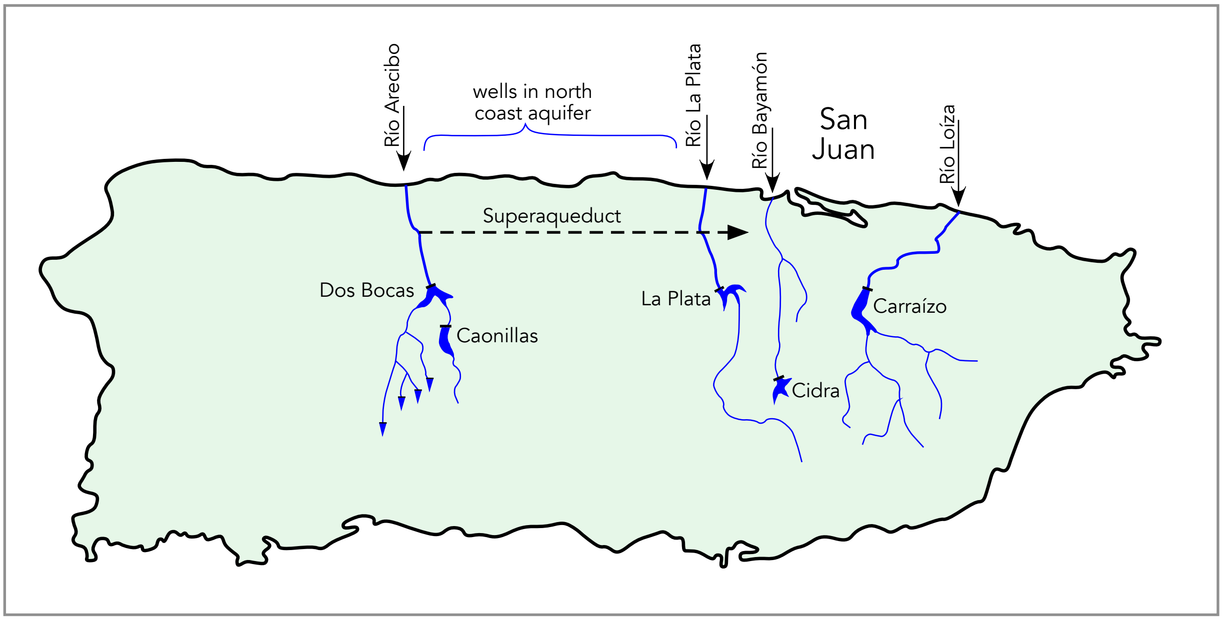
Solving Persistent Water Supply Problems in Puerto Rico: Critical Problems and Actions

White Paper Prepared for ASCE Infrastructure Committee

(American Society of Civil Engineers, Puerto Rico Section, www.asce.org)

San Juan Puerto Rico



December 15, 2020

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CONTENTS

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Abbreviations used in this document:

Mgd	million gallons per day
Mm^3	million cubic meters
PRASA	P.R. Aqueduct & Sewer Authority
PREPA	P.R. Electrical Power Authority

Resumen Ejecutivo

Después de la sequía de 1994, que dejó el Área Metropolitano con servicio intermitente de agua, PRASA comprometió mil millones de dólares en gastos de construcción e intereses del financiamiento para realizar el Superacueducto y su sistema de interconexiones, y el dragado del Embalse Carraízo. (Hoy seguimos pagando los prestamos para dichos proyectos.) Se anunció que el Superacueducto eliminaría el racionamiento de agua en el futuro. Sin embargo, racionamiento severo (servicio de agua cada tercer día) ocurrió nuevamente en 2015, y racionamiento cada segundo día ocurrió en 2020. A pesar de gastos masivos, el problema no se resolvió porque las "soluciones" no fueron enfocados en resolver la sobre-explotación del Embalse Carraízo, problema que al día de hoy persiste.

Si las próximas "soluciones" no subsanan las deficiencias en el diseño y manejo hidrológico del sistema de abasto, los gastos futuros serán igualmente inefectivos que los pasados. Para poder mantener el suministro del agua en el Área Metro de San Juan durante sequía, es esencial entender varios conceptos claves:

1. **El dragado no ofrece protección contra futuro racionamiento**. Ningún volumen de dragado en Carraízo será capaz de resolver el problema de sobre-explotación.
2. **El dragado de Carraízo no es necesario.** Se puede controlar la sedimentación, de manera permanente, utilizando otras técnicas mucho menos costosas.
3. En vez de dragar Carraízo, dedicar los fondos disponibles hacia acciones que <u>SÍ PUEDEN</u> sostener el suministro del agua durante sequía. Específicamente, **para eliminar el racionamiento futuro se debe convertir el manejo de los embalses y pozos de la costa norte a una regla operacional de *uso conjunto*. Esta es la única estrategia que puede eliminar el riesgo del racionamiento severo, y lograr este resultado rápidamente y a bajo costo**. La mayor parte de la infraestructura necesaria ya existe, pero requiere operarla de manera distinta. La clave es incorporar un sistema de pozos con alta capacidad para utilización únicamente durante periodos secos. La mayoría de los pozos necesarios ya existen, pero actualmente están fuera de servicio. También se requieren mejoras al sistema de transmisión.

Este documento resume los conceptos fundamentales de hidrología e ingeniería que apoyan las conclusiones presentadas. Además, se identifican varios otros temas relevantes al abasto de agua.

Para resolver los problemas existentes, más los retos que representan la austeridad fiscal y el cambio climático, se requiere el manejo eficiente de la infraestructura existente. Durante el siglo pasado se enfocó en la construcción de obras, pero el siglo 21 requiere un enfoque de manejo eficiente en base a la ciencia de hidrología y las mejoras prácticas para resiliencia y sostenibilidad. Al fallar con esto, la ausencia de agua en nuestros grifos e inodoros será, una vez más, una fuente de frustración y coraje la próxima vez que deje de llover.

Executive Summary

Following the 1994 drought that left the Metropolitan Area with only intermittent water service, PRASA committed $1 billion in construction plus financing costs to build the Superaqueduct, its interconnections, and to dredge Carraízo reservoir. (Today we are still paying the loans on these projects.) It was announced the Superaqueduct would eliminate future water rationing, yet severe rationing (water available every 3rd day) occurred again in 2015, and every-other-day rationing occurred in 2020. Despite massive expenditure, the problem was not solved because the "solutions" did not resolve the problem of over-drafting at Carraízo reservoir, which was the root cause of water rationing in the first place and which continues unresolved to this day.

If the next set of "solutions" do not resolve existing hydrologic deficiencies in water supply design and management, new expenditures will be just as ineffective as the past ones. To sustain water supplies during drought it is essential to understand several key concepts:

1. **Dredging cannot protect the San Juan Metro Area from future rationing**. No amount of dredging will overcome the over-drafting problem at Carraízo.
2. **Dredging of Carraízo reservoir is not necessary.** Sedimentation can be permanently controlled by a much less costly method.
3. Instead of dredging, allocate funds to actions that CAN sustain water supplies during drought. **To eliminate future rationing, convert management of north coast reservoirs and wells to a *conjunctive use operating rule*. This is the only way the risk of severe water rationing can be eliminated quickly and economically**. Most of the required infrastructure already exists, but it needs to be operated differently. The key is to incorporate high-capacity ground water supplies into the system for use only during drought. Most of the needed wells already exist but are currently out of service. Transmission improvements will be required.

This paper outlines the basic hydrologic and engineering concepts that support the above conclusions. Several additional relevant water supply topics are also identified.

To solve existing problems, plus the challenges posed by fiscal austerity and climate change, requires efficient management of existing infrastructure. The past century focused on new project construction, but the 21st century requires a focus on efficient management of this infrastructure based on the science of hydrology and best practices for resiliency and sustainability. Failing at this, the absence of water in our faucets and toilets will once again feed our frustration and anger the next time it stops raining.

1. Introduction

Municipal water supply systems in developed countries are designed and operated to continuously deliver water, even during drought. Water use restrictions may be implemented during drought but the water supply is never turned off. In contrast, for decades the Puerto Rico Aqueduct and Sewer Authority (**PRASA**) has simply accepted the practice of "rationing" during drought by shutting off the water supply, a strategy characteristic of 3rd world countries. This occurred in 1974, 1994, 1995, 2015, and 2020.

The 1994 drought saw the San Juan metro area suffer for months as water supplies were available only every 2nd or 3rd day (Figure 1). On the day allocated to water supply, some areas saw water pressure arrive after midnight and dwindle away again by 6 AM. Schools closed, business was interrupted, and everyone suffered.

10 DE AGOSTO DE 1994

EL NUEVO día 35¢ metro

para el Secretario federal de Agricultura

VEA LA PAGINA 32

cubano durante un secuestro

De 36 a 40 horas sin agua

AUTORIDAD DE ACUEDUCTOS Y ALCANTARILLADOS

PLAN DE INTERRUPCIONES
DEL SERVICIO DE AGUA

AREA I - Agosto 21, 23, 25, 27

36 horas | 25 horas

Figure 1: Newspaper clippings from 1994 drought.

In response, PRASA declared that the water supply problem would be solved once and for all by constructing a costly new project, the Superaqueduct. This new 100 Mgd water supply would tap Dos Bocas and Caonillas hydropower reservoirs, and was promised to be the end of water shortages:

> *El Superaqueducto solucionaría, a largo plazo, los problemas de abastos de agua.*
>
> *Estamos diseñando el Proyecto de manera que no sólo se suplan las necesidades inmediatas, sino las de nuestros nietos.* (El Nuevo Día, p5, 29 July 1994).[2]
>
> *This [superacueducto] would satisfy water demand until the year 2050, and we wouldn't have to worry any more about droughts - that's the importance of this project right now."* (San Juan Star, Aug. 27, 1994).

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[2] Translation: "The Superaqueduct will solve the long-term water supply problems."
"We are designing the project in a way that will not only supply immediate needs, but also those of our grandchildren."

