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Cover photo: A view of the Milky Way over Phoinix Ranch in Jim Wells and Live Oak counties. ©2022 Rey Garza and Jim Quisenberry

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Optimizing Water Supply through Reservoir Conversion and Storage of Return Flow: a Case Study at Joe Pool Lake

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Abstract: Maintaining an adequate water supply is one of the key challenges faced by the Dallas-Fort Worth Metroplex, where increasing population and rising water demand have elevated the vulnerability of the communities to water shortages. We conducted a preliminary study exploring the possibility of converting flood storage in the Joe Pool Lake to improve water supply reliability and achieve better cost efficiency. This study employs a mixed integer linear programming approach that considers the costs of using flood storage conversion to meet water needs over the northern portion of the Trinity River Basin. It includes tradeoffs between capturing and storing runoff versus return flow from the wastewater treatment facilities of the Trinity River Authority. A set of hypothetical prices and demand figures with the period of record of 1940–1996 was considered to test the mixed integer linear programming model. Results from the mixed integer linear programming produce an optimal strategy that increases the firm yield of Joe Pool Lake and associated storage-diversion on an annual basis. Also, the outcomes of the analyses of the results suggest that while the conversion would have a positive impact on water availability, a lower expansion cost of $20 per acre-foot per year would be required to produce sufficient cost savings.

Keywords: Trinity River Basin, Joe Pool Lake, mixed integer linear programming, optimization, cost efficiency

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Terms used in paper

Acronym/Initialism	Descriptive Name
ac-ft	acre-feet
CRWS	Central Regional Wastewater System
JPL	Joe Pool Lake
LLP	Lake Livingston
MILP	Mixed Integer Linear Programming
TCEQ	Texas Commission on Environmental Quality
TRA	Trinity River Authority
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
WAM	Water Availability Model
WRAP	Water Rights Analysis Package

INTRODUCTION

Population and economic growth intensify the demand for water sources. Reservoirs are important in addressing this growing demand, especially in regions like Texas that experience both significant variability in inter-seasonal precipitation and inter-annual precipitation. Specifically, the state experiences a bimodal precipitation pattern with strong frontal systems producing significant rainfall in the spring and fall. This is bifurcated by hot and dry summers that can last for several months. During this time, surface flow in major river systems is habitually and significantly reduced. For these reasons, reservoirs, which catch runoff from wet months and store them for use during dry months, have been paramount to the development of Texas. Reservoirs are also critical in providing adequate water supplies through multi-year periods of low rainfall relative to normal precipitation. Many of the state's reservoirs were built in the 1950s following the dustbowl years of the 1930s (Reynolds et al. 1999). Relatively few reservoirs have been built in the last few decades, while existing storage capacity has become increasingly stressed by the state's growing municipal, agricultural, industrial, and energy needs (Cervellera et al. 2006).

The population of Texas is projected to increase by 82% between 2010 and 2060 according to the Texas Water Development Board (TWDB; TWDB 2017). During the same time period, TWDB notes that current water resources are expected to decline by 10%, from 17.0 million acre-feet (ac-ft) to 15.3 million ac-ft (TWDB 2012), as siltation consumes reservoir conservation capacity. In addition, the state experiences consecutive periods of droughts and floods that are generally associated with the El Niño–Southern Oscillation cycle (Pu et al. 2016; Naden and Platt n.d.). Extreme examples of droughts and floods can be seen in the meteorological records of 2011 and 2015, respectively. The driest and hottest year was in 2012 (Nielsen-Gammon 2012), the wettest year was in 2015 (National Centers for Environmental Information 2022). Just 3 years later, Hurricane Harvey and Tropical Storm Imelda set records for precipitation in 2017 and 2019, respectively, with both events producing in excess of 40 inches of rain (LeComte 2020).

Texas water managers must therefore balance the needs of water supply with flood control. For this reason, many reservoirs in Texas have both conservation and flood pools. Throughout the 20th century, the United States invested heavily in flood control infrastructure in response to devastating floods along major rivers across the nation. Between 1901 and 1991, 51 major reservoirs were constructed in Texas for flood control or with flood storage capacity (TWDB 2019). In addition, the Natural Resources Conservation Service constructed approximately 2,000 smaller reservoirs to also provide flood control throughout the state (TWDB 2019). Typically, a multipurpose reservoir consists of a sediment or inactive pool at the bottom, a water conservation pool in the middle, and a flood control pool above the water conservation pool. Reservoir operations entail maintaining conservation pools as full as possible, while simultaneously supplying water demands and maintaining flood control pools as empty as possible (Yeh 1985; Yang et al. 2015; Slade 2020; Yaghoubi et al. 2020). Conserving empty flood pool capacity is essential for allowing flooding operations to catch and temporarily store flood waters to reduce downstream flooding. In some situations, agreements are made between the operators and water suppliers to allow the designated conservation storage to be raised or lowered permanently, seasonally, or as a function of other changing conditions (Cromarty et al. 1982).

