POTENTIAL IMPACTS OF COMANCHE PEAK COOLING TOWER OPERATION ON TOTAL DISSOLVED SOLIDS IN THE LOWER REACH OF LAKE GRANBURY

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EXECUTIVE SUMMARY

Lake Granbury is a water-supply and recreational reservoir on the Brazos River in Hood County, and has impounded water since 1969. The lake is maintained at normal pool elevation except for periods of draw-down during protracted low-inflow conditions. The volume corresponding to the normal operating level 693.0 ft (NGVD) has declined due to siltation at an approximate rate of 700 ac-ft/yr, from an estimated 153,500 ac-ft at closure. A narrow run-of-the-river reservoir dominated by the flow of the Brazos River, Granbury has historically exhibited elevated concentrations of TDS due to the salt load in the Brazos from Possum Kingdom. Granbury is proposed as make-up source and blowdown receiving water for Comanche Peak cooling towers, the diversion point and the return discharge both within two miles of the dam. There is potential that the additional evaporative loss associated with the proposed cooling towers could further increase the total dissolved solids (TDS) levels in the lake.

Freese and Nichols (F&N) performed a long-term simulation of Lake Granbury, applying two models in sequence, based upon the hydroclimatology of the 58-year period 1940-97, *viz*. precipitation, evaporation, runoff and streamflow. The first is an application of the Brazos Water Availability Model (WAM), which is a volume-budget simulation of the entire basin. This is a monthly accounting of flows and water retention through the drainage system, operated with various scenarios of human demands, discharges and hydraulic operations, including system operation of Possum Kingdom and Granbury reservoirs. The forced evaporation induced by the cooling water circuit of the existing De Cordova SES is included in the Granbury volume budget as a demand. The second model is a special-purpose spreadsheet-based calculation of TDS developed by F&N to address the dissolved solids problem. It employs the WAM-generated volume budget from the first model in a mass-balance accounting of TDS concentration for the Brazos system, including Granbury.

While F&N evaluated several scenarios, the most relevant for the purpose of assessing the impacts of the proposed cooling tower operation is Scenario 3C, in which the tower blowdown flow is returned to the lake. The cooling tower operation is represented by the make-up rate

109,000 ac-ft/yr and blowdown flow 48,000 ac-ft/yr. To quantify the effect of the proposed cooling towers, these model results need to be compared to a reference condition. For this purpose, F&N defined a Base Scenario without the new units at Comanche Peak. The Base Scenario is intended to be a realistic future operation, however, so F&N adopted the 2060 Brazos G Water Plan, in which all of the system yield is used, including surplus TxU contract water. For both scenarios, the projected BRA 2060 rating was used, in which the Granbury volume at normal level is about 70% of that surveyed in 2003. F&N determined that the cooling-towers scenario (Scenario 3C) raises TDS about 400 mg/L on average above the Base Scenario.

This predicted change is comparatively small relative to the mean (simulated) TDS concentration of about 1,600 mg/L. However, this result should also be compared to the State Surface Water Standard for Granbury, to determine whether compliance of the reservoir with this standard is affected. This standard is 2,500 mg/L applied to an annual mean TDS concentration. Using model data provided by F&N, a further statistical analysis was performed, in which the frequency of violation of the standard under the Base Scenario was determined to be 0% (i.e., no violations in the 58-year period of simulation), while with towers operational, the standard is violated in 14% of the years.

Any simulation model perforce employs assumptions. The central hydrographic assumption underlying both F&N simulation models is that Lake Granbury is a well-mixed homogeneous waterbody. For the volume-budget model, this is not judged to be a significant source of error, basically devolving to an assumption that the surface of the lake is level. For the TDS model, the validity of this assumption requires that TDS exhibit little or no spatial variation in the reservoir. This was tested by an analysis of field data from Granbury.

Vertical variation in TDS can result from the natural density stratification of the lake, or by TDS enhancing this natural density stratification (since dissolved solids increase the density of water). Granbury is a subtropical lake, and therefore would naturally develop a summer stratification, with warm buoyant water overlying cool denser water. This natural stratification can be disrupted, however, by intense, storm-induced mixing, or by high levels of throughflow in the reservoir that substantially replace the reservoir volume in a relatively short time period.