The Superaqueduct entered service in 2000. As a complementary measure Carraízo reservoir was also dredged in 1997, removing 6 million cubic meters (6 Mm^3) of sediment which was discharged into 3 diked containment areas upstream of the reservoir. The cost of these projects, including interconnections and financing costs, came to $1 billion and is part of Puerto Rico's current debt burden.

And then came 2015: another drought. This time the rationing was even more severe than in 1994 (Figure 2). After building the Superaqueduct and dredging Carraízo, and despite all the promises, nothing had changed. How was is possible that a billion dollars could be spent without apparent benefit? And then came 2020, and once again rationing! Fortunately, in 2020 it soon started raining, but the message was clear: **something is very wrong with Puerto Rico's water supply infrastructure**!

MIERCOLES, 27 DE MAYO DE 2015

www.elnuevodia.com

EL NUEVO día

UN GRAN PERIÓDICO

Millonario el costo del racionamiento

Expertos estiman que la falta de agua les cuesta al menos $24 millones semanales a los afectados

PUERTO RICO HOY PÁGINAS 4-5

36.43 Los metros de agua que Carraízo registró ayer

Alberto Lázaro, director de la AAA, explicó ayer en conferencia de prensa que la reducción en el caudal de La Plata los obligará en unas dos semanas a imponer la fase de racionamiento para esa zona.

Ahora serán dos días sin agua

AAA aumenta el periodo de racionamiento en la Isla

pirá el servicio de agua potable desde el mediodía del miércoles hasta el viernes a esa misma hora.

En el caso de los residentes de la zona B, no tendrán servicio de agua desde el miércoles al mediodía hasta el jueves, pero a partir del viernes 12 de junio, entrarán dentro del periodo de dos días sin agua.

De igual forma, Lázaro anunció que otros diez sectores del área metropolitana serán añadidos a la zona B, lo que comprende unos 2,000 clientes: Paseo del Prado, zona industrial Martín González, San Fernando Village, Buena Ventura, Jardines de San Fernando, Estancias de Tierra Alta, PR Industrial Park, Veredas del Río, Río Vista y Parque Juliano. Estos 2,000 clientes, dijo Lázaro, representan 600 millones de galones diarios de consumo de agua.

El ejecutivo recalcó que de ahora en adelante la AAA se referirá a los periodos sin agua por cantidad de días y no por horas, debido a que por lo complejo de la operación, habrá sectores en los que el servicio no se restablecerá inmediatamente.

Figure 2: Newspaper clippings from 2015 drought.

To solve the water supply problem it is first necessary to understand its causes. This requires a basic knowledge of the water sources supplying the north coast, and to understand why the huge expenditure on the Superaqueduct and the first Carraizo dredging produced zero protection against the very drought these projects were supposed to eliminate. Without understanding this problem, and changing the way water is managed, future investments can easily be just as ineffective as the investments made after the 1994 drought.

A commonly held perception is that sedimentation of the Carraízo reservoir is the root cause of water rationing. A second dredging of Carraízo has been proposed to "solve" the water problem, since all the capacity gained by the first dredging in 1997 has already been lost by sedimentation. However, **RESERVOIR SEDIMENTATION IS NOT THE CAUSE OF WATER RATIONING IN SAN JUAN.**

The Superaqueduct could not prevent water rationing because it did not eliminate over-drafting at Carraízo, which was the cause of rationing in the first place. Superaqueduct water was not used to reduce withdrawals from Carraízo. Instead, the water produced by the Superaqueduct water went: (1) to replace many existing north coast wells, and (2) to fed a dramatic increase in water loss (leakage). The Superaqueduct didn't solve the rationing problem, and it also didn't produce any additional revenue because metered deliveries did not increase.

Water supply problems can't be solved with big new projects if infrastructure design and operation is not optimized with respect to hydrology. Puerto Rico's problem is not the lack of infrastructure, but the way the infrastructure has been configured and managed. This paper focuses on the following main themes:

1. **Dredging Carraízo will not solve the water supply problem**. No amount of dredging will produce sufficient yield to meet current withdrawals at Carraízo, but a costly dredging project will divert funds away from projects that CAN prevent severe water rationing.
2. **Increase firm by conjunctive use**. Firm yield can be substantially increased, rapidly and at low cost, by the combined operation of groundwater sources and reservoirs (*conjunctive use*). This requires that both reservoirs and wells operate at variable rates of withdrawal as determined by a scientifically-derived operating rule. Most of the wells needed to implement this procedure already exist, but were abandoned by PRASA when Superaqueduct water became available. This strategy can be implemented quickly and economically to provide a water supply resilient to drought, and avoiding severe rationing in the future.
3. **Control sedimentation by sediment-guided reservoir operation**. It is important to control sedimentation at Carraízo. This can be achieved at negligible cost, without dredging, by implementing a sediment pass-through operation during floods (sediment sluicing). This sediment management strategy was demonstrated effective at Carraízo during hurricane María.

If we don't want the future to simply be a repeat of the past, then we must change the way water is managed. We cannot afford to repeat past patterns of ineffective new projects, or undertake costly dredging while failing to minimize future sedimentation to protect the dredging investment.

The following section explains in more detail the water supply strategy that needs to be implemented to prevent severe water rationing, and why this strategy is appropriate.

2. Carraízo and North Coast Water Supplies

2.1. North Coast Water Supplies

As shown in Figure 3, the north coast is supplied by four main reservoirs: **Carraízo**[3], **La Plata**, and **Dos Bocas** plus **Caonillas** that supply the Superaqueduct. The Superaqueduct began water deliveries in year 2000. Río Bayamón also supplies the Los Filtros plant, and the Cidra reservoir primarily supplies the filter plant in the Municipality of Cidra.

As summarized in Table 1, the rate of water withdrawals from every one of these reservoirs exceeds their firm yield; all the north coast reservoirs are being over-drafted. The largest source of water supply for the Metro Area is Carraízo (Loíza) reservoir, which normally delivers ~90 million gallons per day (**Mgd**) to the Sergio Cuevas filter plant. Although the Superaqueduct is larger (100 Mgd), its supply is divided among municipios from Hatillo to Caguas.

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[3] Carraízo reservoir is called Loíza reservoir in USGS publications.

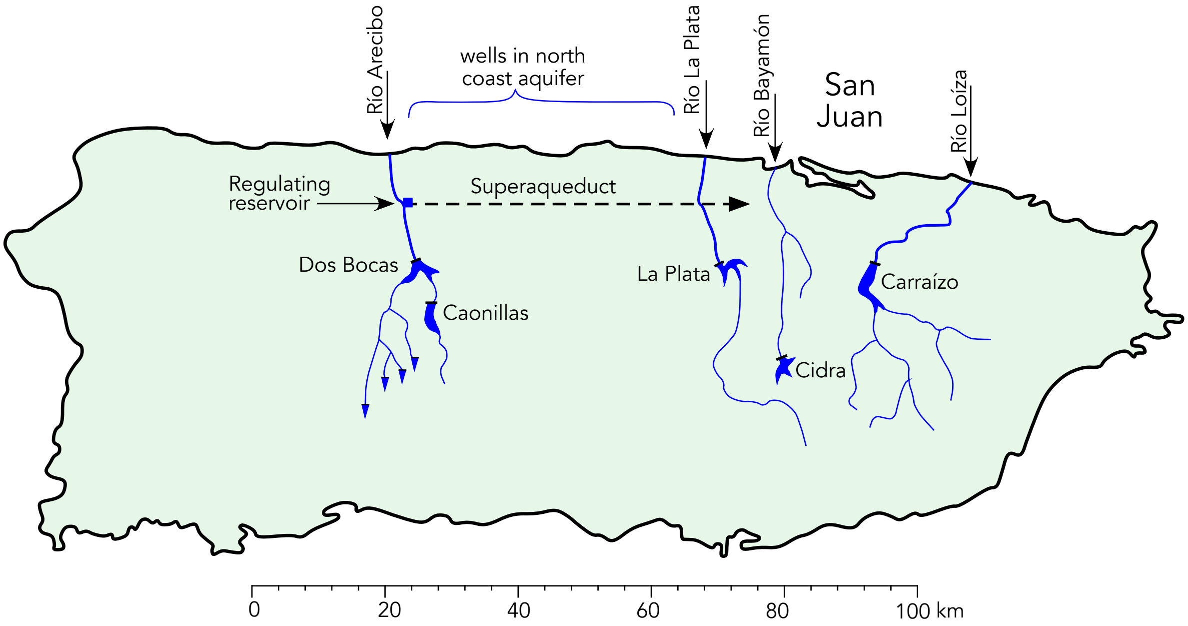

Figure 3: Principal water sources supplying San Juan

Table 1: Withdrawal Rate and Firm Yield for Reservoirs Supplying the North Coast.

Reservoir	Normal Production, Mgd	Firm Yield, Mgd
Carraízo	90 to 100	67
La Plata	55 to 60	49
Dos Bocas + Caonillas (Superaqueduct)	100	78

2.2. Reservoir Firm Yield and Dredging

River flow is highly variable, and reservoirs capture water during wet periods to sustain deliveries during dry periods. The amount of water that can be withdrawn from a reservoir on a reliable basis, including dry periods, is known as the "**firm yield**." For the Loíza watershed supplying Carraízo reservoir the worst drought of record occurred during 1967-68, a drought that extended across 2 years.

How is firm yield calculated? The relationship between reservoir capacity and firm yield is based on daily hydrologic simulations of reservoir behavior, determining the amount of water that can be withdrawn on a reliable basis at each storage capacity[4]. These simulations represent desirable operating conditions; the water supply is never shut off. Periods of water restriction occur, but there is always enough water to keep the

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[4] Firm yield has been calculated as the flow that limits periods of water restrictions (75% of normal deliveries) to not more than 1% of the days.

distribution system pressurized and delivering water. The simulation tracks the daily water storage in the reservoir when following the pre-programmed operating rule. Simulated daily reservoir storage volumes for Carraízo are shown in Figure 4 for the current storage capacity of 15 Mm^3. This simulated behavior is based on historical inflow data for Loíza and Gurabo rivers, adjusted to reflect today's upstream infrastructure conditions. It is not the historical reservoir behavior, which had more drawdown due to over-drafting.