The state thus finds itself with the ever-growing demands for reliable water supplies frustrated by the challenges of new reservoir construction due to economic, financial, environmental, and institutional considerations. However, reallocation of flood storage capacity and related modifications in the operation of existing reservoirs is difficult because it is contentious, and the authors recognize that it might not be possible if the U.S. Army Corps of Engineers (USACE) deems it inappropriate. But the studies on reallocated storage can be used in optimization strategies involving the movement of water between reservoirs, rivers, and other water supply infrastructure. The emergence and widespread adoption of sophisticated models such as RiverWare are enabling entities to view their systems in ways that were heretofore impossible and explore cooperative efforts between entities with disparate water supply infrastructures. This has the possibility of significantly increasing the efficiency of water supply systems, offsetting the need to construct new reservoirs, and providing in-stream environmental benefits.[1]

The Trinity River Basin is located in east-central Texas. The watershed begins to the north within a few miles of the Red River and the Oklahoma border. From there it flows to the south and east some 700 miles before emptying into the Gulf of Mexico. The river is an important source of water, supplying or supplementing supplies for approximately half of the state's population. This is due almost exclusively to the network of reservoirs located throughout the 18,000-square-mile watershed. These reservoirs are owned and operated by several different entities, most notably, USACE, the Tarrant Regional Water District, the North Texas Municipal Water District, and the Trinity River Authority (TRA).

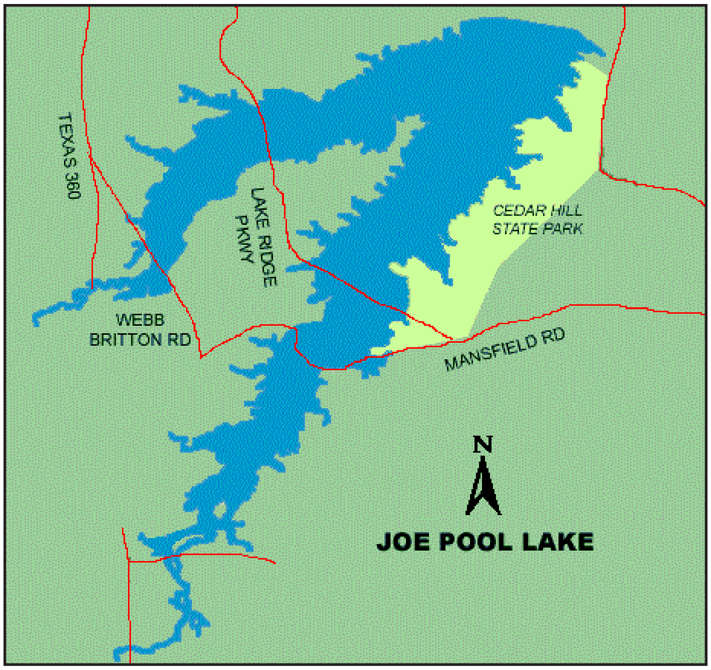

Figure 1. Joe Pool Lake Reservoir and Location Characteristics.

The Joe Pool Lake (JPL) reservoir is located in the Dallas-Fort Worth Metroplex. It is owned and operated by USACE and provides both water supply and flood control benefits. Completed in 1989, JPL reservoir has a capacity of 176,900 ac-ft and collects runoff from a watershed area of 232 square miles, as shown in Figure 1 (Ghimire 2014).

Technical information about reservoir and reservoir storage data in daily time steps is available on the USACE Fort Worth District website (USACE n.d.). Table 1 describes technical features of Joe Pool Dam (Demirel and Wurbs 2015).

TRA is exploring the possibility of expanding the conservation, or water supply, pool capacity of JPL reservoir to address growing water demand in the region along with alleviating potential shortages during droughts. One possibility is to convert flood pool storage into water supply storage and to capture and store treated wastewater from the TRA Central Regional Wastewater System (CRWS). Treated wastewater is increasingly becoming an important source of water in the region containing the upper portion of the Trinity River (the Region C regional water planning area, as defined by the Texas Water Development Board). Economic and environmental issues together are one of the main factors for reusing the wastewater treatment (Haghiri et al. 2018; Gheytaspour and

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[1] Please note that co-author Glenn Clingenpeel is currently working with the USACE on a long-term project that would allow use of the flood pool for water supply. He also co-presented the work on this project at Texas Water Conservation Association's conference in June 2021 under the topic "Forecast Informed Reservoir Operations (FIRO)." This methodology is being implemented successfully in California.

Table 1. Technical details of Joe Pool Lake storage.

Feature	Elevation (feet)	Accumulative (acre-feet)	Incremental (acre-feet)	Spillway capacity (cubic feet per second)
Top of dam	564.5	---	---	---
Maximum design water	559.5	642,400	279,700	11,900
Spillway crest	541	362,700	58,700	---
Top of flood control pool	536	304500	127600	---
Top of conservation pool	522	176,900	142,900	---
Sediment reserve	---	---	38,000	---
Streambed	456	---	---	---

