

Projected Reservoir Rating Curves Based on Sedimentation Surveys And Their Application in Water Planning in Texas

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ABSTRACT

This paper presents a study on sediment in Texas reservoirs and its effect on reservoir firm yield. This study examined the geographical variation of reservoir sedimentation across the state of Texas as well as the sediment distribution inside a reservoir at all depths from streambed to the top of conservation pool. Results indicate that sediment accumulates faster in lower elevations than in higher elevations in most Texas reservoirs but the opposite is true in reservoirs where significant deltaic formations exist. Reservoir elevational sedimentation rates (capacity loss rates) are estimated incrementally at different elevation levels to develop reservoir rating curves according to the vertical distribution of sediment, using the data from hydrographic surveys. Reservoir rating curves for the next 50 years are predicted, assuming a constant sedimentation rate for the prediction period. Based on the predicted rating curves, reservoir firm yields for the prediction periods can be estimated and a relationship between predicted reservoir capacity and firm yield is derived. This provides useful information for water planning in Texas.

INTRODUCTION

Reservoir sedimentation is a natural and unavoidable process that reduces reservoir storage capacity. Sedimentation in Texas reservoirs is also a significant problem affecting water availability in Texas. The International Boundary and Water Commission (IBWC) of the United States and Mexico established the very first suspended sediment station in Texas on the Rio Grande at El Paso in 1889 (Texas Board of Water Engineers 1959). Investigations of reservoir sedimentation have also been conducted based on reservoir volumetric surveys. According to Eakin and Brown (1936), the earliest studies on reservoir sedimentation in Texas were conducted for White Rock Lake and Lake Worth in 1910 and 1915, respectively. Since then, many reservoirs have been built in Texas and sedimentation in Texas' reservoirs has attracted attention by the authorities. In 1991, the 72nd Texas State Legislature authorized the Texas Water Development Board (TWDB) to develop a non-profit, self-supporting reservoir volumetric survey program, the Hydrographic Survey Program. Since 1992, TWDB's Hydrographic Survey Program has completed 178 hydrographic surveys on 112 unique reservoirs. To date, most of Texas' major reservoirs have been surveyed multiple times to allow for reasonable estimates of sedimentation rates. For example, White River Lake, built in 1963 (enlarged in 1971), loses approximately 1.3 percent of its capacity per year (approximately 600 acre-feet per year), one of the highest sedimentation rates among reservoirs in Texas, based on surveys from 1971 to 1992 (TWDB 2003a). In an internal analysis of 108 surveyed major reservoirs in Texas, TWDB found that 7.1 percent of the original storage capacity had been lost by 2009, some having capacity losses as high as 75 percent. Estimated annual storage capacity losses of 176 water supply reservoirs over the next 60-years (through 2070) will range from 66,000 to 128,000 acre-feet per year, with an average of 90,000 acre-feet per year (figure 1).

Sedimentation reduces a reservoir’s storage capacity and therefore may affect its firm yield. Firm yield is the maximum annualized quantity of water that could be diverted from a reservoir every year including drought of record years, based on the historical hydrological record. Texas Administrative Code (Title 31) Rule §357.10 requires Texas’ regional water planners to use firm yield “.....under a repeat of the Drought of Record using anticipated sedimentation rates.....” when estimating future water availability. What are anticipated sedimentation rates? To answer this question is the major objective of this study. That is, to estimate the sedimentation rates in reservoirs to provide more accurate information to water planners.

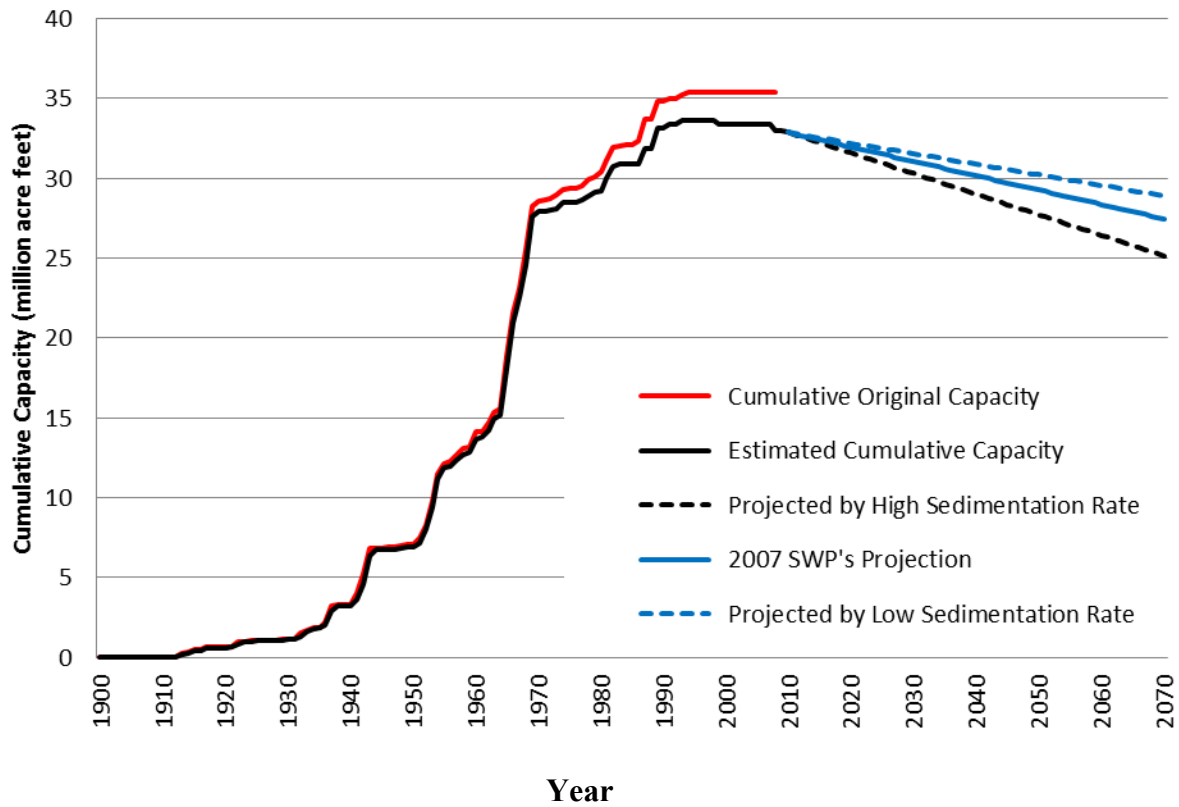


Figure 1. Total storage capacity of 176 major reservoirs in Texas. The red line represents reservoir capacity as built. The black line represents reservoir capacity after factoring in capacity loss of 0.27 percent of the total major reservoir capacity per year due to sedimentation. Dotted black, blue and dotted blue lines represent minimum, average and maximum projected total capacities, respectively.