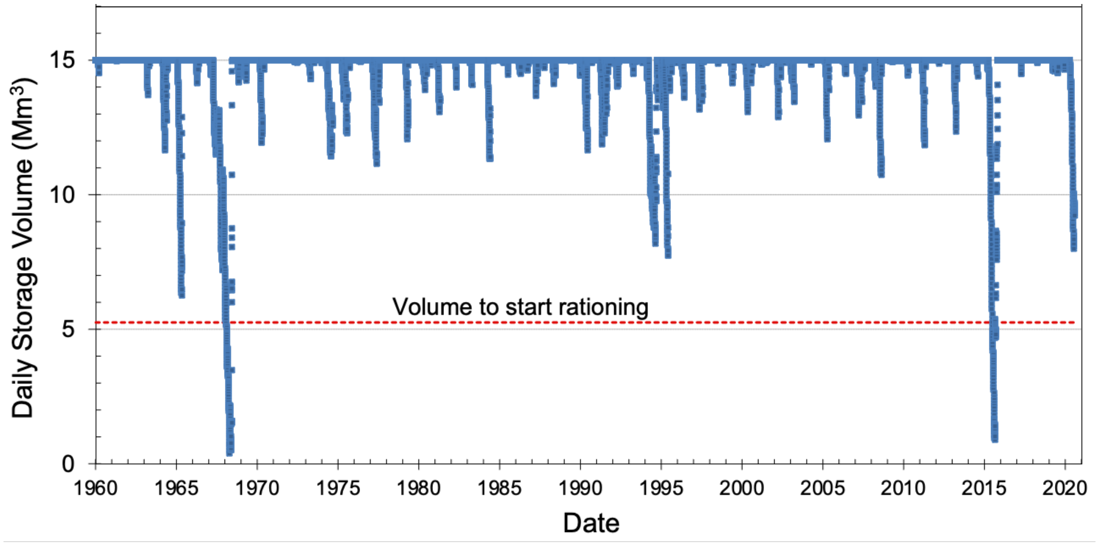

Figure 4: Daily variation in water volume in Carraízo reservoir generated by a firm yield simulation. The deep drawdowns correspond to drought periods. This graph shows the variation in reservoir storage when operated at the firm yield. This is not the reservoir's historical operation.

The results of multiple simulations performed for different storage volumes can be graphed as a "**storage-yield curve**." The curve for Carraízo reservoir (Figure 5) shows how firm yield varies as a function of reservoir storage capacity. An increase in reservoir capacity will increase firm yield because more water will be in storage and thus available for delivery during a drought. Conversely, as storage volume is lost due to sedimentation, the firm yield also declines.

Figure 5 shows the current volume of 15 Mm^3. The original volume was lost by sedimentation, 6 Mm^3 was recovered by dredging in 1997, but since then was lost again by additional sedimentation, bringing the reservoir capacity to where it is today.

Figure 5 also shows that the current rate of extraction is far above the yield curve, regardless of reservoir capacity. Even if all sediments were removed, returning the reservoir to its original 1953 capacity, the firm yield would still be much less than the existing rate of withdrawal. **For this reason, no amount of dredging can prevent severe rationing at Carraízo during drought**.

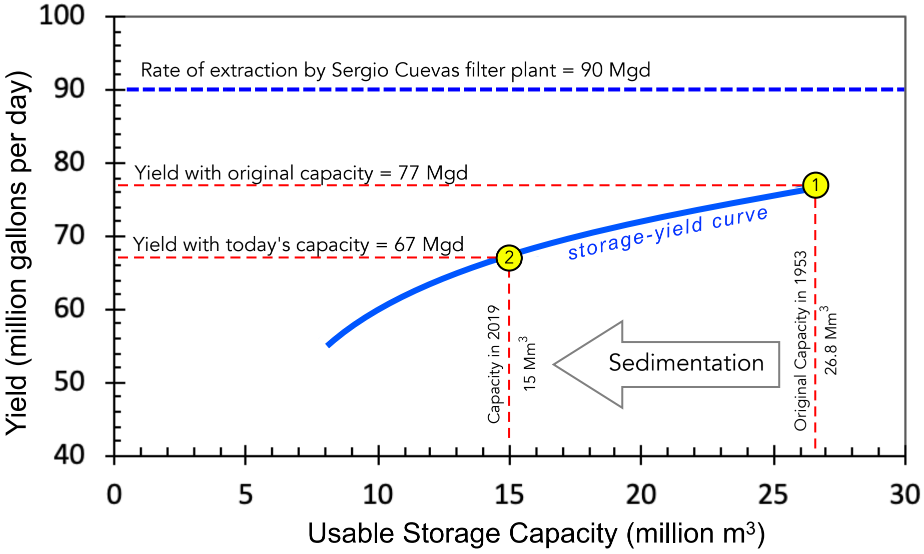

Figure 5: Relationship between storage capacity and firm yield at Carraízo reservoir. Even if all the sediment were removed, the reservoir firm yield would still be much lower than the current rate of extraction.

The rate of extraction at the Sergio Cuevas filter plant is much greater than the reservoir's firm yield, meaning that the reservoir is being "**over-drafted**." As a result, when the reservoir enters a dry period, reservoir storage is depleted rapidly because the capacity is too small to sustain 90 Mgd of withdrawals. To avoid completely emptying the over-drafted reservoir, withdrawals must then be decreased to a rate far lower than the firm yield. This dramatic drop in water supply results in severe rationing. During 2015 water production dropped to zero on some days, as shown in Figure 6, and customers only had water every third day (recall Figure 2).

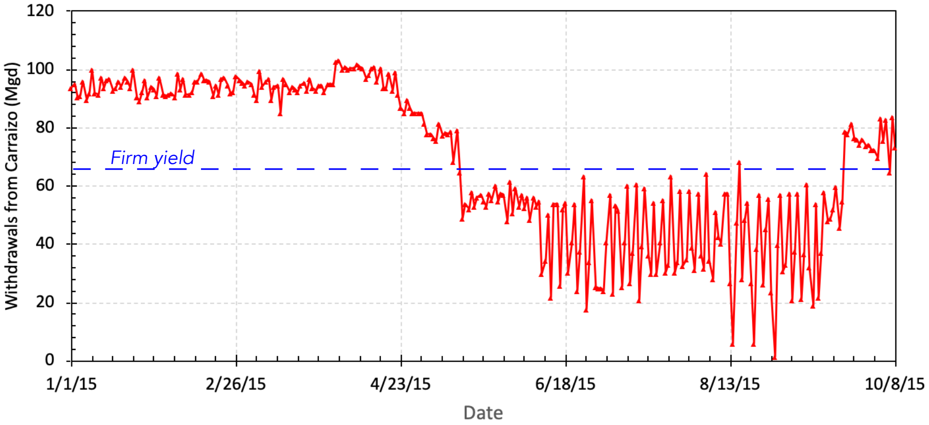

Figure 6: Water deliveries from Sergio Cuevas filter plant, supplied by Carraízo reservoir, 2015 drought.

Dredging can be used to increase reservoir capacity and firm yield. The 1997 dredging of Carraízo cost $60 million and recovered 6 million cubic meters (**Mm³**) of capacity, which was subsequently lost due to additional sedimentation. If we are to repeat that dredging today it would cost about $90 million, but it would only increase yield by about 5 Mgd, far from covering the firm yield deficit (see Figure 7). This represents a cost of $18M/Mgd of yield. Furthermore, dredging is only a temporary solution because firm yield will immediately start declining again due to sedimentation. All the recovered capacity will be lost after about 20 years, unless the sediment control strategy outlined in Section 3.2 is implemented. Continuous small-scale dredging has also been proposed, but the unit cost is even higher than for a large-scale dredging project because it will lack the economies of scale. And finally, all dredging projects face the problem of finding a location to discharge the massive volumes of sediment involved. Will PRASA build another reservoir the size of Carraízo for the sole purpose of holding dredged sediment? Where will it be located? What will it cost? **Dredging is not a sustainable alternative for managing sedimentation at Carraízo reservoir**.

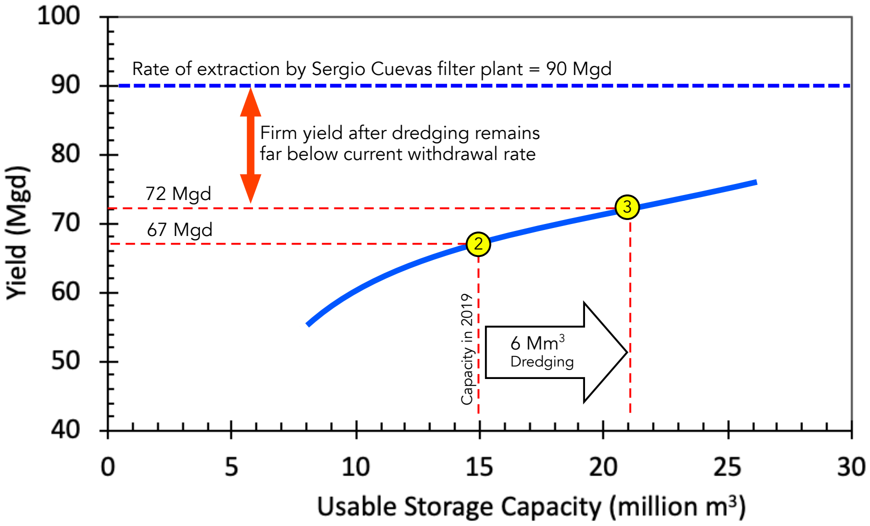

Figure 7: Recovering 6 million cubic meters by dredging will not eliminate the firm yield deficit.

Another idea proposed to increase firm yield is to increase transmission capacity between the existing north coast reservoirs, using water transfers to eliminate severe rationing. The 2015 drought did not affect the Río Arecibo watershed that supplies the Superaqueduct, making it possible to make a small increase in withdrawals from the Superaqueduct to help meet a portion of the deficit in the Metro Area. This approach will work only when drought affects some reservoirs and not others, which will not necessarily be the case during the next drought. For example, the 1994 drought affected all north coast rivers simultaneously, and was very intense in the Arecibo watershed that supplies the Superaqueduct. It is important to remember that all reservoirs supplying the north cost are also being over-drafted, though not as severely as Carraízo (recall Table 1). During the next drought we cannot depend on the strategy of transferring additional water from the Superaqueduct: all north coast reservoirs are currently over-drafted and all can experience drought simultaneously.