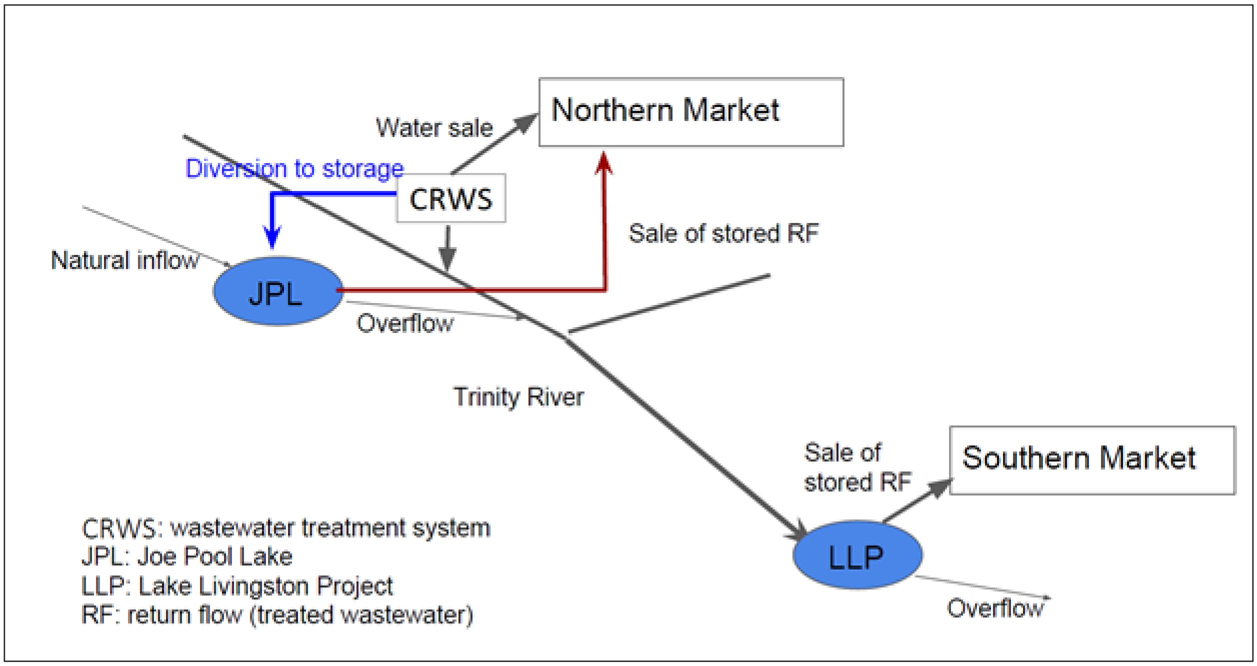

Figure 2. System design of JPL reservoir diversion and sale of stored return flows.

Habibzadeh Bigdarvish 2018; Asgari-Motlagh et al. 2019); however, the reuse of treated wastewater also greatly depends on public agreement, awareness, and support (Daghighi et al. 2020). TRA holds both the water rights for treated wastewater discharged from their facilities, henceforth referred to as return flow, and the water stored in JPL reservoir. Increasing the conservation capacity of JPL reservoir will provide operational flexibility to store and sell a portion of the return flows to adjacent cities. Figure 2 provides schematic design details of this research design.

The cost-effectiveness of the JPL reservoir conversion project is determined by a number of factors, among which are hydroclimate conditions (future precipitation amounts and inflow volumes) over both the upper and lower portions of the Trinity River Basin, water demand in the northern portion of the Trinity River Basin (henceforth referred to as the northern market), water supply from outside the Trinity River Basin, and the operating strategy. The operating strategy will consist of a set of dynamic decisions regarding the amount of return flow to be sold to the neighboring cities or stored at JPL reservoir, the capture and release of runoff, and the amount of stored water to be sold at a given year. The term runoff is used to distinguish between runoff (sometimes called natural flow) and inflows, which include return flows and imported water. These decisions will be formed by considering hydroclimate conditions, water demand, water rights, and contractual and regulatory requirements. Thus, the objective of this project is to determine optimal conversion capacity and associated operational

Table 2. Linear programming problems inputs.

Input	Detail
C_{JPL}	Cost to expand one-unit volume of Joe Pool Lake (JPL) reservoir
C_D (t)	Penalty cost per volume of demand not met
r_{JPL} (t)	Revenue selling from JPL reservoir to northern region per volume sold
r_N (t)	Revenue selling from the Central Regional Wastewater System (CRWS) to northern region per volume sold
r_S (t)	Revenue selling from CRWS to southern region per volume sold
β (t)	Fraction of JPL reservoir first tier flow sold to northern market that returns via CRWS (adds to second tier flow)
γ (t)	Fraction of diverted first tier flow that reaches storage into JPL reservoir (loss is channel and evaporative loss)
V_1 (t)	Volume of available first tier water (different for wet vs. dry years)
V_2 (t)*	Volume of available second tier water
R_{LLP} (t)	Salable runoff volume into Lake Livingston (can vary by year, but for current study fixed at 351,600 acre-feet). It is inflow, but it is only that fraction of inflows that resulted from runoff in the watershed.
D_N (t)	Demand volume for the northern region
D_S(t)	Demand volume for the southern region (constant across different years)
W	Upper limit on JPL reservoir expansion

*The volume of available second tier water can be calculated via $V_2 = \beta(y_N + 365\ y_{JPL})$.

strategies that would minimize an objective function that factors in conversion cost, revenue from water sales, and demand/supply gap, while meeting contractual and regulatory requirements. Mixed integer linear programming (MILP) is one of the most common and user-friendly techniques for water reservoir optimization (Eusuff and Lansey 2003; Ghahraman and Sepaskhah 2004; Daghighi et al. 2017; Samani and Mottaghi 2006). We will proceed by formulating a MILP problem that superimposes realistic runoff and return flow on known historical hydro-climate conditions over multiple years. The Texas Commission on Environmental Quality (TCEQ) is charged with issuing water rights in Texas based upon a legal framework known as the prior appropriation doctrine. This requires an accounting and allocation of available water based on seniority, with the oldest water rights being the most senior. When there is insufficient water to satisfy all water rights, water is allocated first to the most senior rights. The model that TCEQ uses to account for and allocate water among water rights holders is called the Water Rights Analysis Package, or WRAP (Wurbs 2001). WRAP can be used to evaluate the impact of various demand and permit scenarios on water rights, based on historic hydro-climate conditions. These scenario-based model runs are called Water Availability Model runs, or WAM runs for short. The hydrology upon which they are based represents a documented and accepted set of hydrologic conditions that include the drought of record and is used to evaluate the reliability of water rights. This set of hydrologic conditions will be used as the basis of evaluation for MILP. WAM Run 3, last updated on October 7, 2014, will be used in the study.

