Offsetting Patillas Reservoir Storage Decline by Conjunctive Use of a Coastal Aquifer, Salinas, Puerto Rico

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Abstract

As reservoirs age they lose storage capacity and firm yield declines. Hydrologic conditions can also be modified as human activities change. At Salinas, Puerto Rico, recharge to the coastal aquifer has historically benefited from copious supplies of high quality irrigation water from the Patillas and Carite reservoirs, delivered in unlined canal and applied by furrow irrigation. As a result, deep percolation of irrigation water historically constituted about half the aquifer recharge.

Today the Patillas reservoir has only 41% of its original year 1914 capacity due to the combined effects of sedimentation and lowered operating level due to dam safety concerns. As a consequence of depleted reservoir capacity, water reallocation to municipal uses, reduced irrigation deliveries and implementation of high-efficiency irrigation techniques, the coastal alluvial aquifer has lost a major source of recharge, resulting in saline intrusion, salinization of municipal water supply wells, and water rationing affecting the municipal water supply. This situation is not unique to Puerto Rico's south coast, but also occurs in other much larger systems, such as Pakistan's Indus River Irrigation System command area.

Lacking other sources of supply and facing extremely high costs to restore reservoir capacity by either dredging or raising the dam, a highly cost-effective alternative is described in this paper which conjunctively utilizes the region's surface and ground water resources, mitigating the loss of reservoir capacity with aquifer storage. This is achieved by restoring aquifer recharge using water from the Patillas reservoir which would otherwise be discharged to the Caribbean Sea.

The strategies developed for Salinas, centering on the conjunctive utilization of both surface and ground water storage and optimization of the existing infrastructure, can be instructive for addressing similar problems in other jurisdictions.

Introduction

Overview: The water management problems faced by the coastal Municipality of Salinas on Puerto Rico's semi-south coast, mimic, on a small scale, the problems faced by many other systems in different parts of the world, including the world's largest and most complex irrigation system, Pakistan's Indus River System. These systems are characterized by: a regulated surface water supply from a reservoir with diminishing capacity due to sedimentation; a downstream irrigation command area underlain by a fresh water alluvial aquifer in contact with saline water; and a history of "inefficient" furrow irrigation supplied by unlined canals which recharged the aquifer thereby making copious quantities of fresh water available to both irrigation and municipal wells. This type of system is conceptually shown in Figure 1.

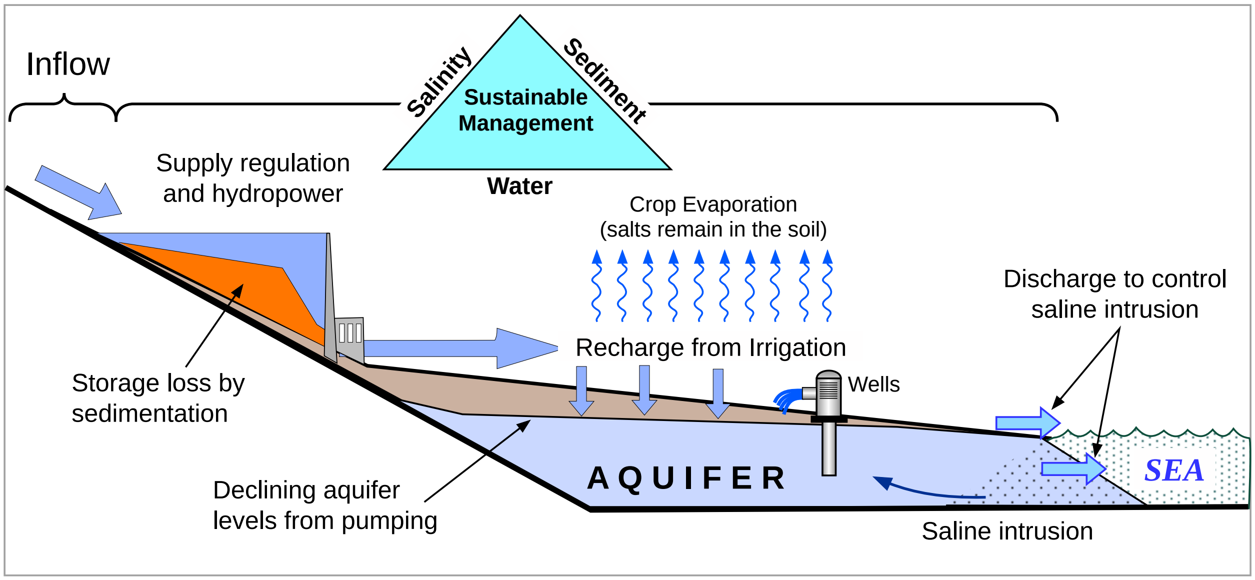

Figure 1: Conceptual model of coastal aquifer under the influence of regulated surface water recharge from irrigation deep percolation.

