100)	13.7	2/1/1990-11/17/2003
Lago Loiza at Damsite nr Trujillo Alto (50059000) (gage reports water level in the reservoir)	Level	1/6/1988 – 4/4/2007

3.4. Model Calibration

Reservoir yield at Carraízo is determined by the long-term gages at Gurabo and Loíza. The period of record for these two gages includes both the 1967-68 and 1994-95 droughts, of which the 1967-68 drought was the more severe.

During the 1994-95 drought Carraízo reservoir did not fill for a period of 200 days, and during this period of drawdown we constructed a water balance across the reservoir based on the following data.

1. Daily stream inflow was from the Gurabo and Loíza gage stations. The combined discharge at these gage stations was multiplied by a constant gage factor, computed by trial-and-error based on the water balance calibration across the reservoir during the 1994-95 drought, as described below.
2. Withdrawals by Sergio Cuevas filter plant were computed as the filter plant production (**Figure 3**), plus an additional 3% to account for filter backwash. The percentage value for filter backwash was based on the 1999 period, when filter plant records included both actual deliveries ("agua servida") as well as total treatment volume which includes water used for backwash ("agua tratada"). Backwash water is not returned to the reservoir.
3. Leakage through gate seals at Carraízo dam, as recorded at the USGS gage station immediately below the dam (gage 50059050).
4. Water level in the reservoir, as recorded by USGS gage, converted to volume based on the stage-storage curve appropriate for the 1994-95 period as reported by Webb and Soler-López (1997) based on reservoir bathymetry.

Calibration was performed during the drought period when there are no spills from the reservoir. This period represents hydrologic conditions during the critical period from the standpoint of yield analysis. Additionally, when the reservoir spills the flow volumes are large and the error inherent in stream gage measurements and calculations will become significant in relation to the flow pumped to the filtration plant.

The simulation was performed starting with the reservoir full and the gage factor was adjusted by trial and error to achieve the best possible match between the observed water levels reported by the USGS and the levels calculated by simulation. The resulting gage factor applied to the total discharge of Loíza + Gurabo gages was 1.22, and the water levels resulting from this calibration are illustrated in **Figure 4**.

The gage factor relating the combined flow at the Gurabo and Loíza gages to reservoir inflow incorporates the following water balance components between the gage stations and the point of withdrawal from the reservoir: (1) the net balance between wastewater discharges and any additional downstream extractions, including the effect of the Caguas regional wastewater treatment plant which discharges to the reservoir downstream of the USGS gage stations; (2) the net balance of interactions between the stream and the shallow ground water system including the possible influence of operation of the Bairoa wells; and (3) the net balance between rainfall and evaporation.

The calibration results were considered reasonable, and this methodology represents the preferred method to determine the gage factor from the data that are available.

3.5. Simulation of Upstream Reservoir Impacts

For the existing condition the simulation of Carraízo reservoir behavior was performed using the sum of the historical gaged inflow at the Loíza and Gurabo stations, multiplied by the gage station adjustment factor as determined by calibration.

For the analysis of yield at Valenciano reservoir the USGS gage on Río Valenciano (50056400) was used. This gage was not adjusted for any upstream withdrawals, since the USGS data indicate that there were no upstream withdrawals during the critical drought (1994-95).

For analyzing yield at Beatriz reservoir, the gage stations on Río Turabo (50053025) and Río Cagüitas (50055100) were used as described in the yield analysis for that reservoir included as an appendix to the P-EIS document for that reservoir (GME, 2007).

Because the same historical file is being used to simulate the proposed condition, it is necessary to modify the historical streamflow file tributary to Carraízo to simulate the net effect of the proposed reservoirs. The Valenciano reservoir will modify the Río Gurabo streamflow dataset while the Beatriz reservoir will modify the Río Loíza streamflow dataset.

- Valenciano. The flow record for USGS gage station 50056400 (Río Valenciano) was multiplied by 0.91 to represent the flow which is tributary to the proposed dam site, and this volume of water was subtracted from the Gurabo gage on a daily basis. The computed flows below the dam, consisting of minimum instream flow plus spills, was then added to produce a dataset at the gage station representative of post-project conditions with the reservoir.