MATERIALS AND METHODS

Definition of input variables

Table 2 specifies the input data that will be required to populate the MILP problem. Most values will change from year to year and are represented as a function of time. But values that are assumed to be static across all years are represented by themselves. Abbreviations are used for Joe Pool Lake (JPL), Lake Livingston (LLP), and CRWS. For the first tier return flow volume ($V_1(t)$), MILP requires the available volume after accounting for channel or evaporative losses. In addition, losses can be incorporated in the fractions β and γ. The MILP formulation allows input parameters to vary by year except for those values pertaining directly to the JPL reservoir expansion.

Definition of decision variables

Table 3 defines the MILP formulation by the decision variables, objective function, and constraints. The primary decision is the expansion of JPL reservoir, the secondary decisions are year-to- year volumes of water sold, and slack variables are used in a penalty approach for demand and reservoir overflow.

The expansion of JPL reservoir is assumed static across all years. The resolution of the MILP is annual, so it is assumed that every day is identical and that there are 365 days per year. Under this assumption, the annual volume of first tier return flow diverted to storage in JPL reservoir and the volume of water from JPL reservoir sold to northern region values are

Table 3. Mixed integer linear programming formulation variables.

Input	**Detail**
x	Increased volume of Joe Pool Lake (JPL) reservoir
x_d (t)	Volume/day of first tier return flow diverted to storage in JPL reservoir
y_{JPL} (t)	Volume/day of water from JPL reservoir (mix of return flows and runoff) sold to northern region
y_N (t)	Volume of first tier return flow sold to northern region
y_S (t)	Volume from LLP (mix of return flows and runoff) sold to southern region
s_N (t)	Slack variable for northern region demand
s_S (t)	Slack variable for southern region demand
s_{JPL} (t)	Slack variable for overflow in JPL reservoir
I_{JPL} (t)	Volume of water available at the start of the year in JPL reservoir (carryover)
R_{JPL} (x,t)	Salable runoff volume into JPL reservoir (table values from the Water Availability Model are a function of year t and the size of the JPL reservoir expansion x)

distributed equally per day. Finally, penalty costs per volume of unmet demand for the northern and southern regions are assumed the same.

Formulation of linear program

The objective function is formulated to minimize the costs minus the revenue obtained. The costs involved in the equation include the cost to expand JPL reservoir ($C_{JPL}\, x$), a penalty cost for not meeting demand ($C_D\, (s_N + s_S)$). The penalty coefficient C_D can be set to zero if no penalty is desired. Relevant JPL reservoir storage per day consists of the diverted first tier return flow that reaches JPL reservoir ($\gamma\ x_d$). Revenue comes from three basic sources (JPL reservoir, CRWS, and LLP), which are permitted to have different revenue rates (r_{JPL}, r_N, r_S) in the MILP. The revenue from JPL reservoir is calculated for the volume of water sold from JPL reservoir for the year ($365\ y_{JPL}$). The revenue on first tier return flow from CRWS that is sold to the northern region is denoted by y_N. The revenue on volume sold to the southern region (y_S) only comes from LLP but is a mix of return flows and runoff. The objective in Equation 1 is obtained by summing up the costs and subtracting the revenues.

$$\text{Min } C_{JPL}\, x + C_D(t)\ [s_N(t) + s_S(t)] - r_{JPL}(t)\ [365\ y_{JPL}(t)] - r_N(t)\ y_N(t) - r_S(t)\ y_S(t) \tag{1}$$

In Equation 2, the JPL reservoir expansion cannot exceed a user-specified maximum (W). In Equation 3, the annual volume of first tier return flow that is diverted to JPL reservoir cannot exceed the annual volume of first tier return flows (V_1). Also, in Equation 4, the diverted flow cannot exceed the available JPL reservoir expansion capacity, where the capacity of the JPL reservoir expansion (x) is reduced by the volume of runoff stored in the JPL reservoir expansion (R_{JPL} (x, t)) and the volume of carryover stored in JPL reservoir from the previous year ($I_{JPL}(t)$). Currently, the carryover in year 1 is set to 0. But the value for the carry-over in year 1 is formulated as an input and can be set to any starting value. In Equation 5, the volume of carryover for the current year is represented as a state transition equation, which is the difference between the aggregate of the volume of water carried over from the previous year, the firm yield of JPL reservoir, and the diverted flow reduced by channel losses and the volume of water sold from JPL reservoir. The firm yield is the minimum amount of water that can be diverted from a reservoir on an annual basis under the hydrologic conditions of the drought of record (1952–1957). It is more loosely defined as the reliable amount of water that a reservoir can produce through a severe drought.