However, the hydrologic sustainability of these systems is challenged as ground water withdrawals increase for municipal and industrial (M&I) use, reservoir yield declines due to storage loss, and aquifer recharge declines in response to a shift toward "more efficient" technologies including canal lining and sprinkler and drip irrigation. In Salinas there has also been a decline in total acreage under irrigation. These factors adversely modify the historical hydrologic balance, resulting in saline intrusion within the aquifer and a net decline in fresh water availability.

In the Indus River System large scale increases in irrigation efficiency are as yet in the planning stage, and the effects of reservoir sedimentation on water supply availability are only starting to be felt. However, at Salinas the widespread increases in irrigation efficiency have already been implemented, and reservoir firm yield withdrawals have been diminished, resulting in the salinization of municipal ground water supplies and periods of municipal water rationing.

Study Area Description: The Town of Salinas (pop. 31,000), on the semi-arid south coast of Puerto Rico, overlies a coastal alluvial aquifer. About 4 mgd of municipal water is supplied from wells operated by the P.R. Aqueduct & Sewer Authority (PRASA). Industrial and military users also depend on wells, while irrigation supplies come from the combination of unlined irrigation canals supplied by the Patillas and Carite reservoirs plus wells. These elements are shown in the location map in Figure 2.

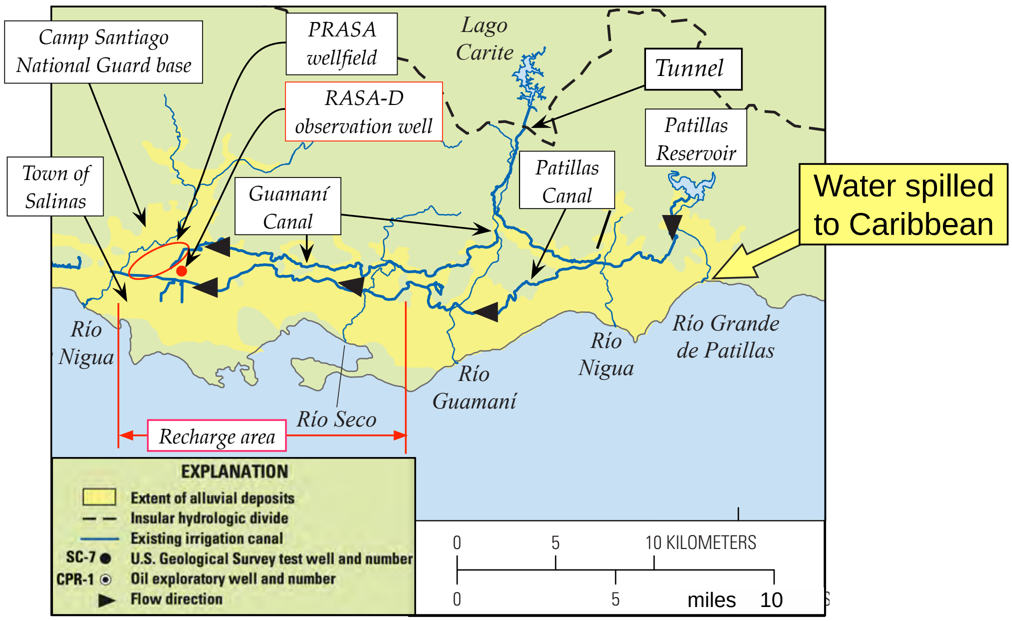

Figure 2: Location map for major hydrologic features of the Salinas area on Puerto Rico's southeastern coast. (adapted from Gómez-Gómez et al. 2014)

The deep percolation of irrigation water from canals and furrow irrigated fields has historically supplied about half the aquifer recharge. As illustrated by the water balance in Figure 3, in the 1960s approximately 30% of irrigation withdrawals percolated back into the aquifer. However, the 1970s saw sugarcane beginning to be replaced with year-around irrigation by crops requiring shorter irrigation seasons, shrinking irrigation acreage, declining canal deliveries, and replacement of furrow irrigation by higher-efficiency sprinkler and drip irrigation (Morris 1979). Data from the irrigation operator, the P.R. Electrical Power Authority (PREPA), show that over the past decade Patillas canal deliveries have averaged ~0.5 m^3s^{-1}, about one-third of delivery rate in the early 1960s. Municipal water also no longer returns to the soil via septic systems. Sewerage systems have been extended to most rural residential communities, and wastewater is now discharged to the sea or used for evaporative cooling following secondary treatment. These factors dramatically reduced the volume of deep percolation back into the aquifer (Rodríguez and Gómez-Gómez 2009).