- Beatriz. At Beatriz reservoir, which is supplied from three streams, the total inflow into Beatriz reservoir from all three sources was computed. However, because these three streams are also affected by the existing gravity and pumped intakes which currently supply the Caguas Sur filter plant, it was necessary to calculate the net impact of the project. This was done by reducing the total inflow by the extraction of 4 mgd which this filter plant was able to sustain during the drought by a temporary flow diversion from Río Turabo in addition to the intakes on Qbda. Beatriz and Qbda. de las Quebradillas. This correction was applied to the Loíza gage daily data.

3.6. Wastewater Return Flow

Most of the wastewater flows in the region are generated at the Caguas regional wastewater treatment plant, and the regional importance of this plant will increase even further as a result of its planned year 2011 expansion by 12 mgd (to a total capacity of 24 mgd). This expansion will handle increased wastewater flows within the region due to growth, expansion of the sewerage collection network into unsewered areas, plus elimination of smaller upstream wastewater plants and diversion of their flow into the regional treatment plant. Return flow of treated wastewater discharged to streams tributary to Carraízo was previously presented in **Table 2**.

The Caguas regional wastewater treatment plant discharges to Río Bairoa less than 1.25 river miles (2 kilometers) from the backwater region of Carraízo reservoir, and thus the entire discharge will be delivered to the reservoir.

The Carraízo gage adjustment factor was calibrated to the drought period of 1994 includes the effect of all wastewater flows in the region. Wastewater flow data are available for 1993 and have been used as indicative of year 1994 wastewater flows. Wastewater discharges in 1994 should be smaller than 1993 due to the lack of water supply due to rationing during the drought. Therefore, computation of the increase in wastewater flows based on 1993 as the starting point will produce a conservative value; actual increases should be larger than those computed by **Table 2**.

Because wastewater flows are essentially discharged directly into the reservoir at a nearly constant rate of flow, it is not necessary to specifically include this flow in the simulation analysis. Rather, wastewater flows may be directly added to the firm yield of Carraízo reservoir.

During drought when there is rationing, and little rainfall, both the volume of wastewater discharge and the infiltration volume will be reduced. Wastewater discharge may be expected to decline, approximately, in proportion to water deliveries. If rationing produces a 25% reduction in water deliveries (the rationing rule used in this analysis), wastewater flow should also decline by approximately 25%, resulting in return flows that are 75% of normal. The increase in wastewater inflows to Carraízo are computed in **Table 5** based on data previously presented in **Table 2** and using different rationing scenarios.

Table 5: Increase in Wastewater Flows Tributary to Carraízo as a Function of Rationing, Using 1993 as Base Year.

Rationing	Flow Increase over 1993 (mgd)	
	Year 2010	Year 2025
No rationing (normal flow)	10.8	14.2
Return flow = 75% of normal	8.1	10.6
Return flow = 50% of normal	5.4	7.1

4. RESULTS

4.1. Yield at Carraízo from Long-term Dataset

The daily simulation model of Carraízo reservoir was run for the entire period of record using the calibrated gage adjustment factor to produce the simulated long-term behavior diagram shown in **Figure 5** which corresponds to a firm yield of 63 mgd. This same simulation model indicates a yield of 78 mgd based on the 1994-95 drought, with withdrawals being reduced to 59 mgd during rationing (as compared to the actual reduction in production to a minimum of 24.5 mgd due to rationing, per **Figure 3**).

Yield at Carraízo are shown in **Table 6** for each of the upstream reservoir alternatives, for the normal wastewater return flow rate and for the most extreme scenario of a 50% reduction in wastewater return flow. Yield at Carraízo increases slightly, despite the upstream reservoirs projects. Thus, the increase in upstream yield does not occur at the expense of a yield reduction at Carraízo even under severe drought conditions.

Table 6: Yield at Carraízo (mgd) Without Considering Wastewater Return Flows, year 2025.

Scenarios	Carraízo Firm Yield a/ (mgd)	Change in Carraízo Firm Yield vs. Percent Return Wastewater Flow (mgd)		
		Zero Return Flow	100% Return Flow b/	50% Return Flow b/
Simulation Period 1959 to 2007, Full Historical Dataset for Carraízo:				
Carraízo only, Firm Yield	63.3			
Simulation Period 1990 to 2003, Zero Return Wastewater Flows:				
Carraízo only	78.5			
Carraízo + Beatriz	75.9	-2.6	11.6	4.5
Carraízo + Valenciano	76.2	-2.3	11.9	4.8
Carraízo + Beatriz + Valenciano	71.7	-6.8	7.4	0.3

a/ Does not take into consideration changes in Carraízo volume and yield due to sedimentation.

b/ Computed by adding to the "zero return flow" value the amount of wastewater return flow per Table 5.