The runoff stored in the JPL reservoir expansion ($R_{JPL}(x, t)$) depends on the available JPL reservoir expansion capacity and the year under consideration. The runoff stored in the JPL reservoir expansion is obtained by using a piecewise linear approximation on the lookup table provided by TRA (impoundment targets from WAM).

$$x \le W \tag{2}$$

$$365\ x_d(t) \le V_1(t) \tag{3}$$

$$365\ x_d(t) \le 365\ x - R_{JPL}(x, t) - I_{JPL}(t) \tag{4}$$

$$I_{JPL}(t+1) = I_{JPL}(t) + (0.1x) + 365\ \gamma(t)\ x_d(t) - 365\ y_{JPL}(t) \tag{5}$$

In the MILP model, we formulate decision variables that consider the expansion of JPL reservoir, which will enable selling from JPL reservoir to the northern region (y_{JPL}). Some fraction (β) of the volume sold to the northern region ($365 y_{JPL} + y_N$) will return via CRWS and become second tier return flow. At that point, this flow must now go to LLP.

To prevent the MILP from going unbounded and to make sure that only the available amount of water is sold, selling constraints are specified in Equations 6, 7, and 8 for the amount sold to the northern region from CRWS (y_N), the amount sold to the northern region from JPL reservoir (y_{JPL}), and the amount sold to the southern region (y_S). It is required that at least 30% of first tier return flows from CRWS must flow to LLP. The first tier return flow volume from CRWS is the input V_1. The first tier return volume that does not flow to LLP consists of the volume from CRWS that is sold to the northern region (y_N) and the volume diverted to JPL reservoir storage (365 x_d). Hence, the numerator in Equation 6 is the first tier return flow that reaches LLP. The 30% requirement in Equation 6 subsequently restricts the volume that can be sold to the northern region annually (y_N), as well as the volume that can be diverted to JPL reservoir per day (x_d)

$$\frac{\left(V_1(t) - [y_N(t) + 365\ x_d(t)]\right)}{V_1(t)} \geq 0.30 \tag{6}$$

Equation 7 presents Equation 6 with a different format in MILP form.

$$y_N\ (t) \leq\ 0.70\ V_1(t) - 365\ x_d(t) \tag{7}$$

In Equation 8, the volume sold to the southern region (y_S) is limited by the first tier return flow that reaches LLP, the volume available second tier return flows, and the amount of runoff in LLP.

$$y_S(t) \leq V_1(t) - [y_N(t) + 365\ x_d(t)] + \beta(t)\ [y_N(t) + 365\ y_{JPL}(t)] + R_{LLP}(t) \tag{8}$$

In Equation 9, the volume sold to the northern region from JPL reservoir (y_{JPL}) is limited by the firm yield of JPL reservoir, which is a function the expansion, the volume diverted to JPL reservoir storage ($\gamma\ x_d$), and the volume of carryover stored in JPL reservoir from the previous year ($I_{JPL}(t)$).

$$365\ y_{JPL}(t) \leq (0.1x) + 365\ \gamma(t)\ x_d(t) + I_{JPL}(t) \tag{9}$$

Given water volume demand requirements for the northern and southern regions (D_N and D_S), constraints are needed to meet demand. These demand values are based on what TRA has been able to sell historically or based on existing contracts. This is formulated as a hard constraint because TRA cannot sell to more than the available pool of customers. The constraints are stated separately for the two regions, as in Equations 10 and 11:

$$365\ y_{JPL}(t) + y_N(t) \leq D_N(t) \tag{10}$$

$$y_S(t) \leq D_S\ (t) \tag{11}$$

In addition, it is desirable to satisfy customer demand. To avoid the instance of an infeasible solution, we have incorporated a penalty approach to encourage that demand is met. The penalty cost (C_D) on failing to meet demand was seen earlier in the objective function in Equation 1. The constraints to satisfy demand are stated separately for the two regions as Equations 12 and 13, respectively:

$$365\ y_{JPL}(t) + y_N\ (t) + s_N(t) \geq D_N(t) \tag{12}$$

$$y_S(t) + s_S(t) \geq D_S(t) \tag{13}$$

Finally, bounds must be specified on nonnegative decision variables, as is presented by Equation 14:

$$x,\ x_d(t),\ y_N(t),\ y_S(t),\ y_{JPL}(t),\ s_N(t),\ s_S(t),\ I_{JPL}(t) \geq 0 \tag{14}$$

RESULTS AND DISCUSSION

The code was tested with different inputs to check whether the MILP appropriately adjusts its optimal solution for different inputs. Because the purpose of the MILP is a hypothetical exploration, unrealistic parameter settings in the current system may be used in the MILP. All runs were executed for the years 1940 through 1996, with this period of hydrological record chosen because it covers a scenario where there was at one time excess water in JPL reservoir, followed by a drought of record. This sequence of events could help determine whether the MILP performs according to the purpose for which it was designed, i.e., storing water in JPL reservoir storage when excess water is available and selling it in years when there is deficit in supply. The cost for expansion per acre feet of JPL reservoir was identified by TRA's board and is an important input for JPL reservoir expansion. Another input was the demand function based on the volume of available water to store in JPL reservoir (supply) and designed to mimic the demand function in real life.

Slack variables in Equations 12 and 13 were used to track whether customer demand was met. If slack variables ($s_N(t)$,$s_S(t)$) are positive, customer demand was not fully met, with the value of the slack variable equal to the volume of unmet demand. If the slack variables are zero, then customer demand was fully satisfied, but there may also be the possibility of surplus volume from JPL reservoir, CRWS, or LLP.

The MILP was created using Matlab, and the Matlab runtime executable code has been made freely available to TRA for its own use.