The resulting unfavorable water balance in this narrow coastal aquifer has resulted in saline intrusion (Rodríguez and Gómez-Gómez 2008, 2009; Torres-González and Rodríguez 2015). The total solids concentration in water supply wells has been gradually increasing for at least 5 years and by 2018 exceeded the recommended secondary drinking water standard of 500 $mg \cdot l^{-1}$.

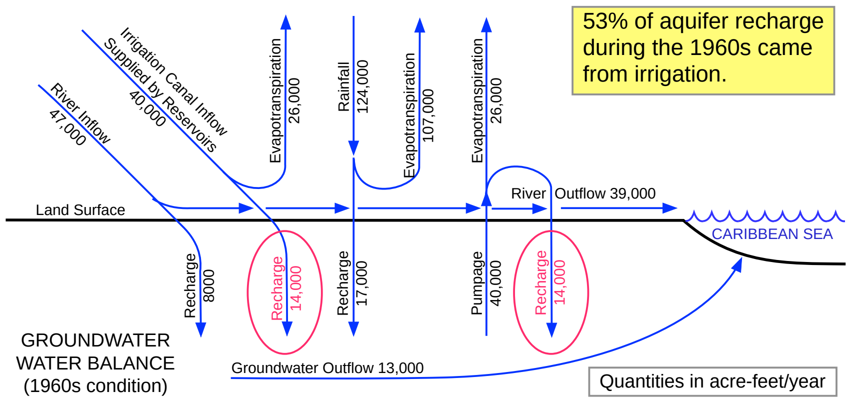

Figure 3: Historical water balance for alluvial aquifer in Salinas area (McClymonds and Díaz 1972).

Tropical reservoirs in semi-arid environments depend on large but infrequent rainfall events for recharge ((Jasechko and Taylor 2015). This has been the experience at Salinas, as seen from the water level data from USGS piezometer RASA-D (Figure 4). Yet surprisingly, the recharge provided by approximately 250 mm of rainfall delivered by hurricane María (Pasch et al. 2018) in September 2017, did not reverse the upward trend in TDS despite a rise of nearly 7 m in the water table. Rodríguez (2006) also documented high nitrate levels in the aquifer which has already caused well closures. Following sewerage connections, the main sources of nitrates are now agricultural fertilizers and manure spreading.

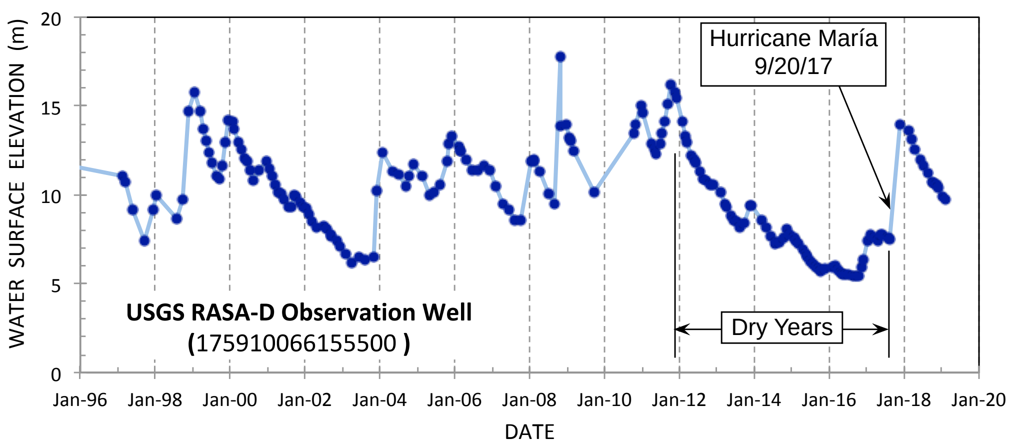

Figure 4: Water level data from RASA-D piezometer in Salinas showing rapid water level increase following large storms and multi-year periods of declining levels. See location in Figure 2 (USGS piezometer 175910066155500).