2.3. Why Did the Superaqueduct Not Eliminate Rationing?

To eliminate severe rationing the withdrawal rate must be limited to the firm yield. This is a fundamental concept of water supply hydrology. Yet, when Superaqueduct water became available PRASA did not use this water to reduce withdrawals from the over-drafted Carraízo and La Plata reservoirs. Instead, most of the wells on the north coast were shut down while the reservoirs continued to be over-drafted. The inevitable result was renewed rationing in 2015 and 2020, and continuing vulnerability to severe rationing today.

After 1994 PRASA was increasing overall water production, even though metered deliveries were flat. In the 15 years following the 1994 drought, PRASA's water production increased by more than 200 Mgd, <u>without increasing metered deliveries to customers</u> (see Figure 8a). This result was achieved by increasing non-revenue water losses from 40% to over 60% of total water production (Figure 8b). The biggest result from PRASA's increased water production during this period was to produce more leakage.

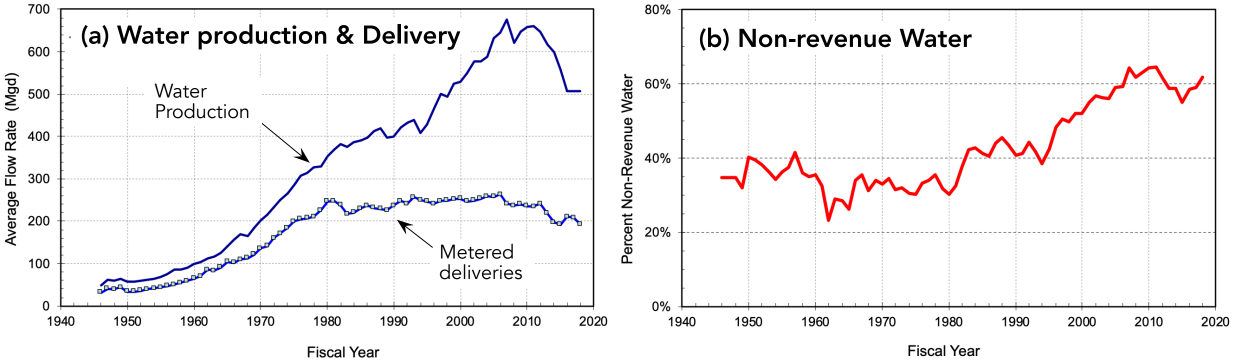

Figure 8: (a) Water produced and metered deliveries. (b) Percent of total production that does not produce revenue. On average, about 98% of non-revenue water is "lost" through either leaks or metering error, the remaining 2% consists of authorized non-metered uses.

Since 2010 Puerto Rico's population has been declining, and both PRASA's water production and metered deliveries have also been declining. To reduce leakage, water production must decline, and the post-2010 decline in water production shown in Figure 8(a) is welcomed. However, when matched against the decline in metered deliveries, the percentage of non-revenue water remains stubbornly high, at about 60% as seen in Figure 8(b). This is in stark contrast to PRASA's plans in 2015 which stated[5], "*PRASA projects a physical loss reduction from 55.9% of the total production (128.9 MGD) to 47.4% of the total production (91.0 MGD) for the Metro Region by 2020.*" Leakage rates per kilometer of pipeline have been decreasing, which is a good trend, but there is still a very long road ahead before leakage reaches acceptable levels. About 98% of non-revenue water is reported to consist of leakage loss[6].

If the water loss problem were solved there would be no water shortage. However, this problem is not going to be solved quickly. For that reason, this paper focuses on strategies that can quickly and economically increase the firm yield available to the San Juan Metro Area to avoid a repeat of the extreme water rationing, even at present levels of water loss.

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[5] Sec. 3.2.1 of MP Engineers. (2015). "PRASA's Metro Region Water Resources Management Plan 2015." Report to PRASA

[6] Based on data in Table 4-15 of Arcadis. (2018). Fiscal Year 2018. "Consulting Engineer's Report for Puerto Rico Aqueduct and Sewer Authority." Report to PRASA, San Juan, PR.

3. Alternatives to Increase and Sustain Firm Yield

Puerto Rico is blessed with abundant water resources and has generally adequate infrastructure. However, the water supply system is not managed in a scientific manner to maximize yield. Today the firm yield at Carraízo is about **25 Mgd below** that needed to cover withdrawals. Two sustainable solutions do exist that can be used together to **permanently end severe water rationing** and to **permanently solve the sedimentation problem at Carraízo**. Both solutions can be implemented **rapidly and at low cost.** They are described below.

3.1. Solution #1: Increase Firm Yield by Conjunctive Use

Each source of water supply previously shown in Figure 3 has distinct hydrologic characteristics. Although rivers discharge large volumes of water, the capacity of reservoirs to store river flow is limited to a few months at the average discharge rate. On the other hand, the north coast aquifer that supplies groundwater to wells has smaller annual flows than rivers, but has a very large storage volume.

To date, each water supply source has been operated at nearly constant rates year-around, managing each one independent of the others. However, the safe yield of the entire water supply system can be significantly increased by operating each supply as component of an integrated system under a *conjunctive use operating rule*. The term *conjunctive use* refers to the management of both surface supplies (reservoirs) and groundwater supplies (wells) at variable rates to increase the firm yield of the entire system. This is a well-known water management strategy that has been in use for many decades[7].

Under conjunctive use withdrawals are made from each source at variable rates in accordance with its hydrologic characteristics and the amount of water available from the other sources of supply. The basic characteristics of each source and the operating strategy to maximize system yield is summarized in Table 2. An important advantage of this approach is that it does not use a large volume of limited groundwater supplies, since wells are only used on an as-needed basis.

Table 2: Water Supply Sources and Withdrawal Priorities for Conjunctive Use.

Priority	Source	Flow Volume	Storage Capacity	Operational Strategy
1	Rivers	Large	0	Always operate at the maximum rate possible based on river flow and filter plant capacity.
2	Reservoirs	Large	2-4 months of average flow	Operate at high rates during wet periods but at lower rates as water levels drop.
3	Wells (aquifer)	Moderate	Years	Keep in standby until needed to compensate for reduced withdrawals from rivers and reservoirs.

Water supply simulations, first reported in the DNER 2016 Water Plan[8], demonstrate that if the abandoned wells on the north coast are re-integrated into the water supply system, and turned on when reservoir levels drop, the conjunctive firm yield (reservoir + wells) can provide the firm yield to match the current rate of

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[7] U. S. Army Corps of Engineers. (1988). Elements of Conjunctive use Water Supply. Institute for Water Resources, Research Document RD-27, Ft. Belvoir, VA.

[8] DNER. 2016. "Plan Integral de Recursos de Agua de Puerto Rico." San Juan. Link for download https://tinyurl.com/PlanAgua2016

extraction from Carraízo. How much well capacity is required? Preliminary simulations show that about 25 to 30 Mgd in standby well capacity (maximum pumping rate during drought) will cover the firm yield deficit at Carraízo. However, the average pumping rate of wells will be less than 5 Mgd because most of the time they are on standby.

The conjunctive management concept is simple. During most years there is enough water to sustain a 90 Mgd withdrawal rate from Carraízo. Wells are used very little during most years; they are held in standby while the north coast aquifer is being recharged by natural processes. However, when the reservoir level drops to a predetermined level, as established by an operating rule developed from hydrologic simulations, the rate of reservoir withdrawal is reduced and wells are turned on to sustain the full water supply to customers.

If the drought becomes severe and water levels continue to drop, a second reduction in the reservoir withdrawal rate is made, and water deliveries are restricted. Firm yield calculations assume that limited water restrictions occur an average of less than 36 days per decade (<1% of days), but water is never rationed (system is never depressurized). Figure 9 compares the rate of total water deliveries under a conjunctive use operating rule with limited water restrictions, against historical deliveries from Carraízo during 2015. The difference is dramatic; conjunctive use eliminates severe water rationing. Both 25 Mgd and 30 Mgd well capacities are simulated in Figure 9. Adding more wells provides more water during drought. When the drought ends the wells are turned off, the rate of reservoir withdrawal returns to normal, and the aquifer is recharged by natural processes.

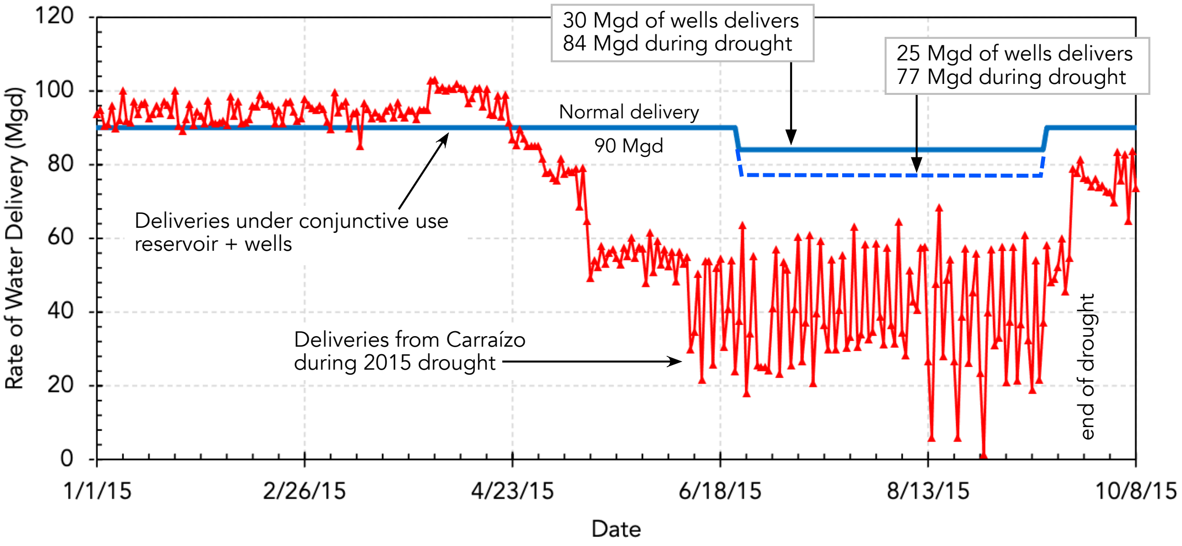

Figure 9: Rate of water delivery for conjunctive use vs historical water deliveries during 2015 drought.