DISTRIBUTION OF SEDIMENT IN A RESERVOIR

Sediment in a reservoir comes from erosion in the reservoir catchment, so the mineral and particle size are related to the nature of soils and geology in the catchment. The coarse materials are usually deposited at the river mouth where it enters the reservoir while fine particles settle farther into the body of a reservoir, usually in the lower elevations of a reservoir. If multiple rivers/streams flow into a reservoir, non-main stem streams will have significant effect on the sediment distribution (Abraham, et al 1999).

Sediment distribution can vary in a reservoir depending on its contributing rivers/streams and geomorphology. The TWDB's hydrographic survey of Lake Buchanan found more sediment in the upstream area (upper reach) of the lake body (figure 2), but in Granger Lake the opposite was found. More sediment was measured in the downstream portion (lower reach) of Granger Lake (figure 3). When a reservoir is built at a confluence of two or more major streams, sediment may differ in different arms of the reservoir. For example, in Waco Lake more sediment occurs in the middle of the southern arm because of the higher percentage of farm land in the Middle Bosque River and Hog Creek watersheds which flow into the southern arm of the lake (figure 4).

Sedimentation varies from reservoir to reservoir across the state of Texas. For the specific reservoir sedimentation rate assessment, we use the TWDB reservoir sedimentation survey results to depict a reservoir specific sedimentation rate (percent capacity loss per year). The available survey data appears to indicate that reservoirs in the northwest of Texas (also known as the Low Rolling Plains) are more vulnerable to sedimentation due to higher erosion rates in that area (figure 5). Available data also indicate smaller reservoirs are being filled faster (figure 6), due to smaller capacity to accommodate the sediment. This result is generally consistent with the study published by the Texas State Soil and Water Conservation Board (TSSWCB 1991), which included detailed erosion and sedimentation rates for 300 yield-point areas covering Texas. However, as stated in the TSSWCB report, one must be careful in using the data presented in the report, because erosion rates or sediment yield rates at those points are defined as tonnage per square acre or square mile and not all sediment may reach a reservoir unless specified. The method of measuring sedimentation rate is different than the method used in this study. The most important factor is that sediment yield rate does not equal reservoir capacity loss rate because the latter is related to the size of a reservoir. Nevertheless, higher sediment yield rate in a reservoir watershed is the primary factor to be considered. According to the TSSWCB, agricultural croplands are subjected to higher erosion rates and hence have higher sediment yield rates (TSSWCB 1991, page 199). For example, Wright Patman Lake has a higher capacity loss rate due to a higher sediment yield rate caused by a combination of higher erosion rates both from agricultural land and channel erosion (presentation by Dr. Mike Buttram, Texarkana College 2017).

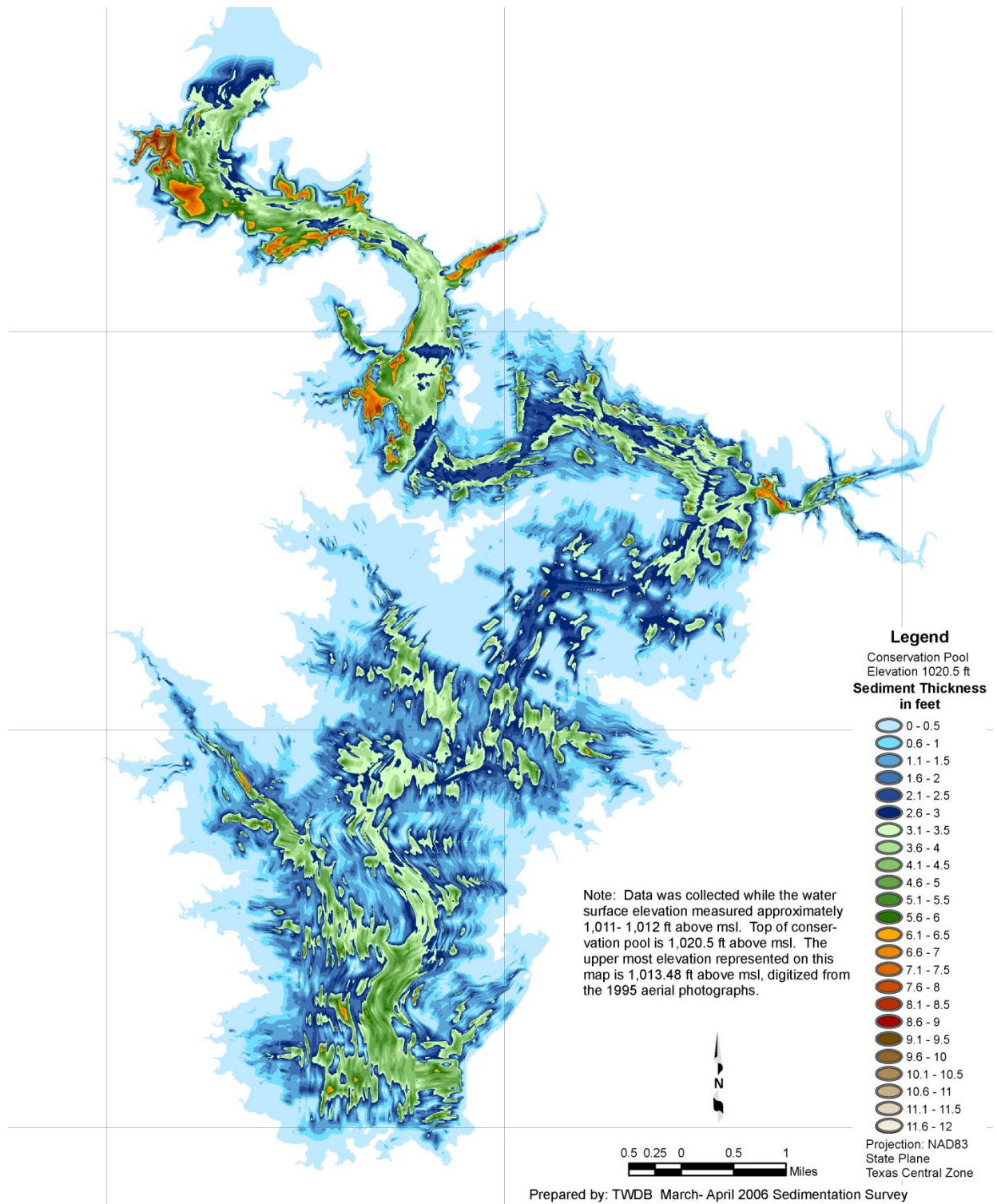


Figure 2. More sediment has accumulated in the upper reaches of Lake Buchanan (TWDB 2007b).