Historical vertical profiles of temperature and dissolved oxygen (which is useful as a vertical water-mass tracer) were compiled and examined. It emerged that the natural stratification in Granbury is weak (low vertical stability) and highly variable. A major factor in preventing a more stable and pronounced stratification is the flow of the Brazos through the lake, which on average replaces the volume of Granbury about eight (8) times per year. The intermittency in the stratification of temperature suggests that storm-induced vertical mixing also plays a role.

The measured vertical change in historical data on TDS and conductivity (which can be directly related to TDS) is consistently negative (i.e., with lower values near the bottom of the lake) but relatively small. The effect on density variation is an order of magnitude less that due to vertical decline in temperature (which, as noted above, is relatively weak), so we conclude that TDS does not contribute to density stratification in the lake. (We speculate that the lower near-surface values of TDS are due to dilution by runoff into the lake.)

Horizontal variation in TDS along the longitudinal axis of the reservoir can be produced by the influx of waters with widely varying TDS concentrations along the length of the lake, in concert with weak longitudinal mixing. The same processes that mix the lake in the vertical, i.e. storm events and water-mass replacement due to the high throughflow, would also mix the lake longitudinally. Nonetheless, this was tested by examination of historical field data. While relatively small longitudinal variations were found to occur along the lake in the historical TDS and conductivity data, these are relatively rare in the data set, and have no systematic consistency, as likely to be negative as positive.

These considerations generally support the assumption that TDS in the reservoir is fairly homogeneous. The concern remains, however, that even though consistent spatial variation in TDS is not indicated in the historical data, the imposition of additional evaporation on the lower reach of the reservoir could result in systematically higher TDS values in the vicinity of the dam. This would undermine the accuracy of a well-mixed model (because the very large mass transfer of TDS from the lake by reservoir releases would be improperly calculated by being based upon, in effect, the spatial average value of TDS, as would the calculated increase in concentration due to evaporation).

By exploiting the particular geometry of Granbury, the nature of its hydrography, and the proposed tower makeup and blowdown locations, a numerical method was devised to estimate TDS concentrations in the downstream 10 mile segment of the reservoir, based upon the model results of F&N. This numerical method results in a 58-year sequence of monthly TDS values for this reach of the reservoir. Statistical analyses of the results indicate that the TDS in this reach of the reservoir will average about 130 mg/L higher than the entire-lake average value. Moreover, the Surface Water Standard will be violated in 19% of the years of the simulation period.

Table of Contents

List of Figures

List of Tables

Acknowledgments

1. Introduction and objectives

The planned expansion of the Comanche Peak nuclear generating station is proposed to employ cooling towers, for which Lake Granbury is being considered both as make-up source and as receiving water for tower blowdown. The anticipated towers will entail bleedstream flow averaging 30,000 gpm (66.8 cfs) at 2.25 cycles of concentration, so the make-up requirement is about 109,000 ac-ft/year.

Lake Granbury is a water-supply and recreational reservoir impounding the Brazos River in Hood County. Operated by the Brazos River Authority (BRA), the lake has impounded water since 1969. There is no flood control storage in the reservoir, so the lake is maintained at normal pool elevation except for periods of draw-down during protracted low-inflow conditions.

This reach of the Brazos River exhibits elevated dissolved solids (deriving from leaky brine aquifers in the Rolling Plains area just off the Caprock, USCE, 1973, Wurbs, 1991), so both Granbury and Lake Possum Kingdom upstream experience increased total dissolved solids (TDS) concentrations, especially under low-inflow conditions coupled with high evaporation rates.

The combination of make-up withdrawal and blow-down return means that the evaporative consumption of the proposed cooling towers will be effectively imposed on Lake Granbury, so there is concern that the tower operation will exacerbate dissolved solids in the lake waters. Freese and Nichols, Inc. (F&N) has applied a long-term solids-mass-balance model to Lake Granbury and determined that under the most likely scenarios of lake operation and power-plant expansion, the TDS in the reservoir would indeed be increased above historical levels, the long-term average increase above a baseline scenario being around 400 mg/L (Albright 2007a, 2007b).