Conjunctive use has important benefits to both customers and to PRASA:

1. Periods of water restriction are shorter.
2. More water is delivered to customers and the water is never shut off during periods of supply restriction.

3. **There are large economic benefits to PRASA because more water is sold to customers.** Not only does this generate more income, but the large expenses associated with water trucking and other rationing-related expenses are eliminated.

Water deliveries can be sustained during restriction periods by a combination of measures such as: temporarily lowering system pressure to reduce leakage, aggressive leak control, or adding even more standby wells.

The north coast aquifer was previously subject to over-pumping, but this is no longer the case. Most of PRASA's wells on the north coast were shut down when the Superaqueduct began operating, and industrial use has also declined greatly as industries closed down. Both factors have allowed the north coast aquifer to recover and water levels in north coast aquifers have been rising[9]. The north coast aquifer today has ample water available to supply standby well capacity. Because the wells are used only intermittently, this results in a low average rate of withdrawal that is sustainable, and it does not represent a threat to the integrity of the aquifer.

Most of the wells needed for this operation already exist. In 2015, MP Engineers[10] undertook a partial survey of PRASA's north coast wells, identifying 30 Mgd of well capacity. Of these, 18.5 Mgd had water quality analysis meeting drinking water standards. Additional PRASA wells were identified, but because they lacked information on their capacity they were not included in the inventory. Even though there are known water quality problems on the north coast, this affects only certain areas. A large groundwater capacity remains available for use, and a scientifically-based and well-managed groundwater extraction program can deliver this water supply.

Conjunctive use is a proven strategy that is used in other parts of the world, and simulations show it will work in Puerto Rico. It is a sustainable strategy that can be implemented quickly and at relatively low cost, since most of the needed wells already exist, although they need to be rehabilitated and re-connected to the system. Transmission system improvements will also be needed to facilitate the necessary water transfers.

3.2. Solution #2: Sediment-Guided Operation of Carraízo

The second solution focuses on controlling sedimentation at Carraízo reservoir. Most sediments are eroded and transported by rivers during intense rainfalls and floods. Observe a flooded river and you will see the water has turned red from the sediment it carries. You may also remember the landslides, and the rivers and quebradas scoured out and eroded by floodwaters as a result of hurricane María in 2017. Those sediments were also carried downstream.

When a river enters a reservoir the flow velocity is reduced, allowing sediments to settle to the bottom where they become trapped. The repeated trapping of sediment in a reservoir over the course of many flood events gradually fills it with sediments, displacing its storage capacity.

Many techniques are available to manage reservoir sedimentation, as described in the Reservoir Sedimentation Handbook[11] and summarized in Figure 10. A strategy uniquely suited to Carraízo is the **sediment pass-through** routing strategy called "**drawdown sluicing**". Under this strategy the dam's gates are fully opened to pass

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[9] Richards, R. (2020). "Are the groundwater levels falling in Puerto Rico? A comparison between a karst aquifer and non-karst aquifers." Proc. 16th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad, New Mexico, 181–191.

[10] MP Engineers. (2015). PRASA's Metro Region Water Resources Management Plan 2015. Report to PRASA.

[11] Morris, G.L. and Fan, J. 1998. *Reservoir Sedimentation Handbook*. McGraw-Hill, New York.

sediment-laden floods through the reservoir at high velocity, converting the reservoir into a fast-flowing river during the flood. This high-velocity flow not only carries sediment through the reservoir, but can also scour sediment out of the reservoir, thereby stabilizing reservoir capacity. The gates are closed near the end of the storm to refill the reservoir with water. Sediment pass-through is uniquely suited for use at Carraízo for several reasons:

1) The dam has large radial gates that control the entire storage volume in the reservoir, as seen in Figure 11A and Figure 12. (The volume behind the concrete dam has been sedimented for decades).
2) The reservoir's geometry is long and narrow (Figure 11B). This geometry is very favorable to passing sediment through the reservoir and downstream of the dam.
3) The reservoir is very small in comparison to the floods that carry high sediment loads, making it possible to pass floods through the reservoir and completely refill the reservoir at the end of the flood event. For example, volume of flood water produced by hurricane María was sufficient to fill Carraízo reservoir 10 times within 24 hours.

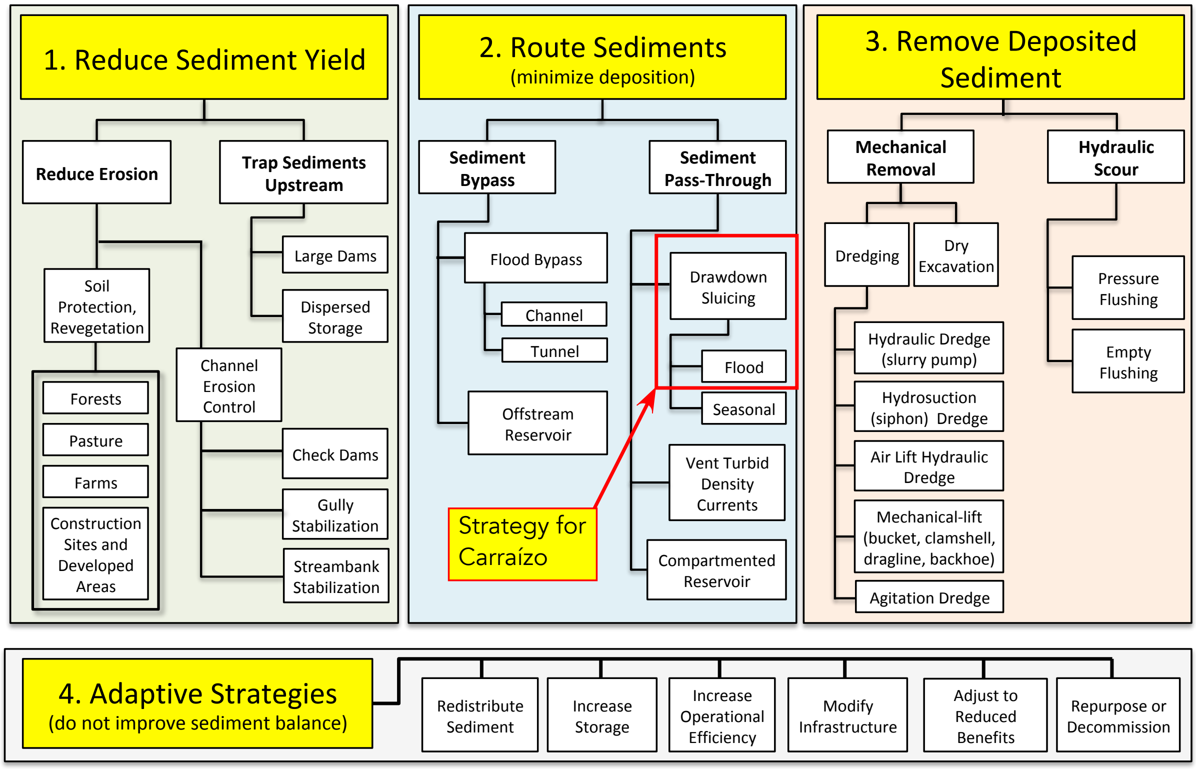

Figure 10: Classification of strategies for managing reservoir sedimentation[12].

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[12] Morris, GL (2020). "Classification of Management Alternatives to Combat Reservoir Sedimentation." Water, 12(3), 861.

Figure 11: Carraízo reservoir showing: (A) large radial gates that extend to the full depth of the reservoir's current storage, and (B) the elongated geometry favors the efficient transport sediment through the reservoir

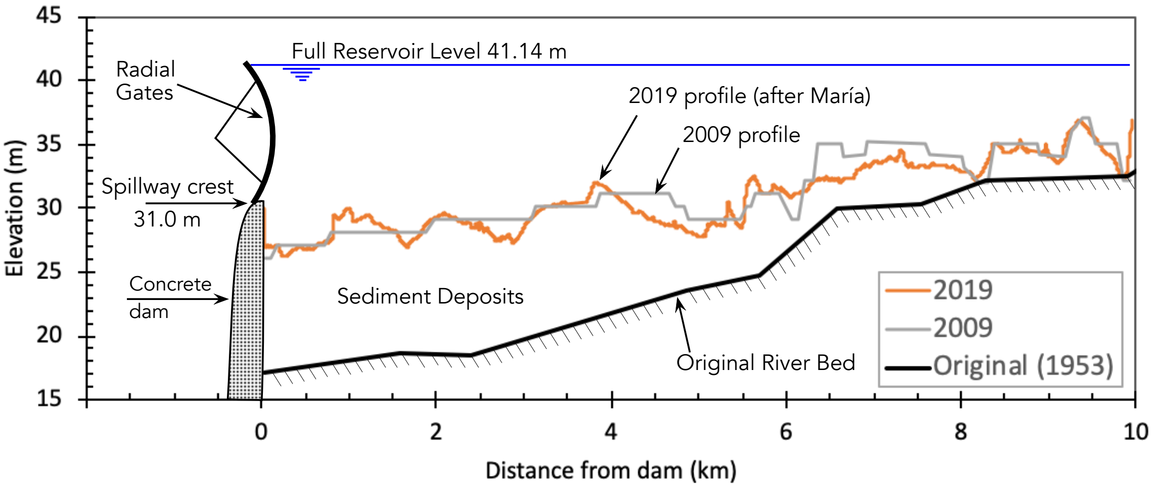

Figure 12: Profiles along Carraízo reservoir comparing 2009 and 2019 bathymetry surveys.