5. CONCLUSIONS

The analysis undertaken has produced the following conclusions.

1. The long-term yield at Carraízo reservoir is 63 mgd based on a year 2007 live pool volume of 16.3 Mm^3, and the critical drought event is 1967-68. By comparison, and using the identical methodology, the yield at Carraízo would be calculated at 78 mgd if only the 1994-95 drought is taken into consideration.

2. If there is no additional return flow into Carraízo reservoir from treated wastewater effluent, the two projects will decrease the yield at Carraízo reservoir by approximately 6.8 mgd, per **Table 6**.

3. Average wastewater flows entering Carraízo reservoir are anticipated to increase by about 10.8 mgd to 14 .2 mgd by year 2010 and 2025 respectively (**Table 5**).

   With construction of the two upstream reservoirs, temporary rationing beyond a 25% reduction of water deliveries should not be required within their service areas, as shown in Table 6. Under this scenario, the wastewater return flows into Carraízo reservoir for both 2010 and 2025 (**Table 5**) exceed the 6.8 mgd reduction in firm yield due to upstream reservoir construction. Under this scenario the yield at Carraízo will be slightly increased by the combination of both reservoirs plus increased wastewater flows.

   Even if wastewater inflows are reduced by as much as 50%, an extreme rationing scenario and one not contemplated with the new reservoirs, year 2025 wastewater inflows into Carraízo will still exceed the reduction in inflow caused by construction of both Beatriz and Valenciano reservoirs. Therefore, firm yield at Carraízo will not be reduced even under this extreme scenario.

4. In conclusion, and as illustrated in Table 6, construction the Valenciano reservoir, the Beatriz reservoir, or the combination of both reservoirs, will not reduce the firm yield at Carraízo reservoir. Rather, as a result of return wastewater flows these new reservoirs are anticipated to generate a small increase in Carraízo firm yield.