The purposes of this study are to further evaluate the potential impacts of the proposed cooling tower operation on the dissolved solids of Lake Granbury, specifically:

(1) Assess the methodology, underlying assumptions and technical constraints of the model employed by F&N, and interpret the results with respect to maintenance of surface water quality standards in the lake, particularly considering the proposed locations of the intake and discharge in the lowermost reach of the reservoir near the dam.

(2) Using historical data from the reservoir evaluate the extent to which natural hydro-dynamic processes may mitigate or further exacerbate TDS concentrations, especially in the lowest reach of the reservoir adjacent to the dam.

(3) Revise or re-formulate the solids-budget analysis to reflect the spatial situation of the proposed withdrawal and return locations in the lower reservoir, as appropriate based upon conclusions from (1) and (2), including the effects of releases from the dam, and operation the existing De Cordova Steam Electric Station (SES).

2. Lake Granbury: Morphology, structure and salts

The physical specifications of Lake Granbury are summarized in Table 1. The lake, part of the original Ambursen 1930's Master Plan for the Brazos River and of the 1950's Six Dam Program (Hendrickson, 1981), was constructed in the 1960's through contractual arrangements with Texas Power and Light to use the lake as a source of industrial cooling water. Deliberate impoundment began September 1969. The lake is a main-stem, run-of-the-river reservoir, with no flood control capability, so excess waters are passed through the tainter gates to the Brazos downstream. The general geography of the lake is shown in Figure 1. The dam impounds approximately 16,000 sq mi of contributing drainage area (of which 14,000 sq mi lies upstream of Morris Sheppard Dam). The original (1969) conservation storage was estimated at 153,500 ac-ft, at elevation 693.0, surveyed at 136,823 ac-ft in 1993, and 129,011 in 2003. The minimum elevation of 685.28 occurred in August 1978 and the maximum of 693.60 in March 1977. At impoundment, the greatest depth in the reservoir was about 70 ft, in the old river channel at the dam.

Table 1
Specifications for De Cordova Bend Dam and Lake Granbury

Feature	*elevation (ft NGVD)*	*area (ac)*
Top of dam	706.5	
Normal pool elevation	693.0	8700 *
Design flood (top of tainter gates)	693.0	
Spillway crest	658.0	1300
Sluice gate outlet invert	652.0	
Lowest sluice gate outlet invert	640.0	