Sediment pass-through is highly feasible at Carraízo, and has already been tested with excellent results. To understand just how effective this sluicing procedure has been, it is first necessary to calculate the sediment that would normally be anticipated in the reservoir, without sediment sluicing. The period used for this comparison extends between the two most recent reservoir surveys, July 2009 and October 2019.

A sediment rating curve and daily flows were used to compute daily sediment inflow from July 2009 until hurricane María. The percentage of sediment inflow trapped by the reservoir is computed using a 76% sediment trap efficiency as estimated by Quiñones[13], giving an expected capacity loss of 2.26 Mm^3. The additional capacity

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[13] Quiñones, F. (2018). Estimados de la Descarga de Sedimentos A los Embalses Principales en Puerto Rico Durante las Crecientes del 20 de septiembre de 2017 Inducidas por las Lluvias del Huracán María. San Juan, PR, 60.

loss due to hurricane María was estimated at 2.05 Mm^3 by Quiñones. This expected capacity loss is compared to the measured capacity loss as follows:

Expected capacity loss pre-María (July 2009 – Aug. 2017)	2.26 Mm^3
Expected capacity loss due to hurricane María (Sept. 2017)	2.05 Mm^3
Total expected capacity loss (assuming no additional loss after María)	4.31 Mm^3
Measured capacity loss between surveys (July 2009 – Oct. 2019)	1.36 Mm^3

Comparing 2009 and 2019 survey results shows a measured capacity loss of 1.36 Mm^3, only 30% of what would otherwise be anticipated. Compare the profiles from 2009 and 2019 shown previously in Figure 12, and again it will be clearly seen that there has been very little sediment deposition. Where did the other 70% of the sediment go? It was carried downstream during the flood by opening the reservoir's gates.

During the peak of the María flood the water level in Carraízo reservoir was 4 meters below normal because the gates were open. Hydraulic modeling[14] showed that this produced flow velocities ranging from 2 to 4 meters per second (7 to 13 feet/sec) along the length of the reservoir. As a result, even though María was the largest sediment-producing event at Carraízo since USGS records began in 1960, by operating the gates to generate a high flow velocity it was possible to pass the sediment downstream. This was achieved even though gate operations during María were not optimized to maximize sediment release. With optimization, even better results can be achieved.

Reservoir operation to pass sediment is a recognized best-practice strategy in numerous publications on reservoir management, including publications by the International Commission on Large Dams[15], the World Bank[16], and the USA National Reservoir Sedimentation and Sustainability Team[17] which is comprised of representatives from multiple federal agencies, universities and the private sector. There are examples of reservoirs outside of Puerto Rico where capacity has been stabilized by river flows alone, without dredging:

- A US example of a reservoir that has reached sediment equilibrium without dredging is the Conowingo reservoir, about 30 miles north of Baltimore on the Susquehanna River. Like Carraízo, it has a long narrow lake and the dam has multiple large radial gates. Studies have shown that floods can scour large amounts of sediment from the reservoir[18], and bathymetric mapping of this reservoir shows bottom scour patterns at bends.

- An international example is the small Kali Gandaki reservoir in Nepal (1/3 the size of Carraízo). Kali Gandaki, operating since 2002, is particularly interesting because this reservoir would completely fill

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[14] GLM Engineering (2020). In-house HEC-RAS hydraulic simulation using 2019 bathymetry and USGS flow and level data.

[15] Basson, G. R., and Rooseboom, A. (1999). *Dealing with Reservoir Sedimentation: Guidelines and Case Studies*. ICOLD Bulletin 115, Paris.

[16] Annandale, G. W., Morris, G. L., and Karki, P. (2016). Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-river Hydropower. The World Bank, Washington, D.C

[17] USA National Reservoir Sedimentation and Sustainability Team. (2019). *Reservoir Sediment Management: Building a Legacy of Sustainable Water Storage Reservoirs*. Denver, CO, 47 p.

[18] Palinkas, C. M., and Russ, E. (2019). "Spatial and temporal patterns of sedimentation in an infilling reservoir." *CATENA*, 180, 120–131.

with sand during a single year were it not managed by drawdown sluicing to release sediments downstream during the monsoon[19].

- The Three Gorges project on the Yangtze River in China is an example of a large reservoir operated to stabilize capacity by water level drawdown during the flood season to generate high velocity flows to sluice sediment. This is the world's largest hydropower dam (22,500 MW), and the reservoir is 600 kilometers long (the distance from San Juan to Haiti).

Experience during María clearly demonstrated that by generating high velocities through Carraízo reservoir, sedimentation can indeed be controlled. Operation during María was not optimized, and with a real-time hydrologic forecast system even better results can be obtained. Optimization will require installation of a real-time hydrologic flood forecast system to guide gate operation to maximize sediment release without increasing downstream flood hazard, and training of PRASA personnel in the system's use. No structural modifications are needed; it simply requires "sediment-guided" operation of the existing gates during floods.

Is there enough water for this procedure? During hurricane María (Sept. 20, 2017) the volume of water that flowed through Carraízo reservoir was **10 times the total reservoir capacity**. In the 3 days following María, the additional flow could have filled the reservoir **3 more times**. Analysis of historical data since 1960 shows there have been 41 different days with enough water to completely fill Carraízo 2 or more times during 24 hours. Clearly, there is no lack of water during large floods at Carraízo. With a properly calibrated real-time hydrologic forecast system, the reservoir can release sediment and then be reliably refilled with water.

Protecting the dredging investment. Even if the reservoir is dredged again, sediment-guided operation is still needed to protect the investment made by dredging. After the first dredging in 1997, PRASA did nothing to protect the reservoir against further sedimentation. The dredged volume was simply allowed to refill with sediment. Although a sediment sluicing system had been developed for Carraízo in 1992, it was never used due to operational problems with the gates. Today the gates are fully functional. It is time to develop and implement an updated flood forecast system and sediment-guided operating rule to control sedimentation.

With or without dredging, sediment-guided operation is essential at Carraízo to protect against future sedimentation.

3.3. Climate Change Resilience

Climate change is happening, and in Puerto Rico one major anticipated impact is an increase in the frequency of extremely strong hurricanes. These storms generate large sediment loads. The most extreme example of hurricane generated sediment loads in Puerto Rico occurred at Caonillas reservoir resulting from hurricane Georges in 1998. Caonillas reservoir had been in service for 50 years when hurricane Georges struck in 1998, delivering 24 inches of rainfall into its watershed. The post-hurricane reservoir survey indicated the hurricane was responsible for depositing as much sediment into the reservoir as had been trapped during the entire preceding 50 years of operation. Caonillas experienced extreme sediment loads from the hurricane due to extensive landslide activity in its watershed.

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[19] Morris, G.L. (2014). "Sustainable Sediment Management: Kali Gandaki 144 MW Hydropower Dam, Nepal." Report to World Bank, Washington, D.C.

The sediment sluicing strategy recommended to control sedimentation at Carraízo will work perfectly with these extreme storms, as has already been proven by the experience during María described above. Drawdown sluicing represents the best possible protection against sediment loads from extreme floods[20].

A second anticipated impact of climate change in Puerto Rico is reduced moisture, a result of warmer and drier conditions. Most importantly, the annual number of consecutive hot and dry days is anticipated to increase, with the greatest impact in the early wet season[21]. Poor rainfall in the early wet season, April and May, is extremely important for water supply from reservoirs. Drought and water rationing invariably occurs when the April-May rains fail to fill reservoirs, limiting the supply of water during the normally-dry summer months. Looking into the future, this makes implementation of conjunctive use imperative to take advantage of the large storage capacity in aquifers.

Finally, a third consequence of climate change is rising sea level. The water level in coastal aquifers extend "uphill" from sea level (this is illustrated further below in Figure 13). As sea levels rise, the water level in aquifers will rise. The water level will also rise in wells drilled into the aquifer. This rise in the overall water level in the aquifer is not expected to have a significant impact on the water supply balance between recharge and discharge within the aquifer, and should not threaten utilization of aquifers for conjunctive use water supply. Of course, the system of wells needs to be designed and operated in to maximize sustainable yield and resilience.

4. Recommended Priority Actions

A reliable water supply, together with a reliable electrical system and well-maintained roads, are hallmarks of modern industrialized societies. This infrastructure needs to function properly if Puerto Rico is going to be competitive in the 21st century. Options exist to sustain water supplies during future droughts that are: relatively inexpensive, can be implemented quickly, and are both resilient and sustainable in the long-run.

Puerto Rico's multiple water supply problems can be solved using cost-effective 21st century approaches. The first four priority actions described below address the issues discussed previously in this paper. Additional actions are listed below which were not described above, but which are also important, including problems that affect other areas of the Island. This list gives an idea of the 21st century focus needed to effectively utilize the Island's abundant water resources to eliminate rationing during drought.

1. Implement **sediment sluicing at Carraízo reservoir**, including modeling, development of a sediment-guided operating rule, and training of PRASA operational personnel.

2. **Prepare a conjunctive use operating rule for all north coast water supplies.** This study should optimize the coordinated operation of all reservoirs and wells to maximize firm yield, identifying the amount of well capacity needed and developing the operating rule for drought management.

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[20] The drawdown sluicing strategy described for Carraízo will not work at Caonillas because that dam does not have gates.

[21] Taylor, M. A., Clarke, L. A., Centella, A., Bezanilla, A., Stephenson, T. S., Jones, J. J., Campbell, J. D., Vichot, A., and Charlery, J. (2018). "Future Caribbean Climates in a World of Rising Temperatures: The 1.5 vs 2.0 Dilemma." Journal of Climate, 31(7), 2907–2926.

The 2015 drought did not affect the rivers supplying the Superaqueduct, making it possible to increase Superaqueduct production to supply the San Juan Metro Area during the drought. However, the 1994 drought was very severe in the Arecibo watershed supplying the Superaqueduct, and when that drought condition repeats it will not be possible to transfer additional water from Arecibo to San Juan. The operating rule must take this limitation into consideration to design a reliable water supply strategy.