Table 4. Mixed integer linear programming Scenario 1 inputs.

Input	Detail
C_{JPL}	$88.82/acre-foot (ac-ft) for the first 20 years and no cost for the remaining years
C_D (t)	$100/ac-ft/year
r_{JPL} (t)	$95/ac-ft/year
r_N (t)	$95/ac-ft/year
r_S (t)	$95/ac-ft/year
β (t)	0.50
γ (t)	0.89
R_{LLP} (t)	Fixed at 351,600 ac-ft/year
D_N (t)	Represented by black line in Figure 3
W	123,100 ac-ft

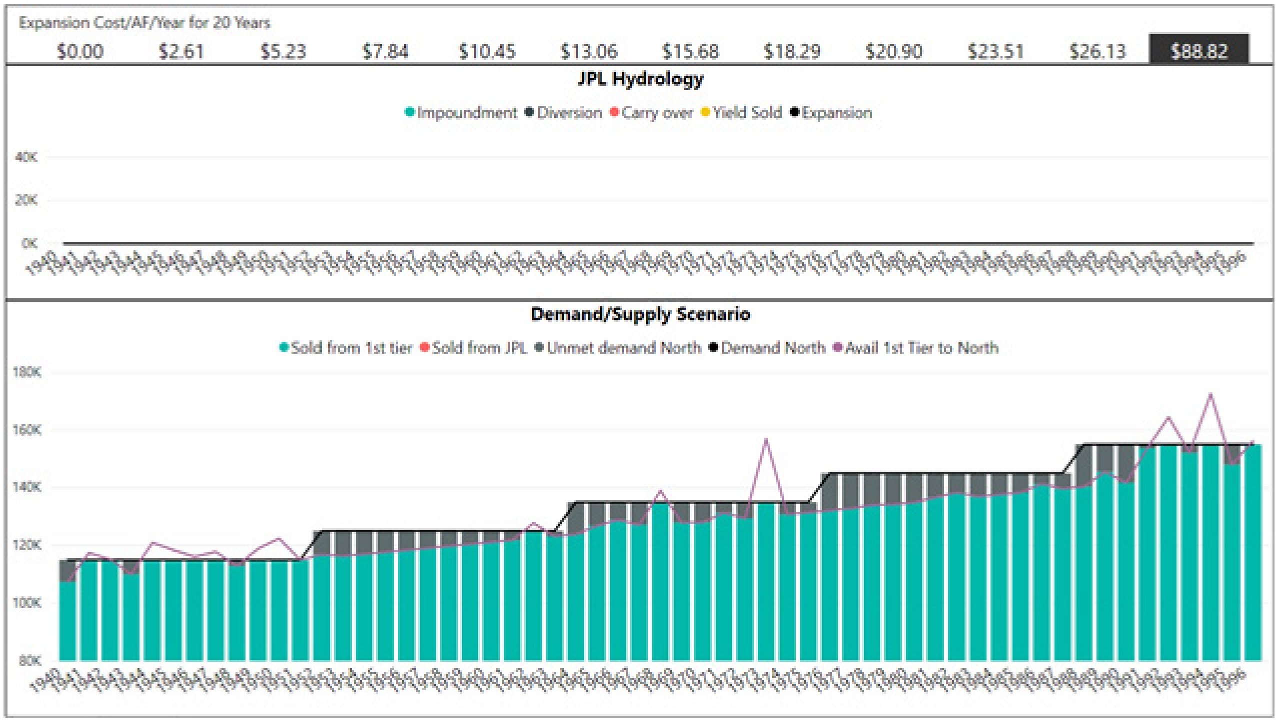

Figure 3. Joe Pool Lake (JPL) reservoir hydrology for Scenario 1.

Scenario 1

Scenario 1 was a scheme devised by TRA's board. The inputs used for this scenario are specified in Table 4.

Figure 3 shows the hydrology in JPL reservoir lake reservoir and the demand/supply scenario in the northern market.

Our results showed that expanding the JPL reservoir is not worthwhile because the cost of conversion is very high when compared to the revenue from JPL reservoir. Even though there is unmet demand and penalty on the unmet demand, the MILP chose not to convert JPL reservoir. Figure 4 shows the cost and revenue for the entire system, including the northern and southern market.

Another result is that the payback period, assuming a cost of conversion per acre-foot of $88.82 and a revenue of $95 per acre-foot, was 170 years, as shown in Figure 5.

Figure 4. Cost and revenue for entire system for Scenario 1.

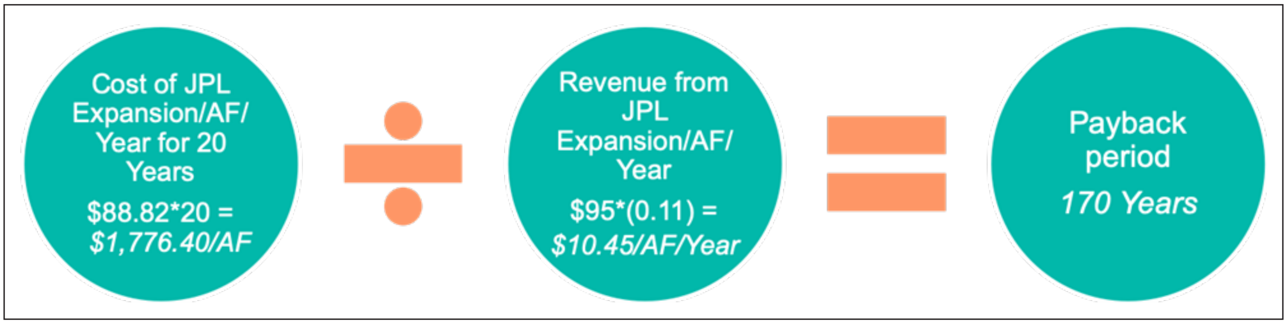

Figure 5. Payback period calculation for Scenario 1 (AF – acre-feet).