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FIGURES

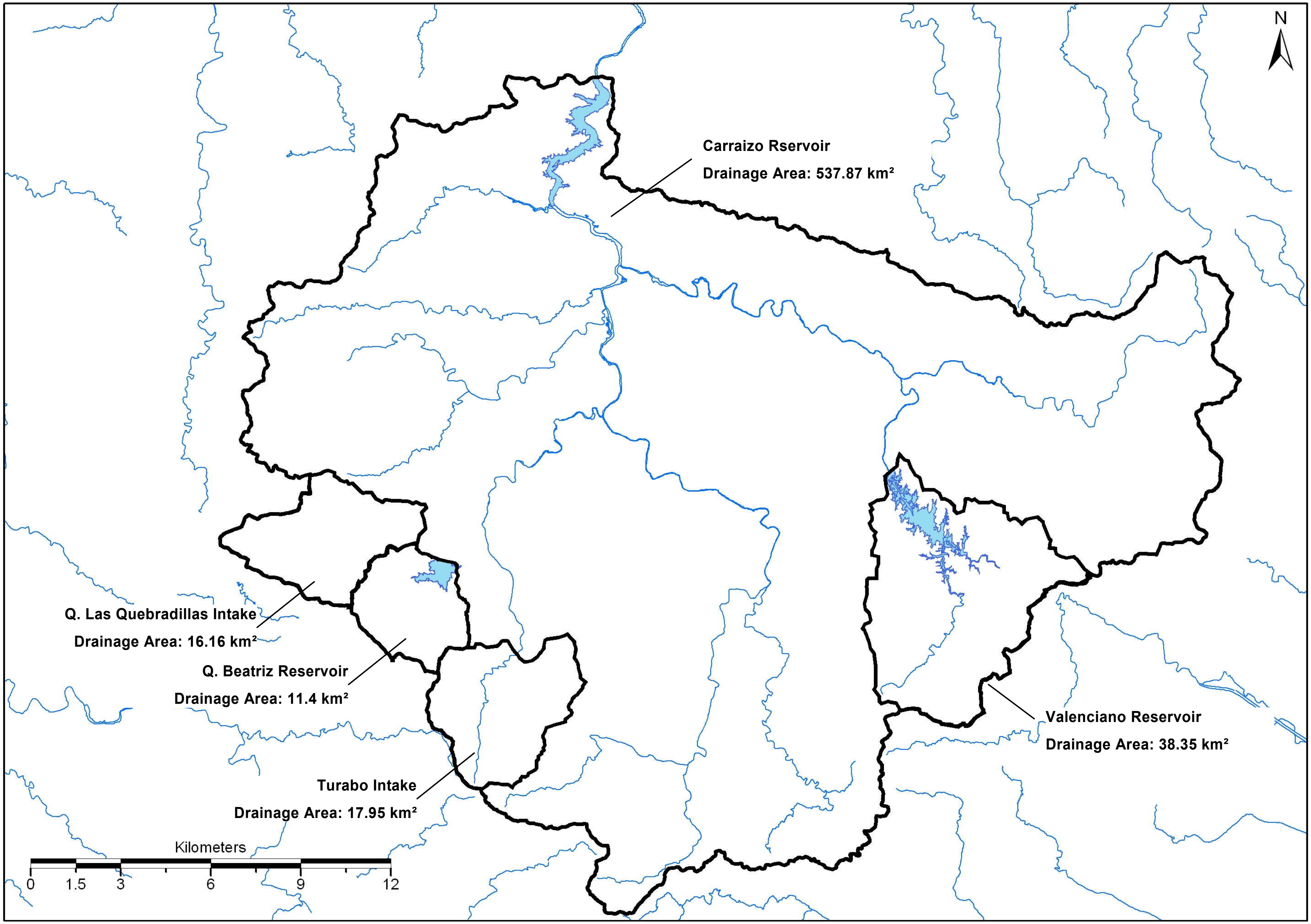

Figure 1: Location map showing the three reservoirs under analysis and their tributary watersheds.