* 8310 ac reported by TWDB hydrographic survey, 1993

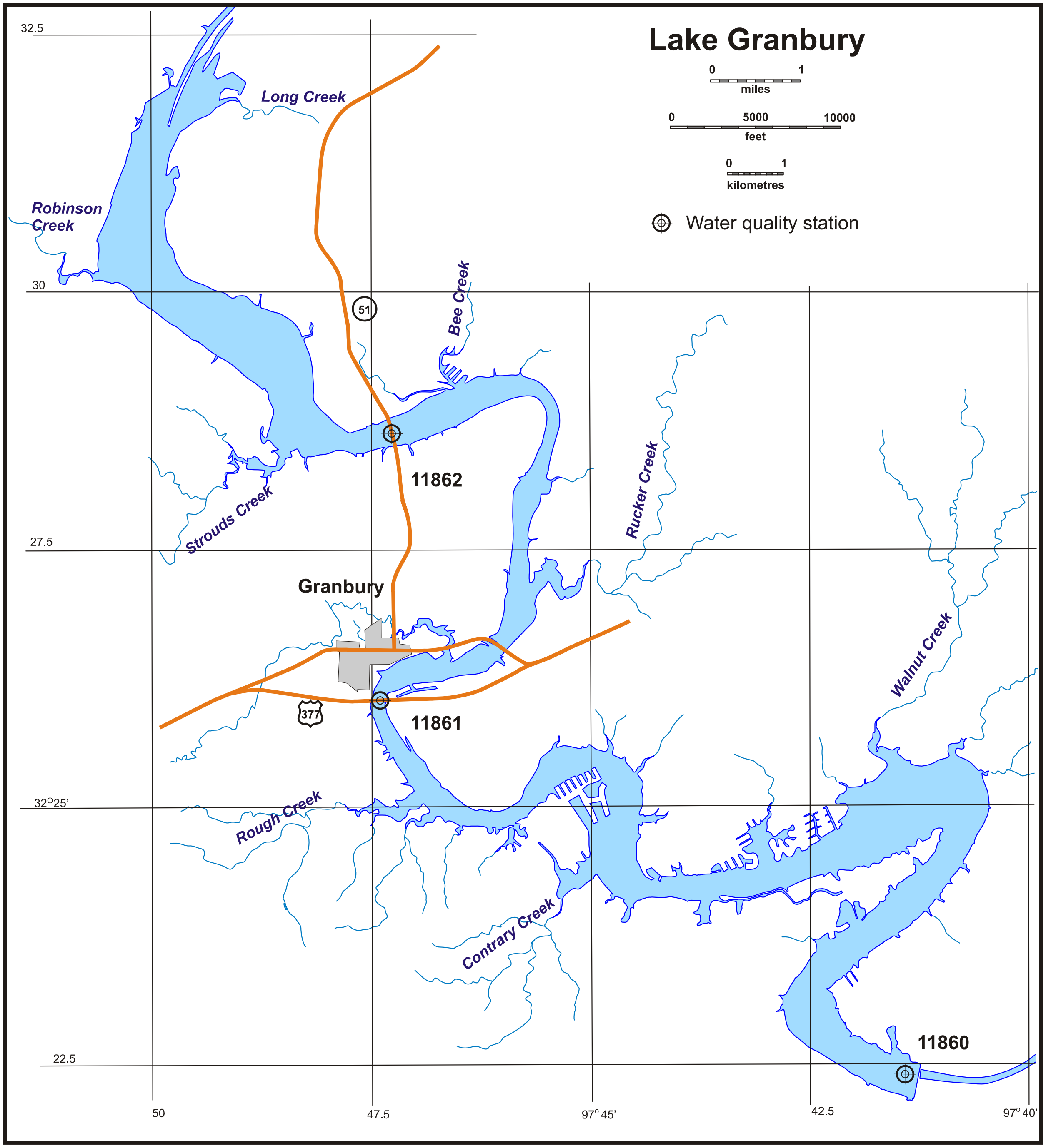

Figure 1 – Lake Granbury

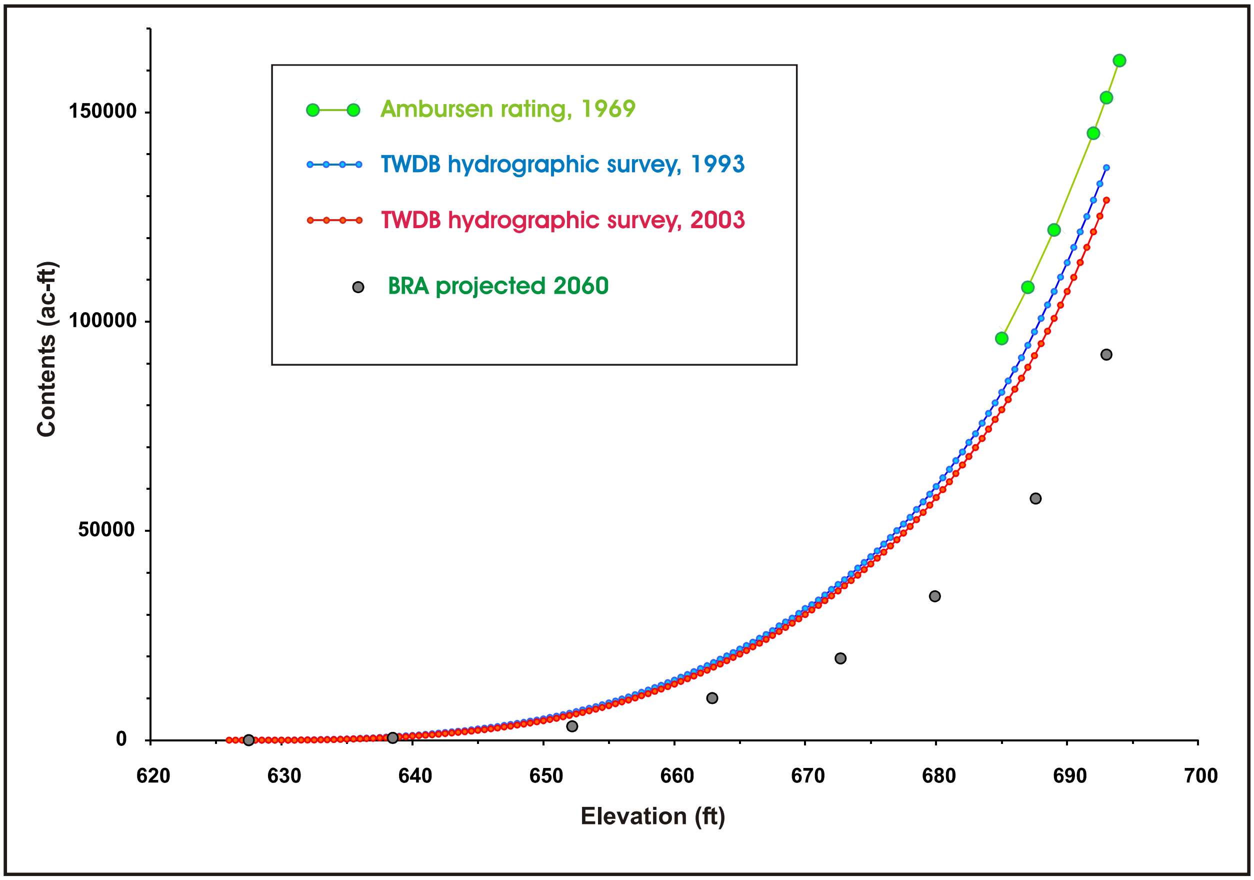

Figure 2 – Volume vs elevation ratings for Lake Granbury

2.1 Reservoir ratings

The rating relations for the lake are quantitative evidence of the diminishment of lake capacity by siltation, see Table 2, and complicate the volume-budget accounting of the reservoir. The elevation- volume relations are shown in Figure 2, and the elevation-area relation in Figure 3. The original bathymetric mapping of the lake was based upon pre-impoundment topography. There apparently has not been a field survey of the lake bathymetry until 1993. Two detailed hydrographic surveys have been performed by the Texas Water Development Board (TWDB) in the past 15 years. While the difference between the original Ambursen rating and the first TWDB survey in 1993 is attributed to siltation in the reservoir, it may include errors in

Table 2
Siltation rates inferred from historical and projected bathymetry

rating		*date*	*volume*	*ΔV/Δt*
	(		*ac-ft)*	*(ac-ft/yr)*
Am	bursen	1969	153,500	
TW	DB	1993	136,823	695
TW	DB	2003	129,011	781
BRA		2060	92,129	647

the regional topographic mapping. The difference between the 2003 and 1993 TWDB surveys is probably a better depiction of the effects of recent siltation on the reservoir's capacity. In the F&N modeling work, a 2060 rating was employed, developed by BRA, see Fig. 2, presumably extrapolating the rate of siltation.

As might be expected, the effect of siltation on the area-vs-elevation rating is much less dramatic, especially for those elevations around the normal operating level of the lake, see Figure 3. There is virtually no difference between the BRA 2060 projection and the surveys of TWDB.