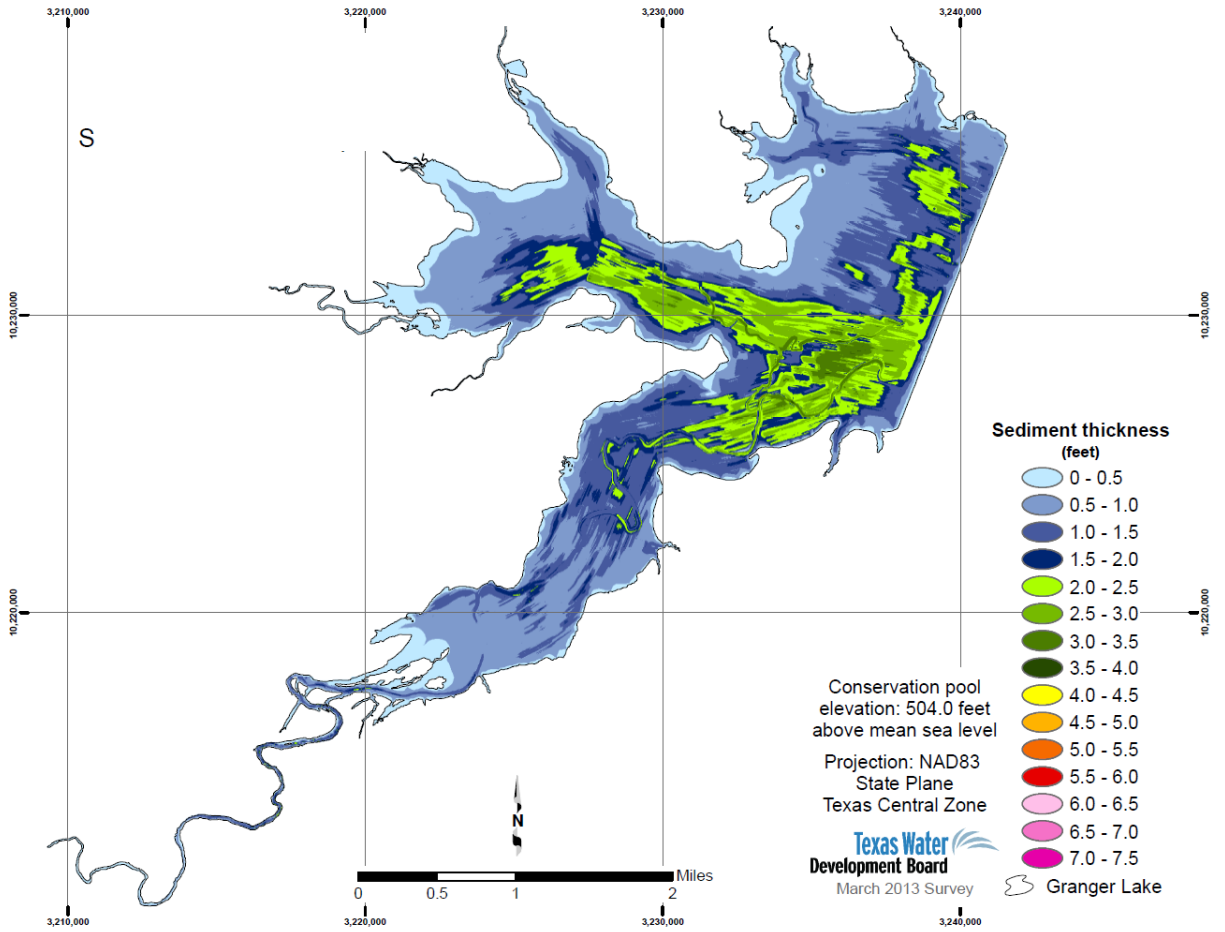


Figure 3. More sediment has accumulated in the lower portion of Granger Lake (TWDB 2014).