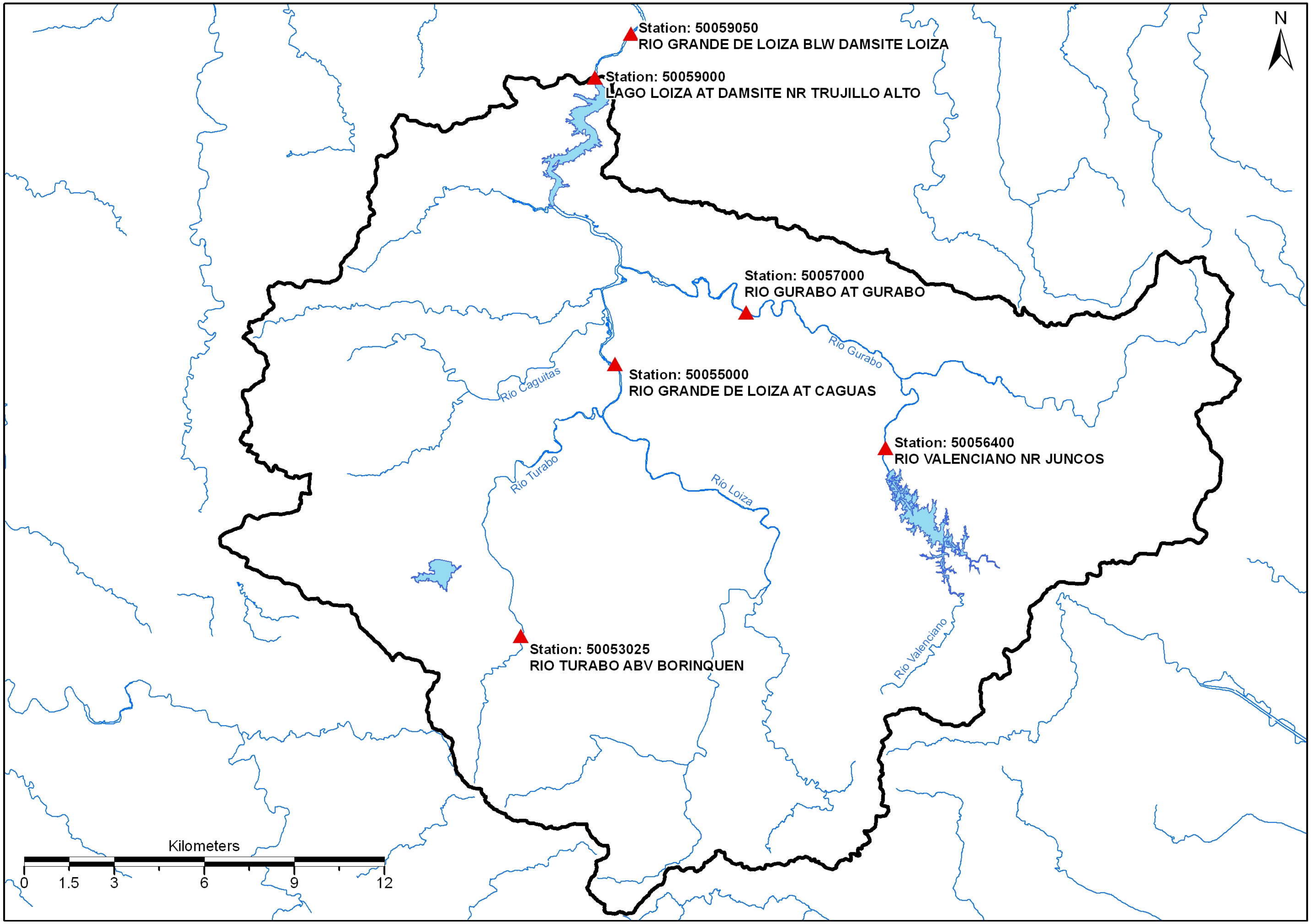

Figure 2: Location map showing the USGS gage stations used in th e analysis in relation to the reservoirs.