Responding to the long-term decline in water levels, on October 15, 2014, the P.R. Dept. of Natural and Environmental Resources (DNER) issued the "Technical Report for Critical Area Designation for the South Coastal Aquifer," which established a moratorium on new well construction. However, as 2015 developed into a drought year, increasingly strict measures were implemented, and in Salinas from July 2015 to February 2016, PRASA was ordered to reduce groundwater withdrawal by 1/3 to protect against saline intrusion. Having no alternative water supply, this reduction was achieved by turning off wells and depressurizing the distribution system on a daily basis. Military, industrial and agricultural wells were unaffected by this order.

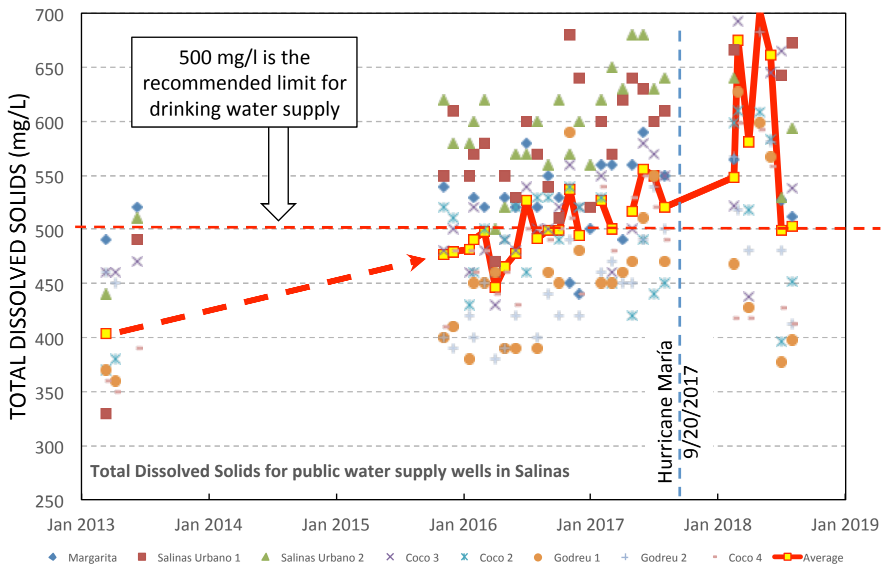

Figure 5: Trend of increasing dissolved solids content in wells for municipal supply in Salinas (data from PRASA)

Water Supply Options

Water supply alternatives for Salinas were evaluated when developing the Water Resources Plan for Puerto Rico (PR DNER 2016). Alternatives considered are briefly described below:

Water Reuse: The reuse of wastewater derived from the local groundwater was not considered feasible due to the high level of dissolved solids. Because Salinas wastewater originates from wells, to return this water to the aquifer after use would only increase the dissolved solids concentration.

Desalination: Seawater desalination was not considered a viable alternative due to high cost plus the availability of other less costly alternatives.

New Surface Water Development: The only streams in the area are ephemeral, Río Nigua in Salinas and Río Coamo about 10 km to the west in Santa Isabel. The Río Coamo irrigation reservoir was abandoned prior to 1970 due to sedimentation. New dam construction was also considered infeasible as no sites were identified in prior surveys of potential water supply reservoirs. Thus, new surface water development was discarded as a potential alternative.

Enhance Utilization of Existing Reservoirs and Canals: Irrigators in Salinas have historically received water from the Patillas reservoir about 28 km easta of Salinas via the Patillas canal, and from the Carite reservoir via the Río Guamaní and Guamaní canal.

The Carite reservoir was constructed in 1914 in the headwaters of the north-flowing Río La Plata, and diverts water via tunnel into the upper section of the south-flowing Río Guamaní. The diverted water is captured by the Guamaní canal headworks at a lower elevation. The Carite reservoir is fully allocated and its spills flow downstream to the La Plata further downstream, one of the reservoirs supplying the San Juan metropolitan area, which is over-allocated.

However, on many days the Guamaní canal is essentially dry, and streamflow originating in the unregulated south-draining watershed above the Guamaní canal intake can be delivered to Salinas via the canal by simply opening the head gate at the river intake. This stream is ungaged, but based on other gaged streams in the area it is expected to be ephemeral. The flow volume is limited and unregulated and, by itself, cannot restore the aquifer balance.

The Patillas dam was built in 1914 as a hydraulic fill structure. In 2016, prior to hurricane María, gross reservoir capacity at the full supply level (FSL) of 67.7 m was surveyed at 12.7 Mm^3 (GLM Engineering 2016). This represents only 58% of its estimated original 21.9 Mm^3 capacity, which was computed by working backwards from a bathymetric survey in 1961 since data on the original volume data are lost. However, in 2016 it became necessary to permanently lower the normal pool to 64.0 m to mitigate liquefaction hazard during earthquake shaking (the Town of Patillas lies immediately downstream of the dam). This reduced 2016 gross storage to 8.93 Mm^3, leaving the reservoir with only 41% of its original capacity, without counting the additional volume loss by sedimentation from with hurricane María in 2017.