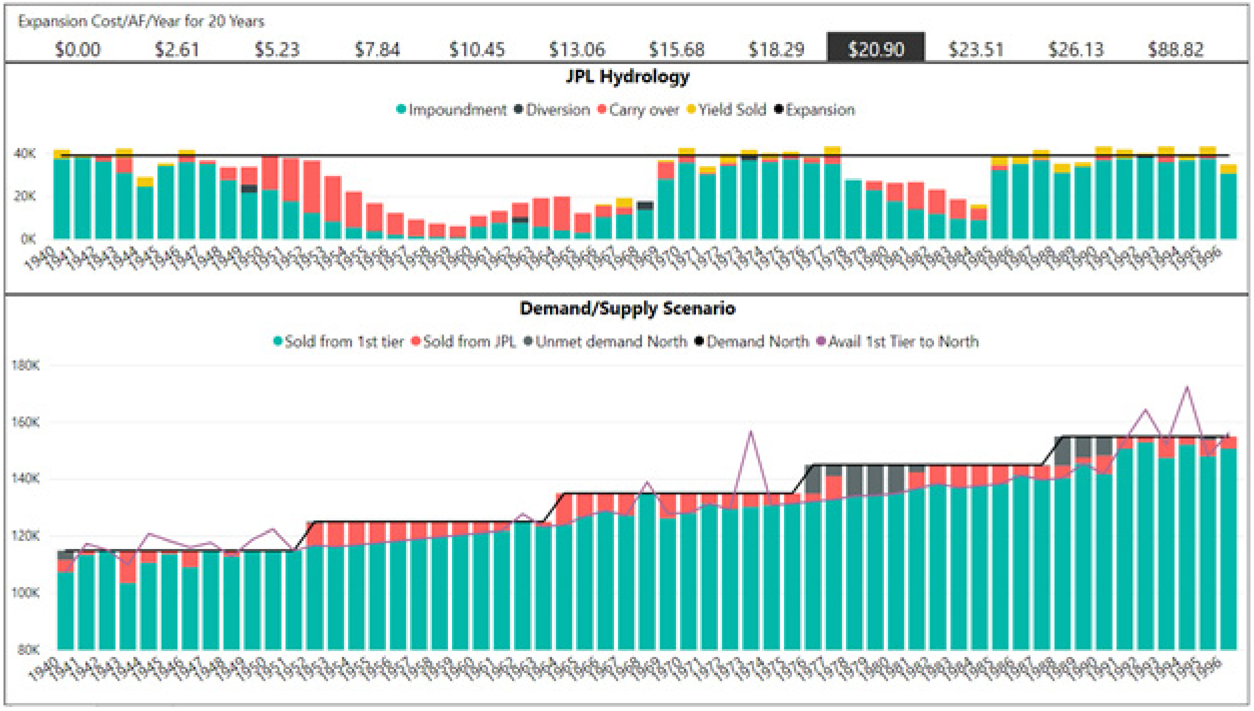

Figure 6. Joe Pool Lake (JPL) reservoir hydrology for Scenario 2.

Table 5. Linear programming Scenario 2 inputs.

Input	Detail
C_{JPL}	$20/acre-foot (ac-ft) for the first 20 years and no cost for the remaining years
C_D (t)	$100/ac-ft/year
r_{JPL} (t)	$95/ac-ft/year
r_N (t)	$95/ac-ft/year
r_S (t)	$95/ac-ft/year
β (t)	0.50
γ (t)	0.89
AR_{LLP} (t)	Fixed at 351,600 ac-ft/year
D_N (t)	Represented by black line in Figure 6
W	123,100 ac-ft

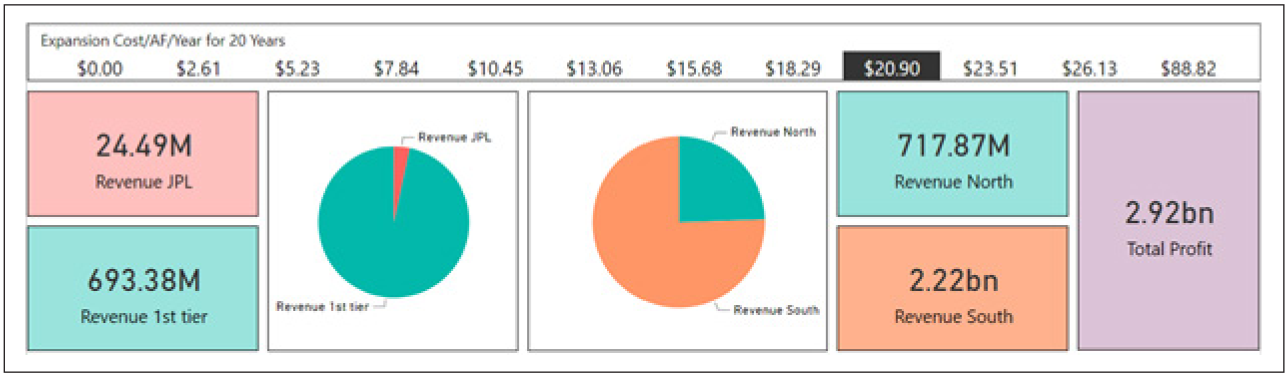

Figure 7. Cost and revenue for entire system for Scenario 2.