2.2 Lower Reach

From the standpoint of this study, by far the most important region of Lake Granbury is the Lower Reach, defined here as the downstreammost 10 miles of the reservoir, approximately depicted in Figure 4 (whose left border lies on mile 8.0 of the reservoir axis). This is where almost all of the action is, hydrographically speaking. This is the deepest section of the

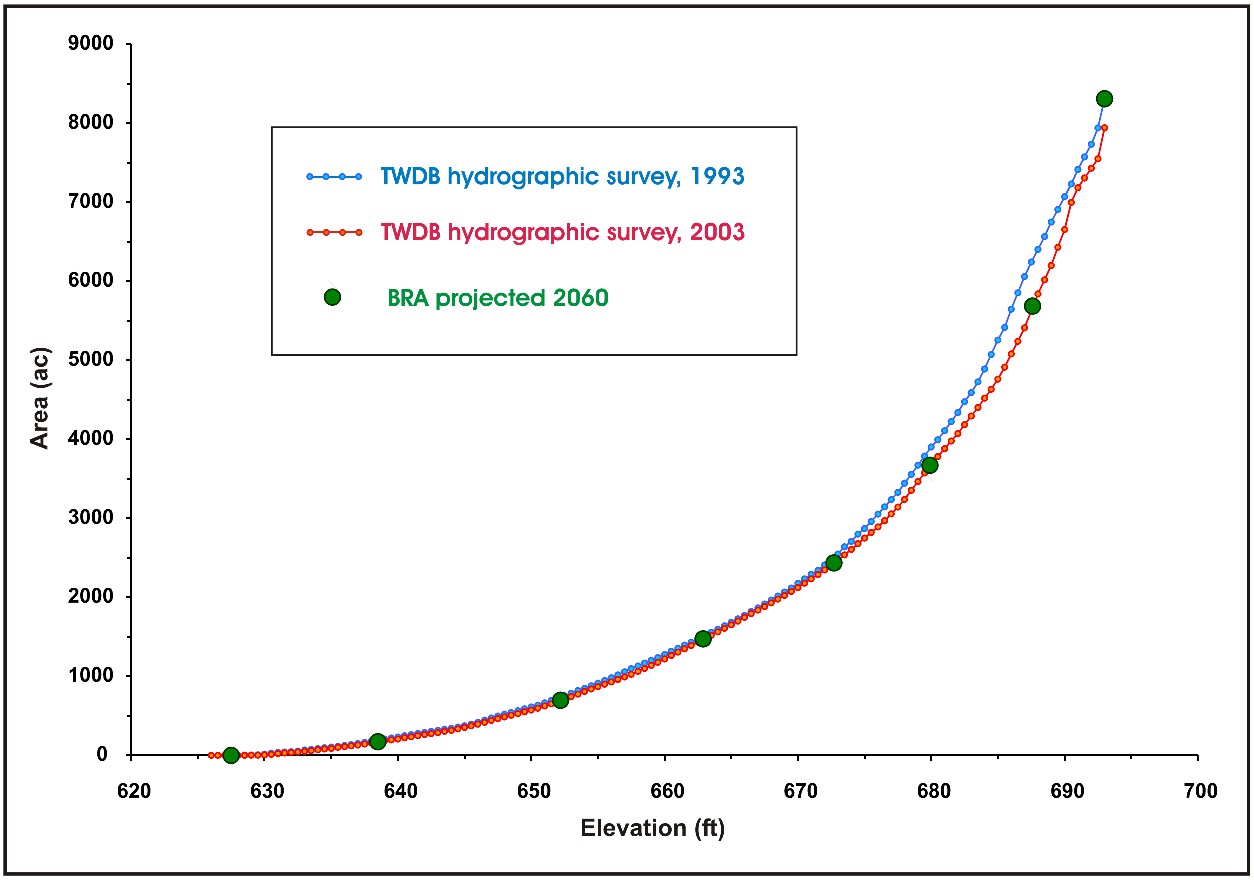

Figure 3 – Area vs elevation ratings for Lake Granbury

reservoir, from which releases to the Brazos downstream are made through De Cordova Bend Dam. Almost the entirety of natural inflows to the reservoir enter upstream and move into this reach along the longitudinal axis of the lake. The cooling loop of the De Cordova SES is entirely contained within this reach, the cooling circuit moving water from the south side of Walters Bend to the north. The proposed sites for the tower withdrawal and return flow are to be located in this reach, just upstream from the dam, separated approximately 1.14 miles.