The reservoir's firm yield is already fully allocated by existing users who withdraw on average 0.82 m^3/s, as summarized in Table 1. With a capacity:inflow ratio of only 0.10, on average 62% of the 86 Mm^3 of average annual inflow is spilled and flows to the sea.

Table 1: Existing rates of withdrawal from Patillas Reservoir.

Water Use	m^3/s	Mgd
PRASA Patillas filter plant (floating intake in reservoir)	0.198	4.5
Patillas canal (includes 4.6 Mgd delivery to Guayama filter plant)	0.595	13.5
Evaporation losses from reservoir (calibration parameter)	0.014	0.3
Total	0.807	18.4

Mgd = million gallons per day

Options for Storage Loss

Options for addressing problems of storage loss in reservoirs are summarized graphically in Figure 6. The feasible options at Patillas reservoir fall into two categories: sediment removal and adaptive measures. Sediment removal includes both dredging and flushing, the latter not considered feasible at Patillas based on multiple considerations (lack of low level outlets, environmental impact, and incompatibility with current water supply commitments which requires essentially 100% availability).

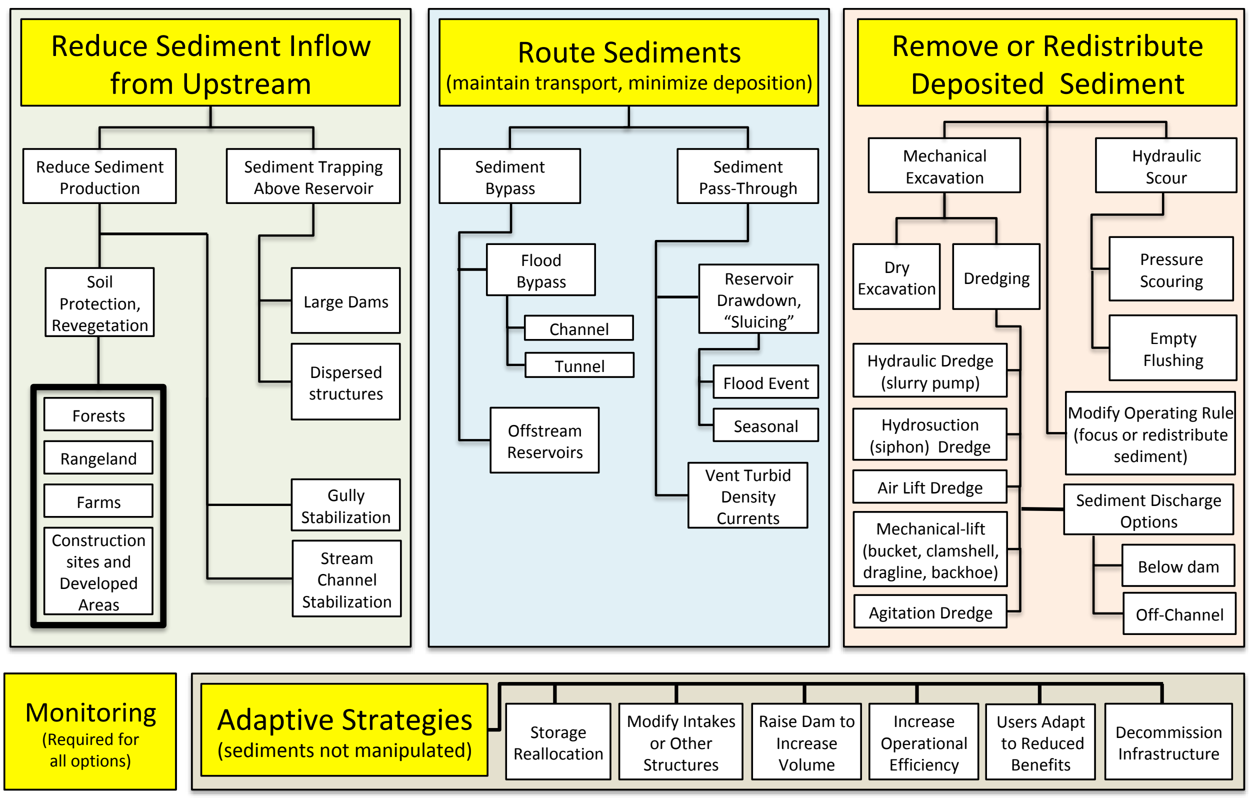

Figure 6: Methods for managing reservoir sedimentation (after Morris 2015).