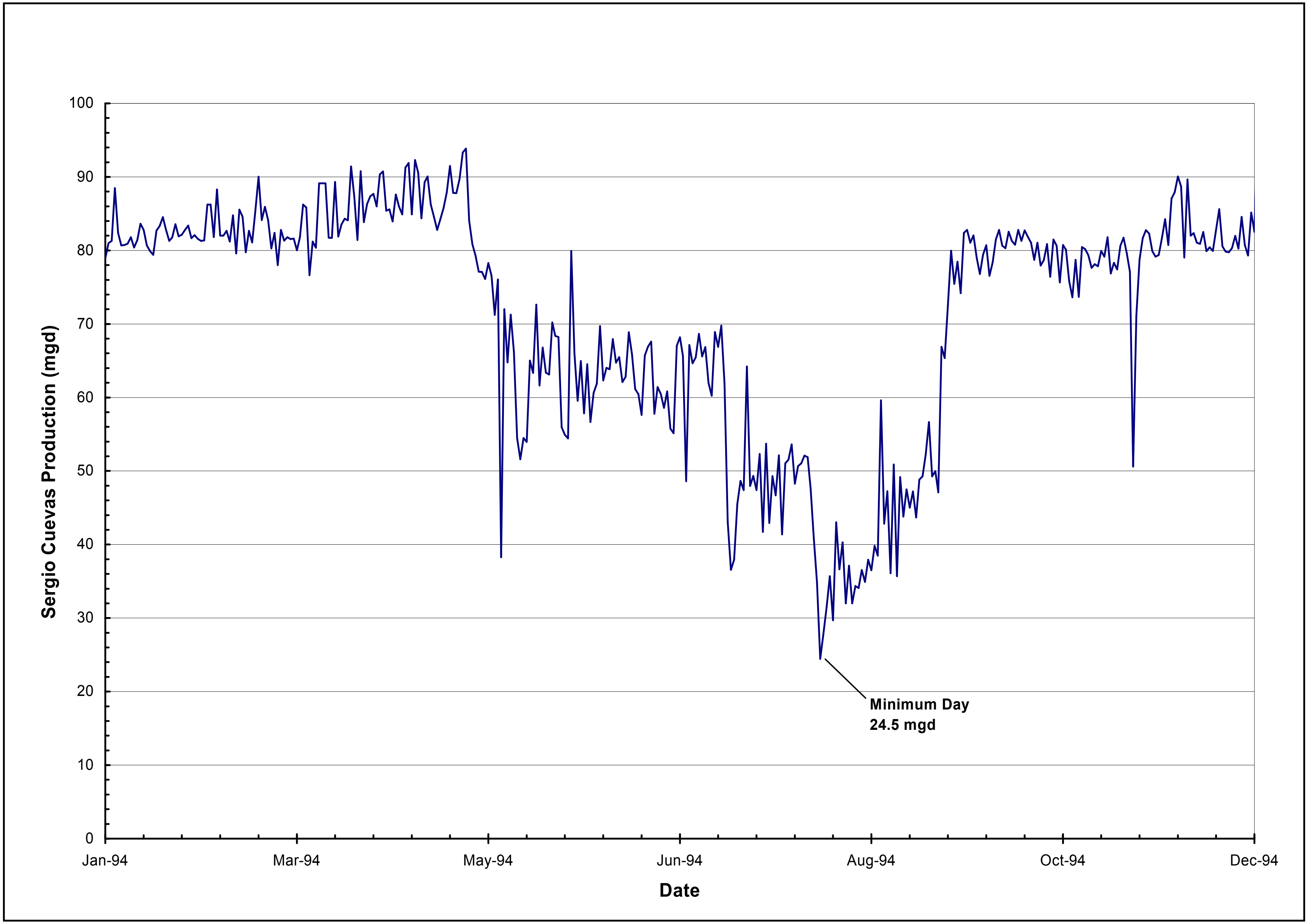

Figure 3: Water production at Sergio Cuevas filter plant during the calibration period, not including water used for filter backwash. (Source: PRASA operational records at Sergio Cuevas filter plant).

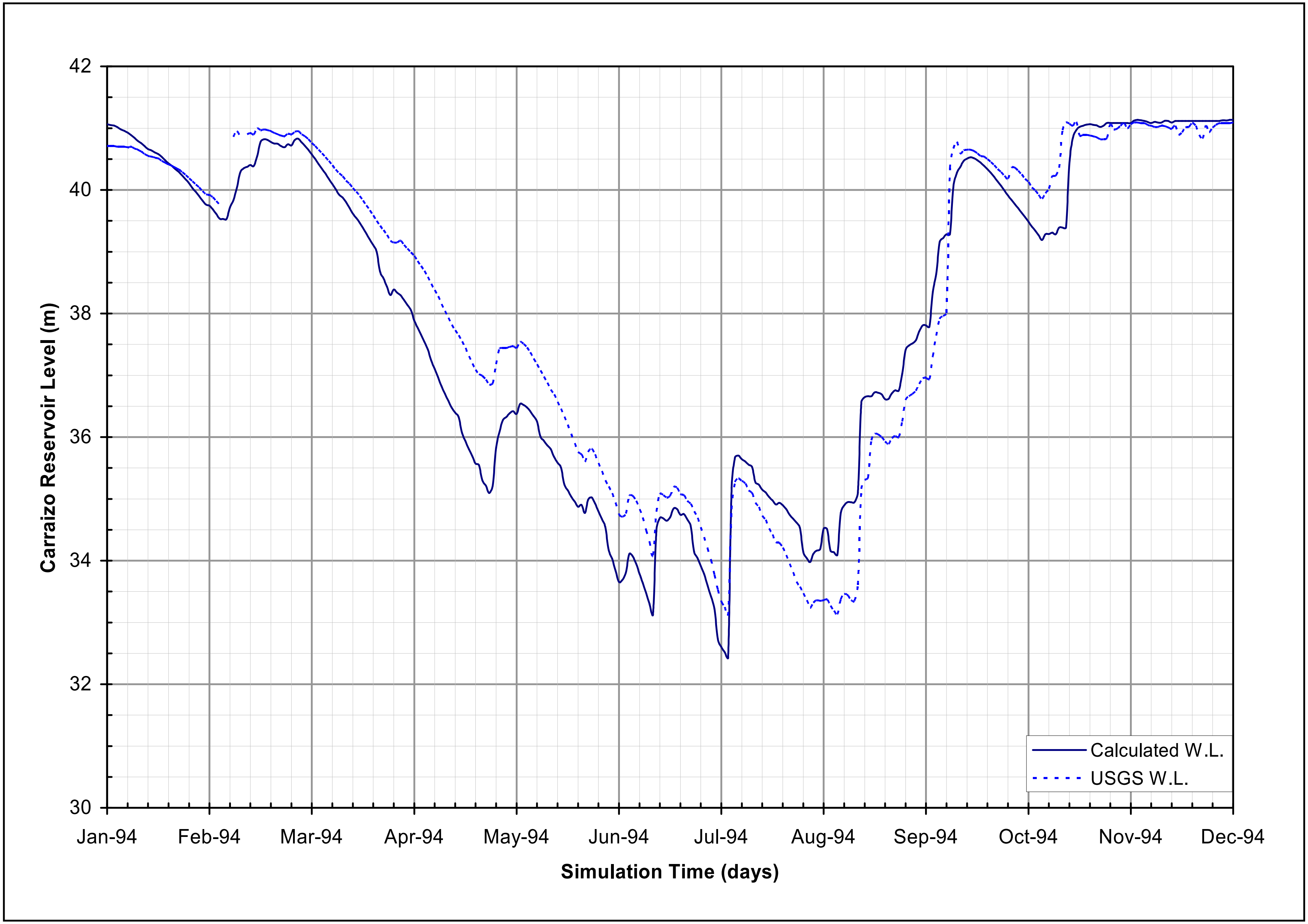

Figure 4: Observed and calibration water levels in Carra ízo reservoir during the calibration period.