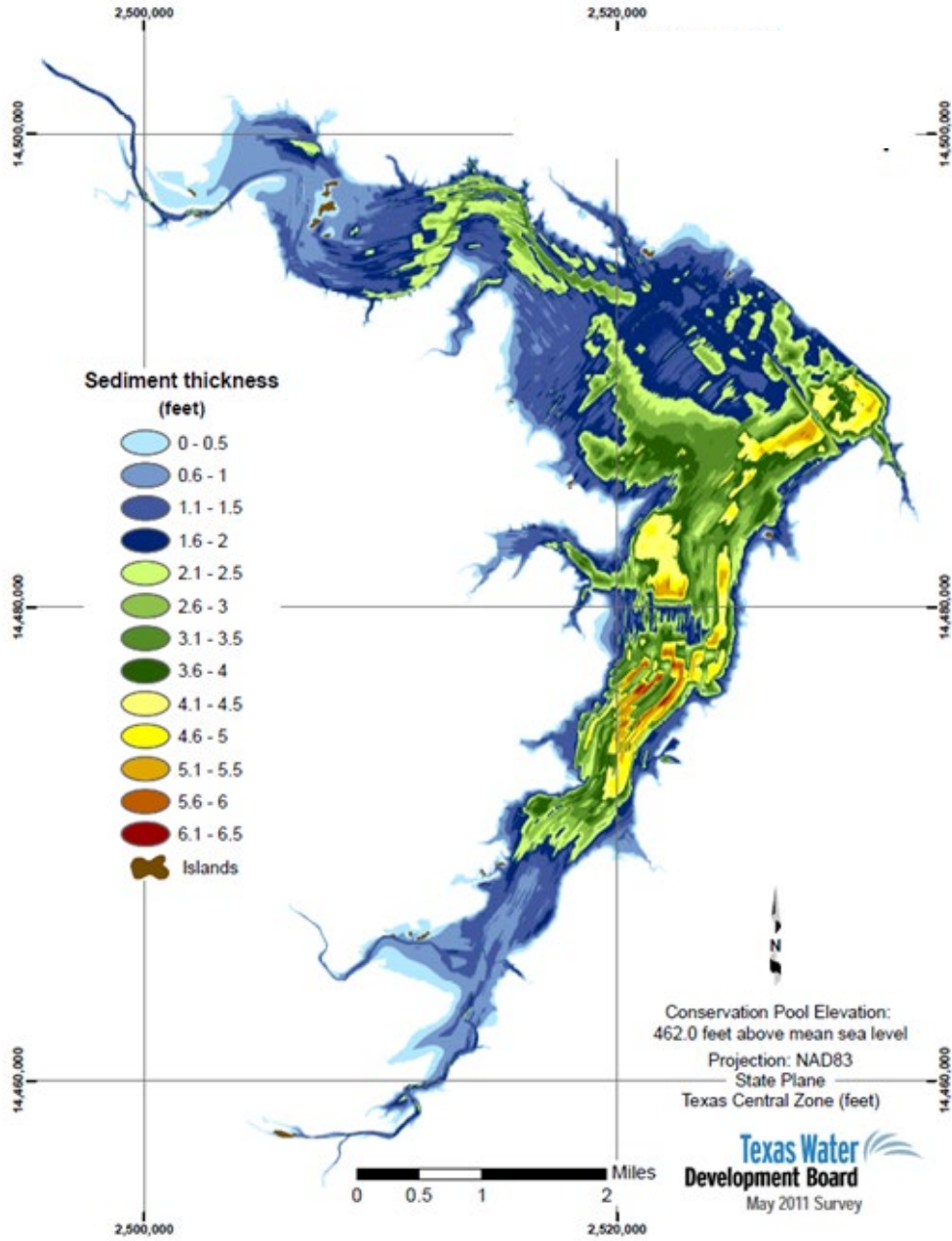


Figure 4. Sedimentation is greater in the middle of the southern arm of Waco Lake (TWDB 2012).

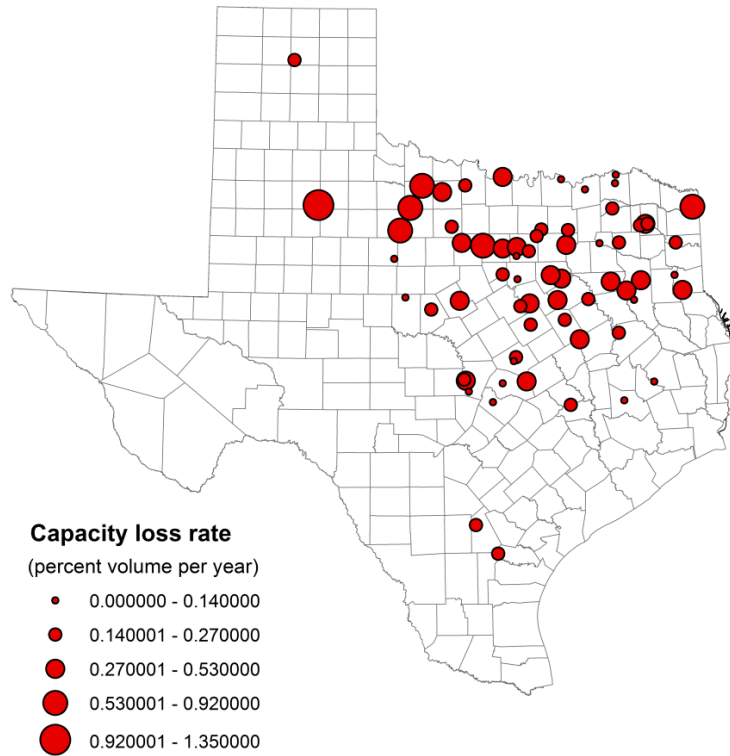


Figure 5. Capacity loss rates trend higher to lower from the northwest to southeast across Texas.

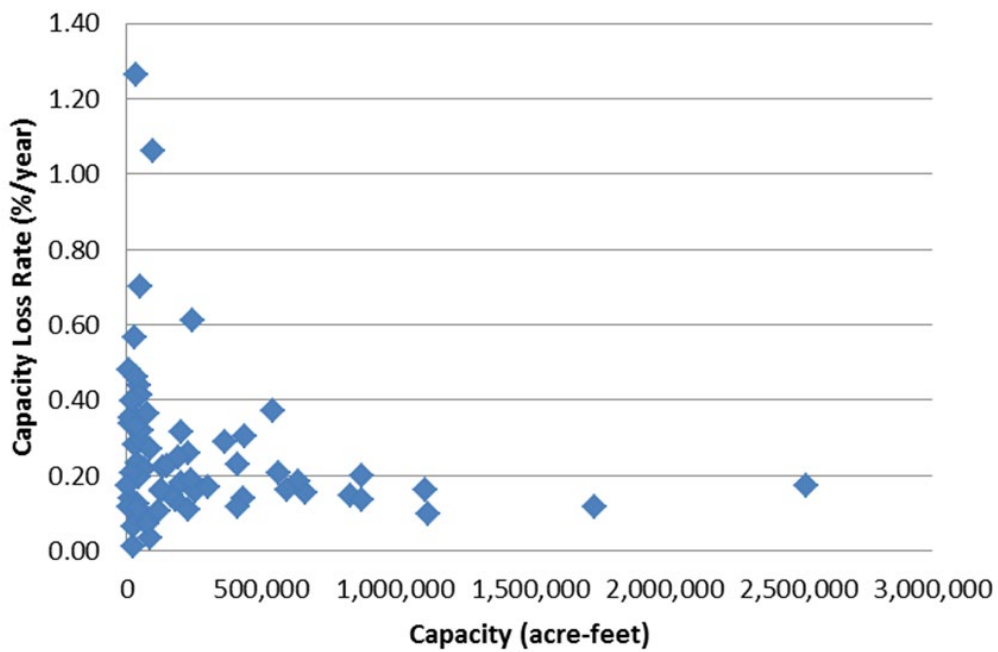


Figure 6. Capacity loss rates generally decline with capacity increases. *On average, reservoirs with less than 500,000 acre-feet of capacity have a higher capacity loss rate.*

METHODOLOGY FOR DETERMINING ELEVATIONAL SEDIMENTATION RATES

Although the sedimentation rate for a reservoir usually refers to an average sedimentation rate for the entire reservoir body up to the top of conservation pool, sediment can settle unevenly in a reservoir. Therefore, reservoir specific sedimentation rates vary along the elevational gradient. This is defined as the elevational sedimentation rate in this study. The curve of such rates along the elevational gradient also defines the capacity loss along the elevational gradient of a reservoir. Therefore, in this study, we will call this curve the capacity loss rate curve. We developed the capacity loss rate curve using the hydrographic survey data after careful consideration of all information from both the sedimentation survey and the volumetric survey. Once a capacity loss rate curve is developed, it is used to project future reservoir elevation-area-capacity rating curves from the latest survey, with an assumption that the rates will remain consistent during the projection period.