Dredging and Dam Reconstruction: Two options for recovering reservoir storage capacity at Patillas are dredging and reconstruction of the dam to allow the FSL level to be raised back to 67.7 m. The all-in cost of dredging 6 Mm³ of sediment from Loíza reservoir in Puerto Rico in 1996-1997 was ~$10/m³ (Morris and Fan 1998). To make a ballpark cost estimate this same unit dredging cost was applied to Patillas reservoir. The cost of reconstructing the hydraulic fill dam was roughly estimated to exceed $50M. Table 2 compares these costs to the corresponding increase in firm yield determined by the reservoir simulation model described below. Storage recovery by either dredging or dam reconstruction was considered too costly in relation to the water supply benefit to be considered feasible.

Table 2: Cost and Yield Benefit of Reservoir Storage Recovery Options.

Scenario and Description	Storage, Mm^3	Dredge Vol., Mm^3	Cost, $M	Yield m^3s^{-1}	Yield Mgd	Yield Increase m^3s^{-1}	Yield Increase Mgd
1) FSL 64 m, 2016 volume	8.93	0	0	0.82	18.6	0.0	0.0
2) FSL 67.7 m (reconstruct dam)	12.69	0	>50	0.89	20.3	0.1	1.7
3) FSL 64 m, dredge all sediment	18.14	12.97	130	1.00	22.8	0.2	4.2
4) FSL 67.7m, dredge all sediment	21.90	12.97	>180	1.06	24.2	0.2	5.6

Adaptive Strategy to Enhance Yield

Conjunctive Use: Given the substantial volume of water released over the spillway to the Caribbean Sea, and the need to restore aquifer recharge in Salinas, the option of conjunctive use of Patillas reservoir and ground water was evaluated. The strategy would restore higher flow rates along Patillas canal, diverting additional flow into the canal for recharge on an as-available basis, when the reservoir close to or at the point of spilling. The additional volume earmarked for recharge would be released into seasonally dry ephemeral streambeds and spreading basins. The spreading basins would be located in areas of high soil permeability and could be used for crops tolerant to intermittent flooding, such as some grasses for hay production. The main project components are conceptually illustrated in Figure 7.

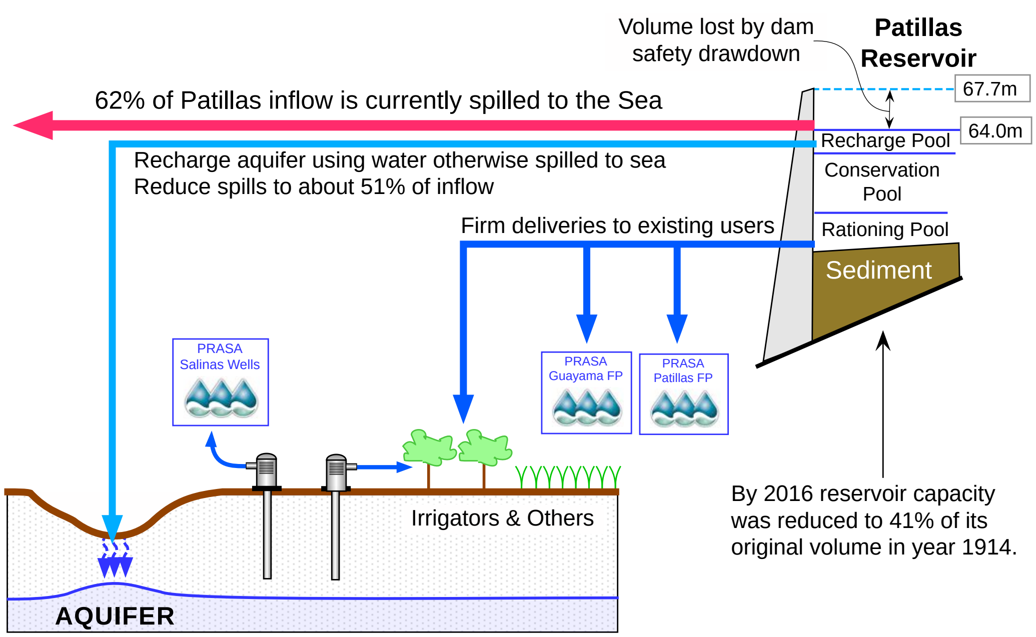

Figure 7: Project conceptualization schematic.