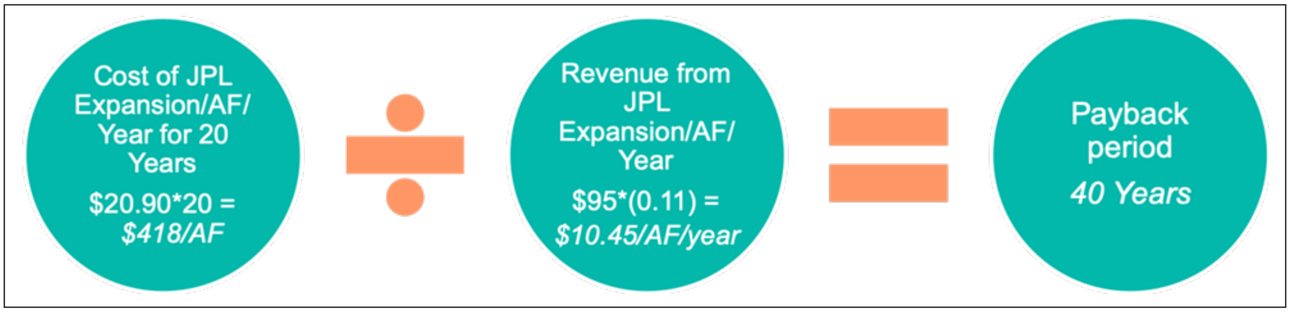

Figure 8. Payback period calculation for Scenario 2 (AF – Acre Feet).

Scenario 2

Scenario 2 was performed as a theoretical exercise using a cost of expansion per acre-foot of JPL reservoir from the result of a break-even analysis and to test the functionality of the MILP model. The break-even analysis identified the cost of expansion per acre-foot of JPL reservoir at which it would be feasible to expand the reservoir given the demand/supply scenario and revenue from expansion per acre-foot of JPL reservoir. The cost of expansion per acre-foot of JPL reservoir was determined to be around $20, so the MILP was run with this input to check whether the MILP performed as expected. Table 5 shows the inputs used for Scenario 2.

The MILP solution recommends expansion of the JPL reservoir to around 40,000 ac-ft, and Figure 6 shows the hydrology in JPL reservoir and the demand/supply scenario in the northern market.

Our results showed that the excess water available when there was sufficient rainfall in the earlier years after meeting the demand was stored and carried over to the later years when there was a rainfall deficit. The results also showed that the demand was met using the additional carryover water when there was not enough water to meet the demand with just the first tier flowing. Despite this compensation, there was unmet demand in a few years because there was not enough water available to carry over, due to most of the surplus water from earlier years being used to compensate for the drought of record. Another reason for this result is that there was an effective evaporation coefficient of 0.89 (or 89%) applied to the water stored in the reservoir, which in turn impacts the amount of water available to be carried over the water to the following years. Figure 7 shows the cost and revenue for the entire system, including the northern and southern market.

Another result is that the payback period for Scenario 2, assuming a cost of conversion per acre-foot of $20 and a revenue of $95 per acre-foot, was 40 years, as shown in Figure 8.

CONCLUSION

Because of growing water demand and water shortage in the Dallas-Fort Worth Metroplex, TRA is considering expanding the capacity of JPL reservoir. The two main sources for JPL reservoir are the natural stream flow and the return flow from the CRWS. Based on these inputs, TRA tries to meet the demand in dry years by creating additional storage and diverting excess water to the storage during wet years. The optimal conversion capacity of JPL reservoir was determined by modeling the hydrology of the different sources as an MILP with the objective of minimizing the costs of expansion.

Several scenarios with different penalty costs and costs of expansion per acre foot of JPL reservoir were run to determine whether the designed MILP could store sufficient water in JPL reservoir during wet years and sell it during a drought period. We presented two scenarios that yielded contrasting results in this paper. Based on the data availability and scenario coverage, years 1940 through 1996 were chosen because there were wet years followed by a drought record for the example and testing timeline.

In Scenario 1, the expansion cost for JPL reservoir was taken as $88.82 per acre foot for the first 20 years with no cost for the remaining years. This model did not meet the requirements for expanding JPL reservoir storage because the expansion cost was too high in comparison to the penalty of unmet demand and selling revenue.

In Scenario 2, the cost of expansion per acre-foot of JPL reservoir, based on the payback period calculation, was set to be about $20. The model chose to expand the JPL reservoir to 40,000 ac-ft, implying that the model chose to save water during wet years and store it in the JPL reservoir to meet the demand during drought. Even though the model attempted to meet water demand during dry years, there was still some unmet demand in the later years because there was not sufficient water to meet the demand. Testing the MILP with different scenarios demonstrates that the MILP works and takes into consideration the different hydrology and inputs.

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DATA AVAILABILITY

Some data, models, or code that support the findings of this study are available from the corresponding author, Srividya Sekar, upon reasonable request. Data or code available on request are:

- Input data for Scenario 1 and Scenario 2;
- Output data for Scenario 1 and Scenario 2;
- MATLAB code (.m) file; and
- Executable MATLAB file (.exe).

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