The capacity loss rate curve is cumulative in this study. The sedimentation rate at an elevation is the total sedimentation rate for the entire water body below this elevation. For each elevation interval E_i , the cumulative capacity loss rate (CLR_i) is computed by the following formulation:

$$CLR_i = (V_1 - V_2) / T * V_1 * 100$$

Where CLR_i – capacity loss rate at elevation E_i (percent per year)

V_1 – volume of survey 1 (older survey) at elevation E_i

V_2 – volume of survey 2 (younger survey) at elevation E_i

T – duration between surveys 1 and 2 (in decimal year format).

Area loss rate (ALR_i) follows the same algorithm as the capacity loss rate (CLR_i). The difference is the volume (V) is replaced by area (A) in the above formulation.

$$ALR_i = (A_1 - A_2) / T * A_1 * 100$$

Where ALR_i – area loss rate at elevation E_i (percent per year)

A_1 – area of survey 1 (older survey) at elevation E_i

A_2 – area of survey 2 (younger survey) at elevation E_i

T – duration between surveys 1 and 2 (in decimal year format).

Selection of available surveys for computing detailed elevational sedimentation rates (capacity loss rates) should consider the following factors:

1. Time between two consecutive surveys should be long enough to avoid short term sudden changes of sedimentation due to human activities or short-term climate variations that may cause short term change of natural erosion – sedimentation process. We usually do not select surveys when the time gap is less than 10 years.
2. When multiple surveys are available, a simple regression may be derived on capacity against time. Selected survey should be close to the regression trend line, so the computed capacity loss rate represents the general trend of silting to the reservoir. When the regression trend line is a non-linear, selected surveys should be consistent with the latest trend or projected future trend of the sedimentation rate, because we use the capacity loss rate for projection of future capacities and rating curves.
3. The technology being used in reservoir volumetric and sedimentation surveys has advanced significantly during past decades. For comparable purposes, the same or similar

survey technology should be placed in high priority in selection of surveys for computing the elevational capacity loss rate.

4. When there is no clear trend of sedimentation rates, due to limited surveys, a more conservative projection based on surveys that yield a higher sedimentation rate over a lower sedimentation rate is preferred.

By this method, capacity loss rate curves for 70 reservoirs were developed based on the available hydrographic survey data. Results indicate that higher capacity loss rates occur at the bottom and lower capacity loss rates at the top of conservation pool of a reservoir in almost all reservoirs. In other words, reservoirs silted faster at the lower portion of a reservoir body. The maximum capacity loss rate at the bottom of a reservoir was calculated at 10 percent per year (White Rock Lake), but most are around 2 to 7 percent per year. Area loss rate follows the same pattern, although in general, area loss rate is mostly smaller than capacity loss rate, especially at higher elevations.

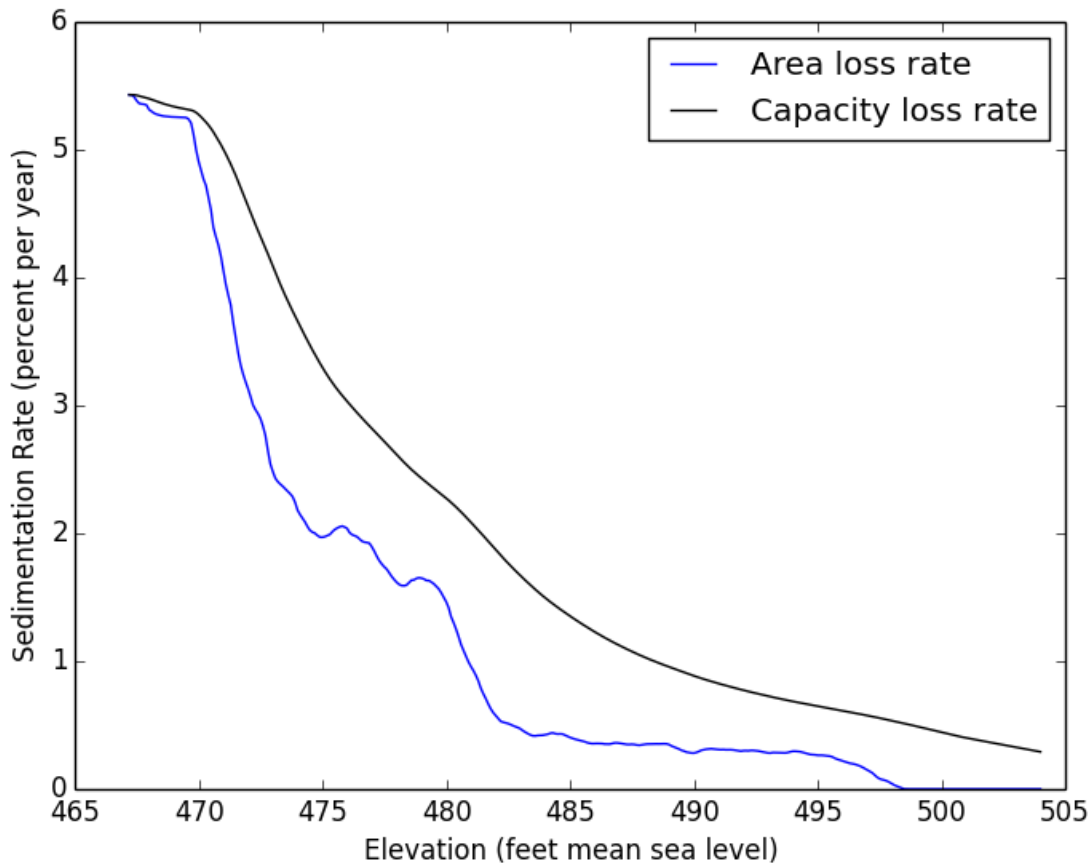


Figure 7. Capacity and area loss rate curves for Granger Lake computed using the elevational sedimentation rate method using the TWDB 1995 and 2013 survey results.