RESERVOIR SIMULATION

A reservoir simulation model was constructed to develop a storage-yield relationship for Patillas reservoir and to also compute the operating rule that could maximize diversions to aquifer recharge without affecting either the volume or reliability of deliveries to existing users.

Reservoir Operations: The reservoir was configured to have three operational pools as previously shown in Figure 7: recharge, conservation and rationing. The operational concept is described below.

1. Water supply deliveries to existing customers are made on a continuous basis, being reduced only when the water level falls into the rationing pool. When the reservoir levels falls within the rationing pool deliveries are reduced to 66% of normal firm yield.
2. Additional water is delivered into the Patillas canal for recharge when the reservoir level enters the recharge pool. The small recharge pool captures as much runoff as possible from small runoff events, and releasing at the highest rate possible to recharge areas subject to hydraulic limitations in the conveyance canal and recharge areas. These additional deliveries are halted as soon as the level drops into the conservation pool.

Reservoir firm yield for any storage capacity is defined by the yield which produces rationing on 1% of the days during the simulation period, and the reservoir is never allowed to empty.

The impact of the recharge pool on firm yield is extremely small because of its small volume. As illustrated in Figure 7, many agricultural users have the option of using either well water or canal water, and the recharge impact on firm yield can be reduced to zero by simply requiring one or two agricultural users to marginally increase their use of well water (which benefits from recharge), instead of using canal water, during periods of drawdown.

Reservoir Simulation Model: A reservoir water balance behavior simulation model (McMahon and Mein 1986) was constructed with a 1-day time step. The operating rules were incorporated into the model. The inflow time series consisted of the historical discharge data reported from 1961 to 2016 at the USGS gage station on Río Patillas (50092000). Rainfall records indicate this data period includes the most severe drought since year 1900, which occurred in 1967-68, as well as the 2015 drought which triggered water rationing in Salinas.

A constant reservoir draft rate was used to compute the firm yield. With little seasonal variation in temperature, water demands in Puerto Rico do not exhibit significant seasonal variations making this a realistic assumption. The model was calibrated against the recent USGS record of reservoir levels (gage 50093045). The gage adjustment factor to account for the 11% ungaged area and reservoir evaporation rate were the two calibration parameters, and both values fell within the expected ranges in the calibrated model. Calibration to historical reservoir levels during the most recent period of significant drawdown is shown in Figure 8 indicating a good fit.

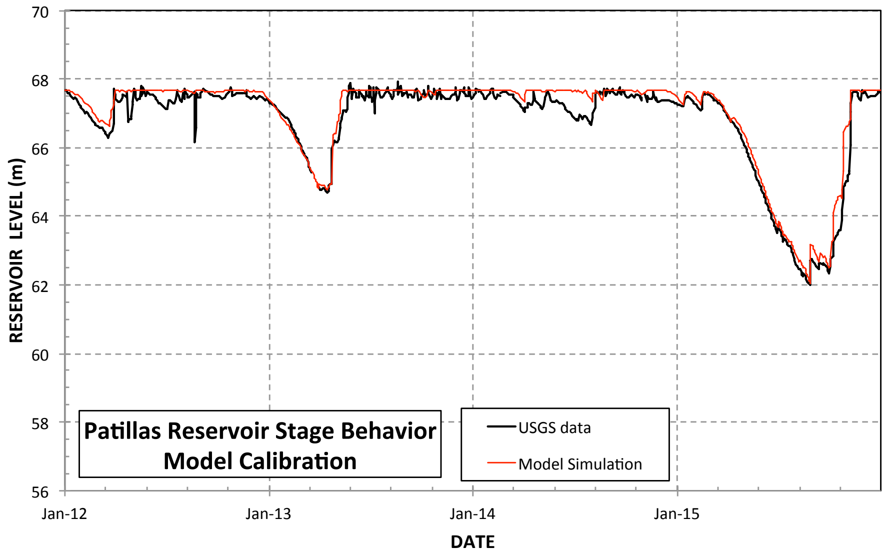

Figure 8: Results of reservoir behavior model calibration to historical water levels.

Simulation Results: The calibrated reservoir model was first exercised to determine the storage-yield relationship used to evaluate the benefits of storage recovery previously described in Table 2. The reservoir has historically not had specific pools assignments, so subsequent modeling focused on establishing pool limits and the draft rate for releases to recharge. Several rates of recharge delivery were evaluated and a maximum rate of 0.42 m^3/s (15 cfs) was selected based on the capacity of the irrigation canal (which has not been used to its design capacity for decades) and the anticipated limit of recharge capacity.