3. **Prepare a preliminary engineering report for rehabilitation of north coast wells.** Identify the locations and capacities of existing wells to be rehabilitated, plus any proposed new wells, which will together provide the needed capacity identified in activity #2 above.

4. Based on hydraulic simulations, **design and construct transmission system improvements** needed to facilitate the water transfers identified as a result of activity #2 above, plus the well locations as determined in activity #3.

   A key strategy will entail re-connecting wells to temporarily supply north coast communities west of the Metro Area during dry periods. This will allow more Superaqueduct water to reach the Metro Area during drought, while the communities from Hatillo to Dorado rely more heavily on wells. Transmission and pumping improvements will be needed to allow Superaqueduct water to temporarily reach higher elevations areas within the Metro Area. The hydraulic design should not create high pressure zones that will increase leakage, and it should also support sectorization of the distribution system to facilitate water loss management, as discussed under action item #10 below.

5. **Implement managed aquifer recharge at multiple locations on the south coast** to reverse declining water levels and saline intrusion in that important aquifer. This problem is particularly important in Salinas and Santa Isabel, which are completely dependent on wells. Both have saline intrusion problems.

   An aquifer is simply a porous geologic formation filled with water that can be removed by a well. On the south coast the main aquifers consist of porous layers of sandy sediments deposited by rivers over many thousands of years. Puerto Rico's coastal aquifers are connected to the sea, and for this reason a deep well drilled at the coast will normally yield salt water. Salt water intrusion occurs as withdrawals from wells increase, or recharge decreases, causing the seawater to move inland within the aquifer (Figure 13). Saline intrusion can be reversed by increasing recharge or by decreasing pumping.

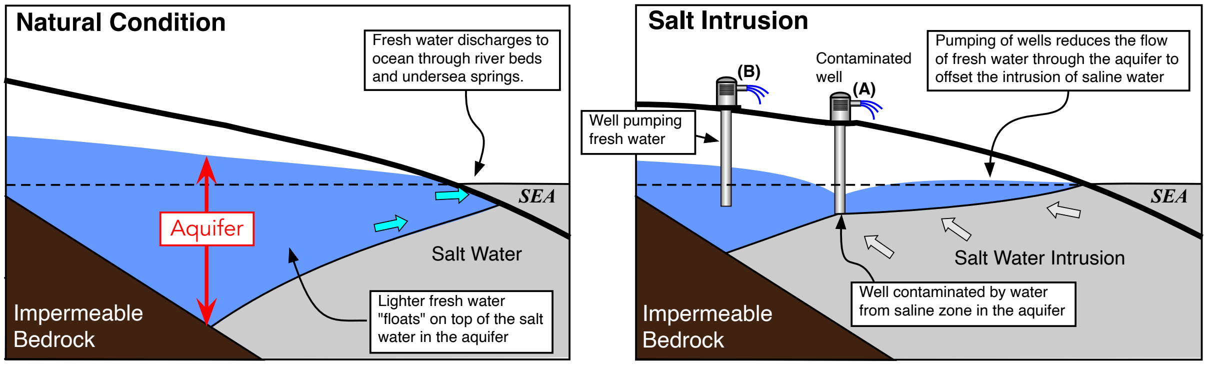

Figure 13: Saline intrusion into a coastal aquifer showing impact of pumping wells.

The south coast aquifer was historically recharged by irrigation water, of which about 30% percolated into the aquifer due to "inefficient" furrow irrigation of sugarcane (*riego por zurco*). Percolating irrigation water provided 53% of total aquifer recharge in the early 1960s, as documented by the USGS[22]. However, the dramatic reduction in irrigation deliveries, together with today's more efficient drip and sprinkler irrigation systems, results in very little aquifer recharge from irrigation. Today the aquifer suffers from this reduction in the rate of recharge.

The firm yields of south coast reservoirs are already fully allocated to existing users. However, in wet years large volumes of water are spilled into the ocean by rivers and some reservoirs. A strategy of Managed Aquifer Recharge can be used to divert a portion of this water to recharge the aquifer, similar to what historically occurred during more than 50 years of sugarcane irrigation. To provide reliable water supplies, and also increase the water quality in the aquifer, both wells and reservoirs can be converted to a Conjunctive Use operating rule, together with Managed Aquifer Recharge. In both California and Arizona, the combination of Conjunctive Use and Managed Aquifer Recharge has been highly successful in reversing aquifer decline and making water supplies for all users more resilient[23]. In Orange County, California, (home of Disneyland), Managed Aquifer Recharge has been successfully practiced since the 1930s, and currently averages over 250 Mgd of recharge. A short article summarizing four recharge projects in California is available on the Internet from the American Geosciences Institute[24].

A managed recharge project (also known as aquifer storage and recovery) is currently underway in Salinas with FEMA funding, but local agency support has been weak. By significantly expanding this approach it will be possible to provide reliable south coast water supplies, to improve water quality in the aquifer, and provide underground water storage not subject to the long-term decline in capacity that affects reservoir storage due to sedimentation.

6. With water demand dropping and other supply options available, construction of new reservoirs is not a priority at this time. However, this will not always be the case. An island-wide study of potential reservoir sites identified the **Beatriz off-channel reservoir site in Caguas** as a sustainable reservoir site where the impacts of sedimentation can be controlled. This is a prime reservoir site that needs to be acquired for future use. A preliminary design has been prepared at Beatriz, and an environmental impact statement was prepared and approved following public hearings.

   PRASA began construction of Valenciano reservoir instead of Beatriz, having acquired the Valenciano reservoir site over 50 years ago. However, Valenciano was designed as a conventional reservoir, without effective long-term sediment management measures. Monitoring data collected by the USGS revealed

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[22] McClymonds, N. E., and Díaz, J. R. (1972). Water Resources of the Jobos Area, Puerto Rico: A Preliminary Appraisal 1962. San Juan.

[23] Scanlon, B. R., Reedy, R. C., Faunt, C. C., Pool, D., and Uhlman, K. (2016). "Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona." Environmental Research Letters, 11(3), 035013.

[24] Search Internet for "Managed Aquifer Recharge in California: Four examples of managed groundwater replenishment"

the sedimentation rate at Valenciano will be high. Due to multiple constraints, no easy or inexpensive sediment control technique is available for Valenciano, such as the sediment pass-through strategy that will work at Carraízo. Valenciano will require dredging. It is not a good long-term water supply solution.

An updated yield analysis, including data from the 2015 and 2020 droughts, is summarized in Figure 14. The firm yield at Beatriz and Valenciano are virtually the same when analyzed using a consistent methodology. (A prior analysis of Valenciano by others allowed zero water delivery during rationing periods, producing a higher "apparent" yield). Figure 14 also shows the large difference in the sedimentation rate. Volume loss after 50-years of sedimentation will have a large impact on the firm yield at Valenciano.

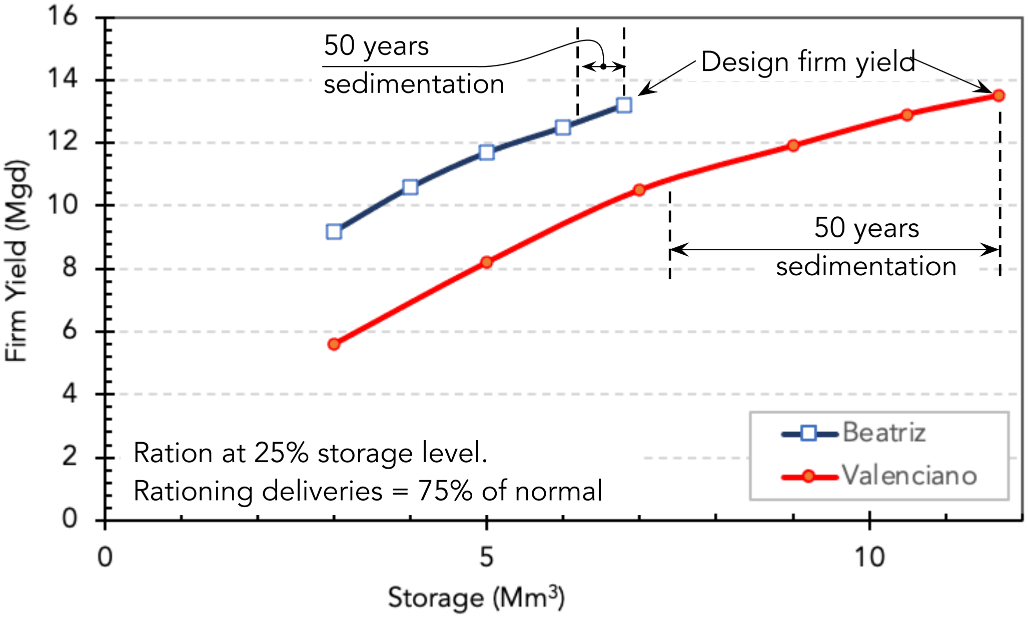

Figure 14: Firm yields and sedimentation rates compared for proposed Beatriz and Valenciano reservoirs (firm yield updated to 2020). Because the operating rule affects firm yield calculations, both reservoirs were analyzed using identical operating rules.

Because Beatriz has been designed off-channel (like the Fajardo and Río Blanco reservoirs), sedimentation is minimized, even during hurricanes. Small volumes of maintenance dredging will be required, and an adjacent disposal site is proposed for acquisition. For the purpose of comparison, the 50-year dredging volumes for proposed and existing reservoirs in the Loíza watershed are: Beatriz (0.6 Mm^3), Valenciano (4.3 Mm^3), Carraízo (12 Mm^3, equivalent to 80% of today's reservoir volume). Valenciano requires 7 times more dredging than Beatriz, and Carraízo requires 20 times more. However, when we compare the firm yields, the dredging volume per 1 Mgd of firm yield at Valenciano is about double that of Carraízo. If Valenciano is built, our grandchildren will inherit an expensive sediment-laden problem.

Given its advantage of long-term sustainability, together with similar levels of cost and firm yield, the Beatriz site should be acquired as a priority site for future use instead of Valenciano.