A typical example is Granger Lake. After detailed examination of the available survey data, we selected the October 1995 survey and the March 2013 survey for capacity loss rate curve

development, with the time lapse of approximately 17.5 years. This selection is based on the following justifications: 1) longest duration between surveys, 2) survey technology is similar, and 3) sedimentation rate derived by these two surveys is consistent with the long-term sedimentation rate trend.

Although the pattern depicted in Figures 7 is typical for most reservoirs studied, a small number of lakes do show an opposite pattern, where higher capacity loss occurs at higher elevations with a lower rate at the bottom. This phenomenon occurs in reservoirs where significant sediment deposits near the river mouth of a reservoir. Once the detailed capacity loss rate curve for a reservoir is determined using the elevational sedimentation rate method, projected rating curves for that reservoir for future decades can be computed, assuming a constant capacity loss rate and no change in sedimentation pattern for the projection period. The future capacity or area are computed by applying this detailed capacity loss rate to the latest elevation-area-capacity rating curve and multiplying by the length of time (decimal year) from the latest survey to the projected date. As an effort to support water planning in Texas, rating curves were projected for 2030, 2040, 2050, 2060, 2070, and 2080. Figure 8 illustrates both existing rating curves from surveys and projected rating curves for Granger Lake for aforementioned decades.

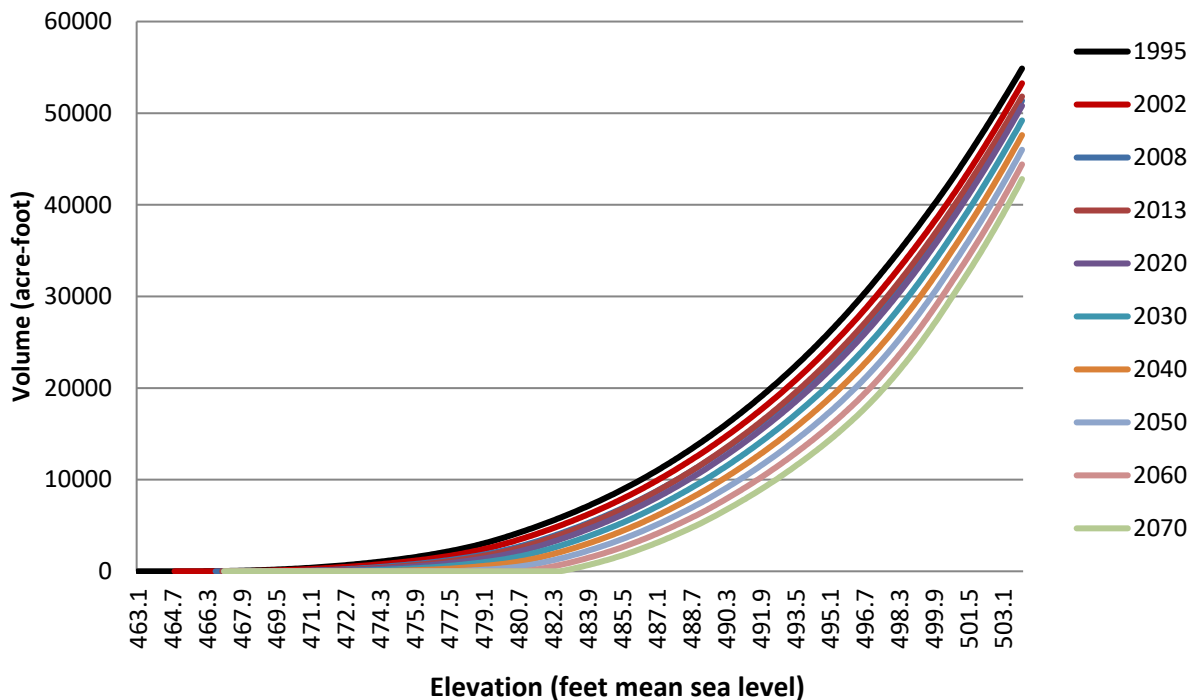


Figure 8. Existing (TWDB 2003b, 2003c, 2009b, 2014) and projected rating curves for Granger Lake. Using the elevational sedimentation rate method, Granger Lake is projected to lose 9,120 acre-feet, or 17.7 percent of total capacity from 2014 to 2070.

ESTIMATION OF RESERVOIR FIRM YIELD BY PROJECTED RATING CURVE

As mentioned before, reservoir storage reduction may affect its firm yield. In the past, one practice used in water planning in Texas was to assume a one-to-one capacity loss and firm yield loss relationship. That is, to assume one percent capacity loss will lead to one percent firm yield loss. However, this is a rough estimation that has not been verified. After projected rating curves are generated, we used them to assess their effect on firm yield. The Texas Commission on Environmental Quality’s (TCEQ) Water Availability Model (WAM) RUN 3 is used to compute reservoir firm yield with revised reservoir capacity, area-volume rating, inactive pool capacity, seasonal pool capacity, and/or the storage related diversion algorithm (drought index card) as they are related to the rating curve updates. Results indicate reduced reservoir capacity reduces firm yield, following a non-linear relationship. Taking Granger Lake as an example, when reservoir capacity reduces from 65,500 acre-feet to 42,808 acre-feet (22 percent loss), firm yield decreases from 18,997 acre-feet per year to 12,623 acre-feet/year, or approximately 27.7 percent (figure 9). Because of the non-linear relationship between capacity loss and firm yield loss demonstrated here, it is clear that the presumption of the one-to-one relationship between capacity loss and firm yield loss is incorrect. Now that we can project a reservoir’s storage rating curve, we are able to project its firm yield from 2020 to 2070 (figure 10), assuming no new drought of record or change in water use pattern.