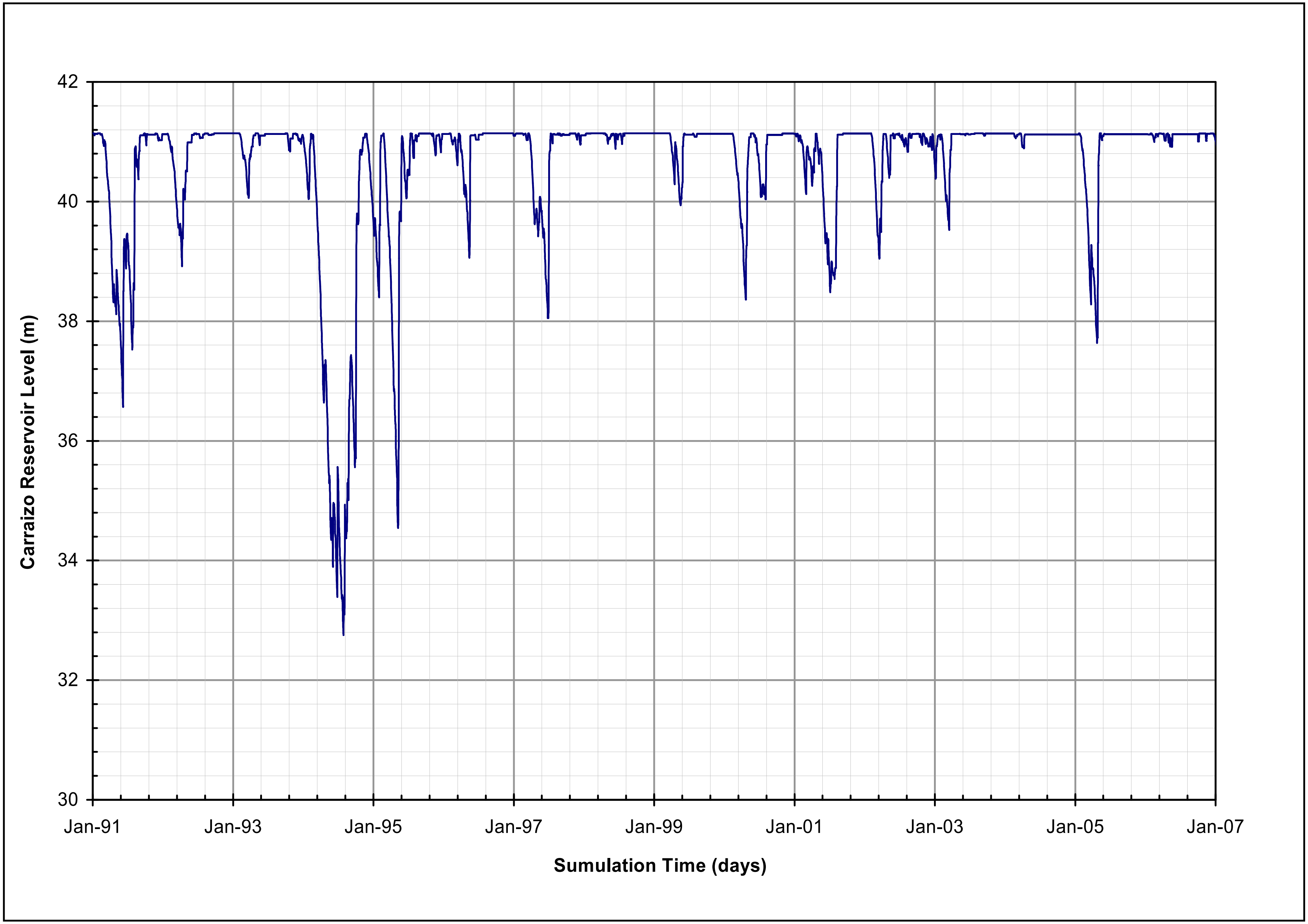

Figure 5: Long term behavior diagram for Carraízo reservoir, without upstream reservoirs.