Simulation scenario names are listed below and consist of the pool elevation and the aquifer recharge flow rate: *"Max. Pool El. (ft) – Recharge Flow Rate (cfs)"*.

1. **222-0 (baseline condition)**. This corresponds to the water withdrawals given in Table 1 and the reservoir operated at a FSL of 67.7 m (222 ft). This baseline condition is provided for the purpose of comparison. There is no aquifer recharge under this scenario (there is no recharge pool).
2. **210-0**. Reservoir FSL 64 m (210 ft). This simulation corresponds to the 2016 condition with the reservoir level drawn down to a FSL of 64 m. There is no aquifer recharge under this scenario (there is no recharge pool).
3. **210-5**. Reservoir FSL is 64 m (210 ft). Aquifer recharge rate = 0.14 m^3s^{-1} (5 cfs or 3.2 Mgd).
4. **210-10.** Reservoir FSL is 64 m (210 ft). Aquifer recharge rate = 0.28 m^3s^{-1} (10 cfs or 6.5 Mgd).
5. **210-15**. Reservoir FSL is 64 m (210 ft). Aquifer recharge rate = 0.42 m^3s^{-1} (15 cfs or 10 Mgd).

Simulation results are summarized in Table 3. In all simulations the delivery rate to existing users remains unaltered, and the impact of the different rates of rationing delivery is reflected in the changing number of days of rationing per year. The average realized recharge rate represents total recharge divided by the number of days in the simulation. Note that the total beneficial water use, consisting of delivery to existing users plus the recharge volume, increases significantly. This is important because agricultural users depend on both canal water and ground water, and recharge which helps the aquifer is also helpful to the irrigation sector as well as the municipal and industrial users. Under the recommended alternative, 210-15, the average annual volume diverted to recharge (7.5 Mm^3) is greater than the average annual municipal water supply withdrawal for Salinas of 5.5 Mm^3yr^{-1} (4.0 Mgd).

Table 3: Summary simulation results.

	Yr 2015	Opn. Rule Scenarios for Reduced Storage				
Parameter	222-0	210-0	210-5	210-10	210-15	210-20
Input Parameters:						
Full Supply Level (FSL), m	67.7	64.0	64.0	64.0	64.0	64.0
Constant Delivery to Existing Users , m^3s^{-1}	0.79	0.79	0.79	0.79	0.79	0.79
Max Diversion Flow to Recharge, m^3s^{-1}	0	0	0.14	0.28	0.42	0.57
Simulation Results:						
Days Rationing, % of days	0.7%	1.1%	1.3%	1.4%	1.4%	1.4%
Days Reservoir Empty in Simulation Period	0	0	0	0	0	0
Avg. Days per Year Recharge is Possible	-	-	250	225	205	189
Avg. Realized Recharge Rate, m^3s^{-1}	-	-	0.10	0.18	0.24	0.29
Avg. Annual Recharge Volume, Mm^3		-	3.1	5.5	7.5	9.3
Total Beneficial Water Use, Mm^3yr^{-1}	25.4	25.3	28.4	30.8	32.8	34.6
Spillage to Sea, % of total inflow	62%	62%	58%	54%	51%	48%

Costs: A detailed cost estimate for the recharge system has not yet been worked out. However, inasmuch as this strategy focuses on optimizing the operation of existing canals and other infrastructure, the cost items are expected to consist of minor structures (e.g. recharge turnouts), automation of the Patillas head gate, and miscellaneous improvements, in all totaling less than $0.3M. Another $0.25M, approximately, may be anticipated for monitoring infrastructure including additional observation wells to monitor both level and quality within the aquifer. The most significant cost, if required, will be land acquisition for recharge spreading areas.

Conclusions

Sustaining water supply yield by restoring reservoir capacity can be extremely costly, to the point of being infeasible. However, adaptive water management strategies may exist for sustaining or enhancing water yield which are far less costly than the restoration of reservoir capacity.

This paper described a conjunctive use strategy for a reservoir-coastal aquifer system in which the reservoir operating rule has been optimized to maximize the diversion to aquifer recharge of water that would otherwise be spilled to the sea. Although surface and ground water resources have traditionally managed separately, in Salinas and other systems having similar characteristics, such as the Indus River Irrigation System, surface water deliveries from reservoirs and alluvial aquifers are intimately interconnected. When reservoir capacity is lost to sedimentation in these systems, there is the opportunity to manage both the reservoir and the ground water system to sustain or increase total water yield at low cost compared to other alternatives.

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