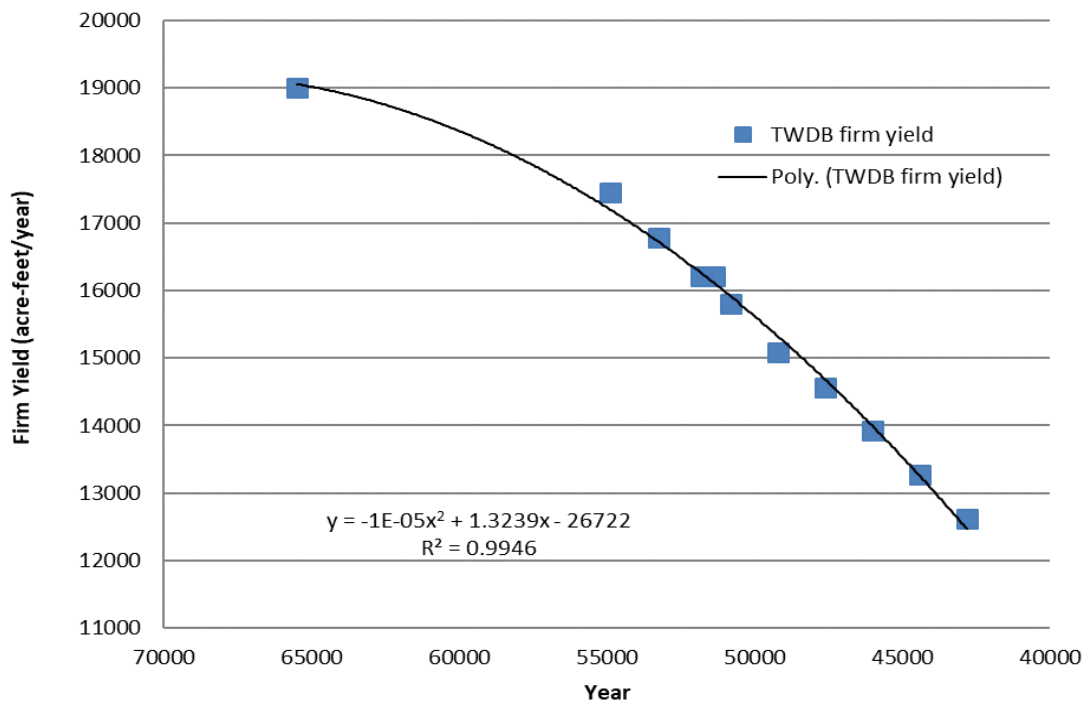


Figure 9. Firm yield and capacities for Granger Lake (blue squares represent firm yield while the black line shows the best regression between firm yield and capacity)

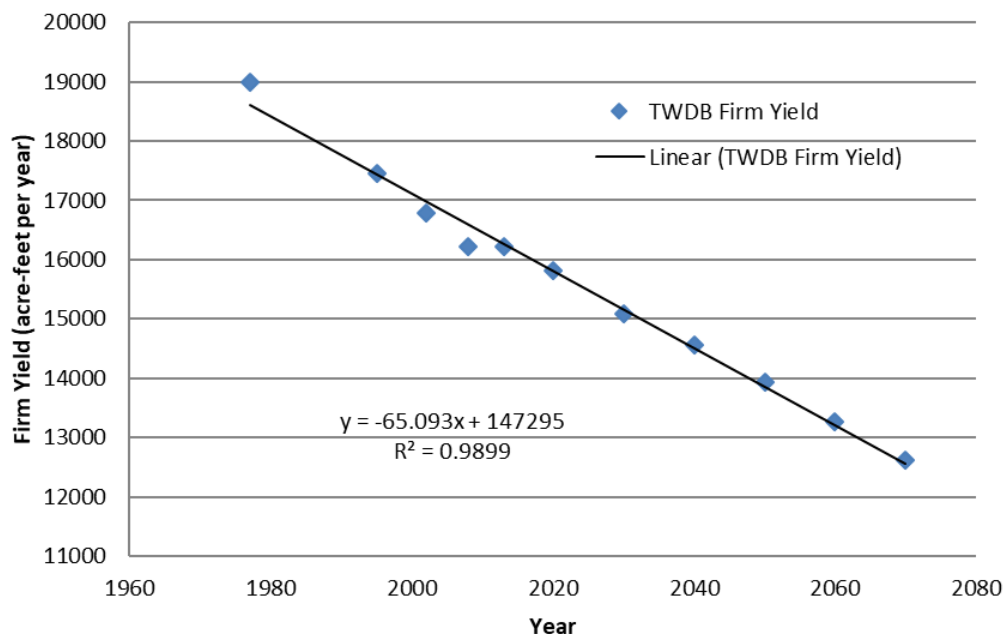


Figure 10. Firm yield decreases due to capacity loss since impoundment for Granger Lake (blue diamond represents firm yield while the black line shows the best regression between firm yield and years)

COMPARING WITH OTHER METHODS

Other methods have also been used to project reservoir capacity with the consideration of sedimentation. These methods include, but are not limited to, trapezoidal, conic, or prismoidal formulations (Taube 2000). Taking the trapezoidal formulation as an example, volume (V_i) from elevation $i-1$ to elevation i is computed by the following formulation:

$$V_i = V_{i-1} + (E_i - E_{i-1}) * (A_i + A_{i-1})/2$$

Where V_{i-1} is volume at elevation $i-1$

E_i, E_{i-1} are elevation i and elevation $i-1$, respectively

A_i, A_{i-1} are areas at elevation i and elevation $i-1$, respectively.

The total volume for a reservoir is a sum of all incremental volumes. In order to project the future capacity, an operator would reduce area by a constant for all elevations until the total capacity reaches the sediment filling goal. By the trapezoidal method, the capacity reduction will be 167 acre-feet per year. Although the total capacity at 504 feet, the top of conservation pool elevation, is the same as that calculated using the elevational sedimentation rate method discussed above, the capacity estimated by the trapezoidal method consistently exceeds the capacity estimated by the elevational sedimentation rate method below 504 feet (figure 11). As a result, firm yields computed by these rating curves are higher than that computed by the rating curves generated by the TWDB's capacity loss (elevational sedimentation rate) method (figure 12). Not only does the elevation-capacity rating curve affect firm yield, the elevation-area rating curve, which determines lake surface evaporation, also affects firm yield.