7. **Restore Superaqueduct firm yield**. All reservoirs and diversion dams supplying the Superaqueduct are owned and operated by the P.R. Electric Power Authority (PREPA). As illustrated in Figure 15, the system includes two storage reservoirs, Dos Bocas and Caonillas, and 4 smaller dams in the humid upper Río Arecibo watershed. The 4 small dams divert water into Caonillas via tunnels. Water delivery to Caonillas is important because it's the largest reservoir in the system, with 2.5 times the capacity of Dos Bocas. Also, while the water in Dos Bocas is sustained at a high level to enable navigation to properties and restaurants around the lake, water levels in Dos Bocas can be varied without restrictions.

   The rate of withdrawal from the Superaqueduct averages 100 Mgd, its original design firm yield. However, actual firm yield had dropped to 78 Mgd by 2017 (pre-María). Part of this drop is due to sediment accumulation in Dos Bocas and Caonillas storage reservoirs, but an even larger factor is sedimentation of the 4 diversion dams and diversion tunnels resulting from hurricane Georges in 1998, thus preventing water diversions into Caonillas. These 4 diversions are important because they help maintain high water levels in Caonillas, maximizing the volume of water stored in that reservoir at the beginning of a drought.

   The small reservoirs associated with these small diversion dams are subject to rapid sedimentation and maintenance is highly problematic, even without counting the effect of extreme hurricanes. The extent of the sedimentation problem in these small diversion dams can be appreciated from the photo in Figure 16.

   Yield simulations have shown that the most cost-effective way to recover a large part of the Superaqueduct firm yield is to re-connect the upstream diversion dams (Adjuntas, Pellejas, Viví, Jordan) to once again deliver water into Caonillas reservoir. As seen in Table 3, rehabilitation of diversion dams and tunnels, even without dredging, is the action that produces the greatest increase in firm yield. To recover firm yield, restoring the diversion dams and tunnels to operation is more important than dredging. To quickly restore as much firm yield as possible to the Superaqueduct, restore the upper-watershed diversion infrastructure to supply Caonillas reservoir.

   Prepare a Preliminary Engineering Report focusing on re-construction of the diversion dams in the upper Arecibo watershed to sustainably manage sedimentation, together with tunnel clean-out. Implement recommended improvements.

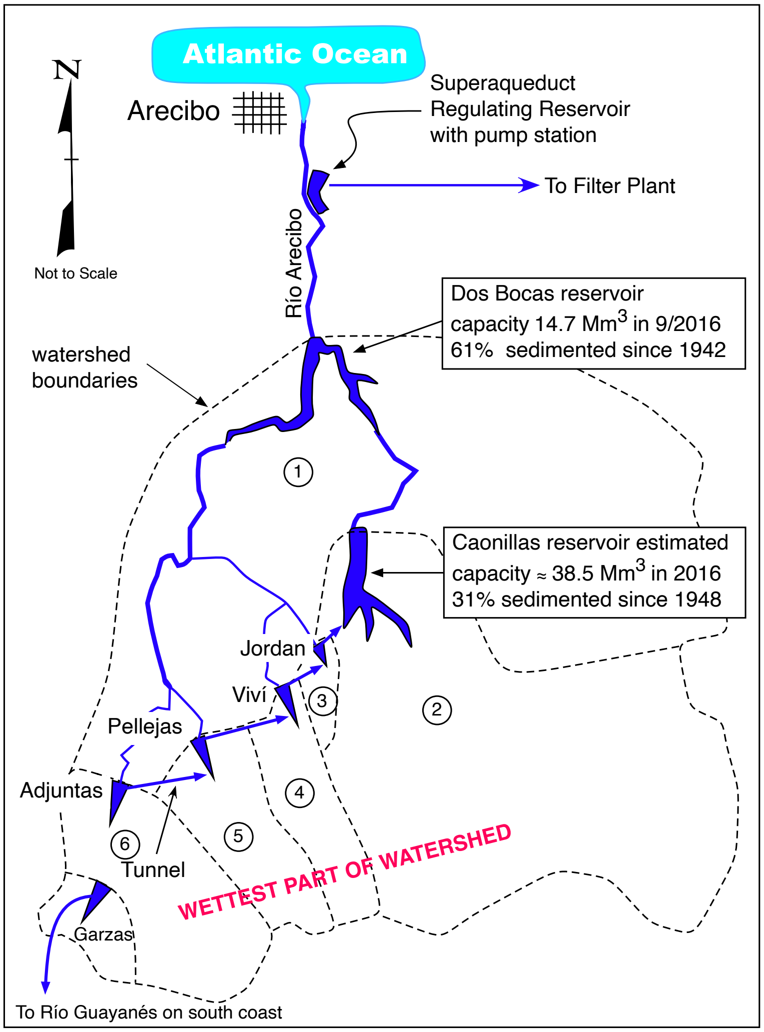

Figure 15: Schematic of dams regulating flows from watersheds suppling the Superaqueduct.

Figure 16: Sediment accumulation upstream of Pellejas dam.

Table 3: Superaqueduct Firm Yield for Various Project Rehabilitation Configurations[25].

Description	Rehabilitate Tunnels	Dredge 5 Mm^3		Firm Yield (Mgd)
		Dos Bocas	Caonillas	
Existing condition	No	No	No	78
Dredge 5 Mm^3 from Dos Bocas	No	Yes	No	79
Dredge 5 Mm^3 from Caonillas	No	No	Yes	82
Only rehabilitate tunnels, no dredging	**Yes**	**No**	**No**	**91**
Tunnels + dredge 5 Mm^3 from Dos Bocas	Yes	Yes	No	92
Tunnels + dredge 5 Mm^3 from Caonillas	Yes	No	Yes	95

The sediment problem at the Dos Bocas intake. In Dos Bocas reservoir, sandy sediment deposits are approaching the power intake that is also used to release water downstream to the Superaqueduct. Once this sand reaches the intake it will no longer be possible to operate the hydropower plant to release water; the sand will destroy the turbines. The only option will be to allow water to spill over the dam, and Dos Bocas will no longer act as a storage reservoir. This will reduce Superaqueduct firm yield. Sediment encroachment at the Dos Bocas intake is an that requires an urgent solution.

Sediment pass-through could represent an attractive alternative at Dos Bocas, but it would require reconstruction of the dam to incorporate deep gates. It would also require relocation of the Superaqueduct regulating pond, located further downstream, which currently acts as a sediment trap during floods. For the current infrastructure configuration, releasing sediment from Dos Bocas would simply create a larger sedimentation problem in the regulating pond. If the Superaqueduct regulating pond is relocated, then sediment pass-through can be an effective strategy for Dos Bocas if the dam is reconstructed. To minimize the required capacity in the relocated regulating pond, Dos Bocas releases could prioritize water supply. This would place an additional constraint on power generation.

A dredging alternative does exist at Dos Bocas and a disposal site for the one-time discharge of 5 Mm^3 of sediment has been identified near highway PR-22. There is also a designated offshore disposal site for harbor dredging which might be usable for long-term disposal.

Sediment management at Caonillas has not been formally studied to date.

8. **Develop a coordinated sediment management strategy for all reservoirs islandwide.** Some reservoirs have very low sedimentation rates and a low priority for action. Others have more severe problems. Each has unique challenges based on location, type of dam structure, hydrology, land use, etc. Prepare preliminary engineering reports for the highest priority sites.
9. The water supply for Vieques and Culebra depends on a single undersea pipeline installed in 1977, which will not be easily or quickly repaired when a break occurs underwater. **Standby wells can be used as an emergency water supply in Vieques**, rehabilitating or reconstructing wells previously

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[25] GLM Engineering (2017) "Dos Bocas Sedimentation Studies and Preliminary Engineering Report." Report to P.R. Electric Power Authority, San Juan, PR. Values from figures 47 & 48.

used for water supply. This will entail an assessment of current groundwater conditions, potential groundwater protection measures, and either rehabilitation of existing wells or drilling of new wells. This can be undertaken at relatively low cost and will provide Vieques with a much more resilient water supply. Options for Culebra are more limited due to the lack of groundwater resources there.

10. **Water loss management** is a complex topic. Comprehensive field studies have been undertaken involving detailed monitoring and analysis of metering and leakage problems for 25,000 PRASA meters, both large and small. These field investigations point to four key issues that need to be considered to successfully address the water loss problem[26]:

    a) The metering system is highly deficient, and comprehensive metering improvements need to be implemented as a top priority to reduce apparent losses due to meter errors. This will also boost PRASA revenue. Water production at filter plants and wells must be reliably metered as well.

    b) Pressure management is the most cost-effective measure to reduce pipe breakage and reduce leakage rates. Less pressure equals less flow through leaks. Implement pressure management throughout the system, giving priority to high-leakage areas.

    c) Many areas of owner-built housing lack water distribution systems designed and constructed to PRASA standards. These systems were found to have extremely high leakage rates, whereas engineered urbanizations built to PRASA standards typically have extremely low leakage rates. This indicates that a considerable reduction in leakage can be achieved by focusing efforts in specific areas of the pipe distribution network.

    d) The most effective way to track and control water loss is by sub-dividing the distribution system into discrete sectors that can be hydraulically isolated to measure water inflow, and to compute water loss within each sector by subtracting metered deliveries from measured inflow. Each sector may contain on the order of 5,000 customers in urban areas, and a smaller number in rural areas. The long-term objective is to continuously and automatically track water balances throughout the entire PRASA system. This will enable leak control interventions to be prioritized by area, and to measure how much leakage remains to be detected and repaired. Without the ability to measure the balance between water inflow and metered deliveries, leak detection and repair is operating blindly. Sectorization into District Metered Areas is a recognized best practice for leakage control.

Summary. Avoiding future water shortages requires better water management based on the principles of hydrology, instead of repeating the past pattern of costly projects that have not solved problems. Puerto Rico requires 21st century management approaches to successfully address 21st century problems, making water supplies more resilient against the combined challenges of drought, climate change, and fiscal austerity.

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[26] GLM Engineering. 2009. "Water Accountability Pilot Project: Final Report." Report to PRASA, San Juan, PR.