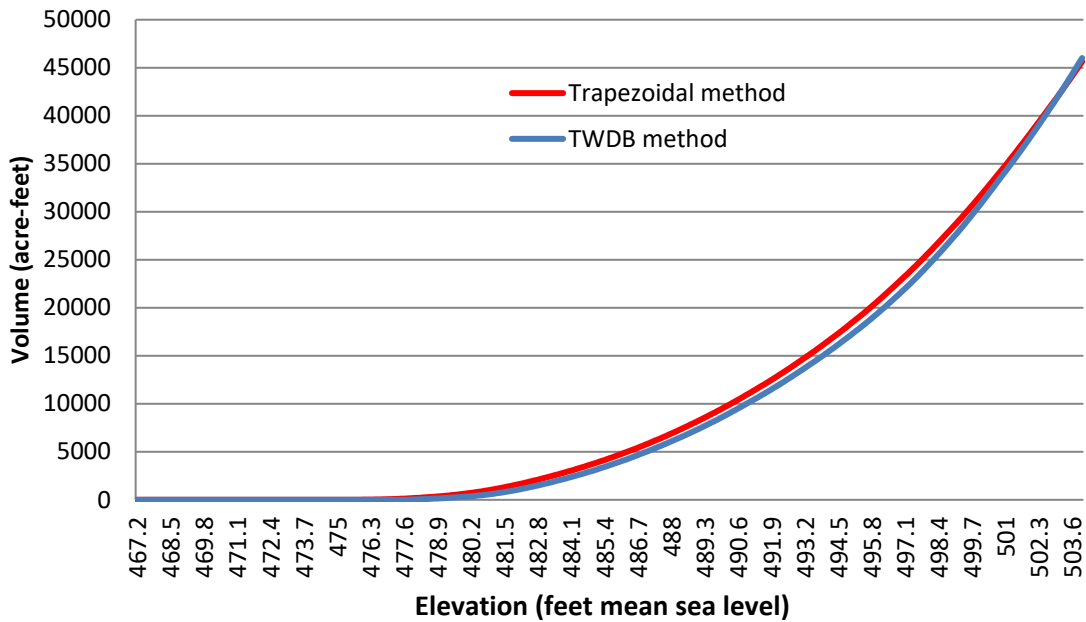


Figure 11. On average, the trapezoidal method (red line) over estimates capacity along the elevational gradient by 845 acre-feet between elevation 480 and 500 feet compared to TWDB’s elevational sedimentation rate method (blue line) for 2050

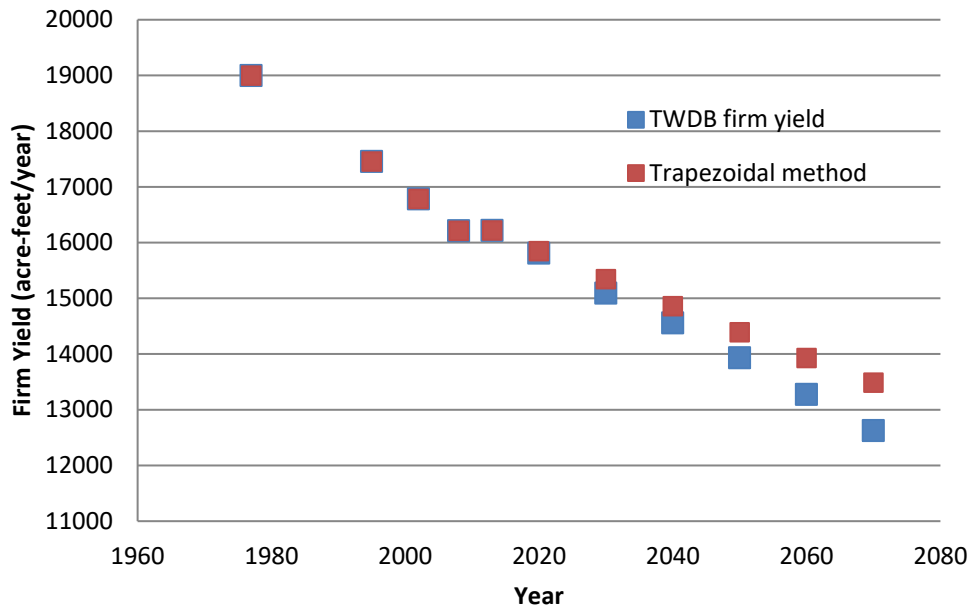


Figure 12. Granger Lake firm yields using rating curves by trapezoidal method (red squares) and TWDB elevational sedimentation rate method (blue squares). By 2070, firm yield calculated by trapezoidal method over estimates water available during a drought year by 864 acre-feet per year, about 7 percent more than estimated by TWDB’s elevational sedimentation rate method.

CONCLUSION AND RECOMMENDATIONS

Sedimentation in reservoirs is a significant problem in Texas. Sediment reduces a reservoir's storage capacity and therefore may affect its ability to yield water for beneficial usage. In order to estimate the firm yield for Texas' 50-year water planning horizon, future reservoir rating curves are projected based on a detailed understanding of sedimentation characteristics in a reservoir. After a detailed examination, we found that sediment distribution varies inside a reservoir and sedimentation rates vary at different elevations along a reservoirs elevational gradient. This suggested a new method (elevational sedimentation rate method) for estimating the sedimentation rate (capacity loss curve) for a reservoir was needed. Based on available sedimentation surveys, capacity loss curves for 70 Texas reservoirs were developed. Using the capacity loss curves and assuming a constant sedimentation rate for the future for a reservoir, reservoir rating curves for the next 50 years were developed, specifically for 2030, 2040, 2050, 2060, 2070, and 2080. We recommend that Regional Water Planning Groups (RWPG) consider using these projected rating curves and capacities to compute the projected firm yield for each planning decade.

For reservoirs that are only surveyed once, no projected rating curves can be derived by the elevational sedimentation rate method. Water planners may still use other analytical methods, such as trapezoidal or conic formulations to compute future rating curves, however, at least one survey is needed and the sedimentation rate must be obtained by survey or by other reliable sources. The Texas State Soil and Water Conservation Board (TSSWCB) published comprehensive sediment yield data for Texas in 1991 (TSSWCB 1991), which may be a good reference for estimating sedimentation for a reservoir with no hydrographic survey data. Nevertheless, we suggest projected firm yield for planning periods be derived through projected rating curves whenever possible.

As a foundation for estimating the future capacity of a reservoir, detailed volumetric and sedimentation surveys are critical. Therefore, we recommend reservoir owners have volumetric and sedimentation surveys completed for their reservoirs.

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