The dilution of the dissolved solids load from the Brazos by intermixing with tributary inflows

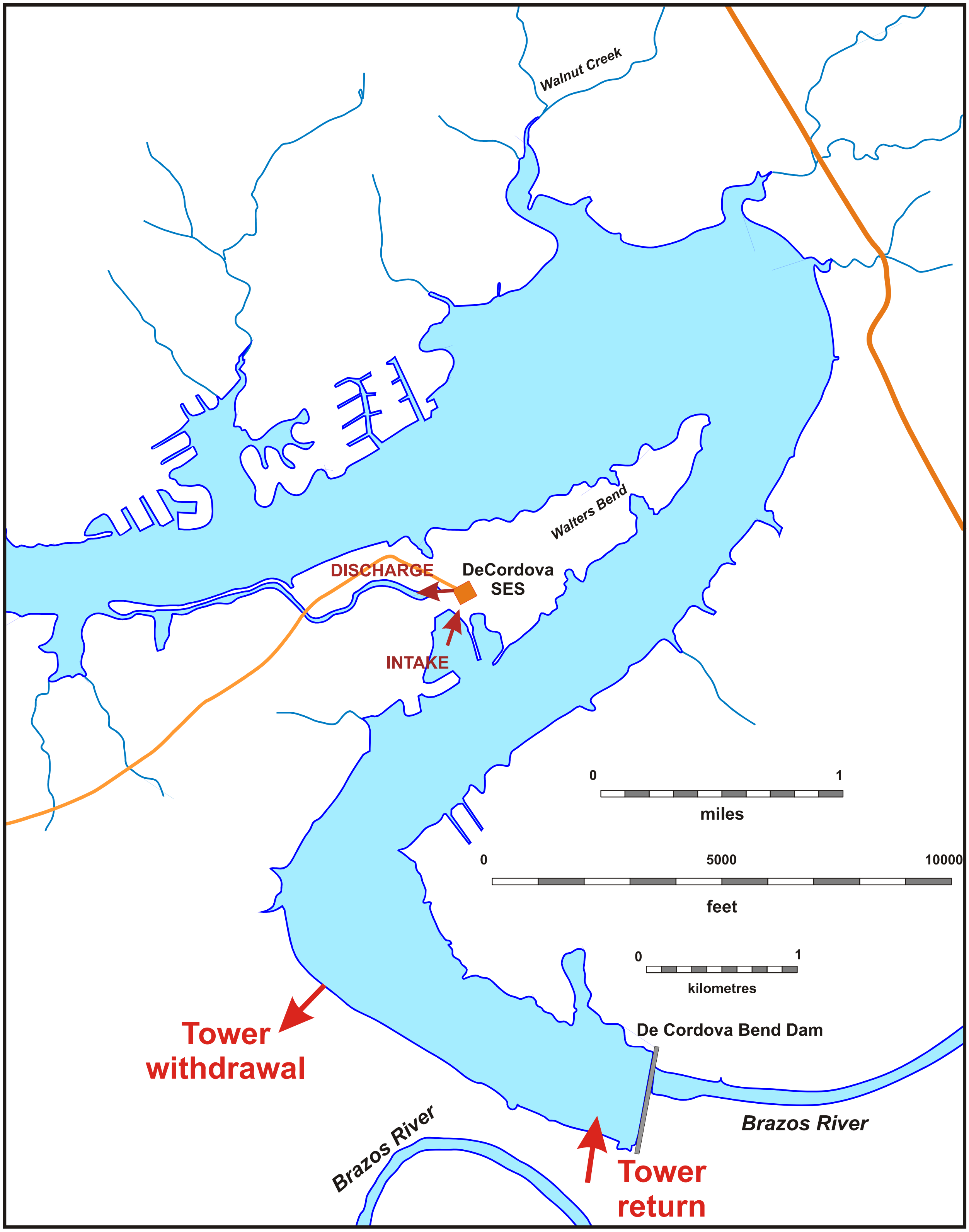

Figure 4 – Detail of Lake Granbury near dam

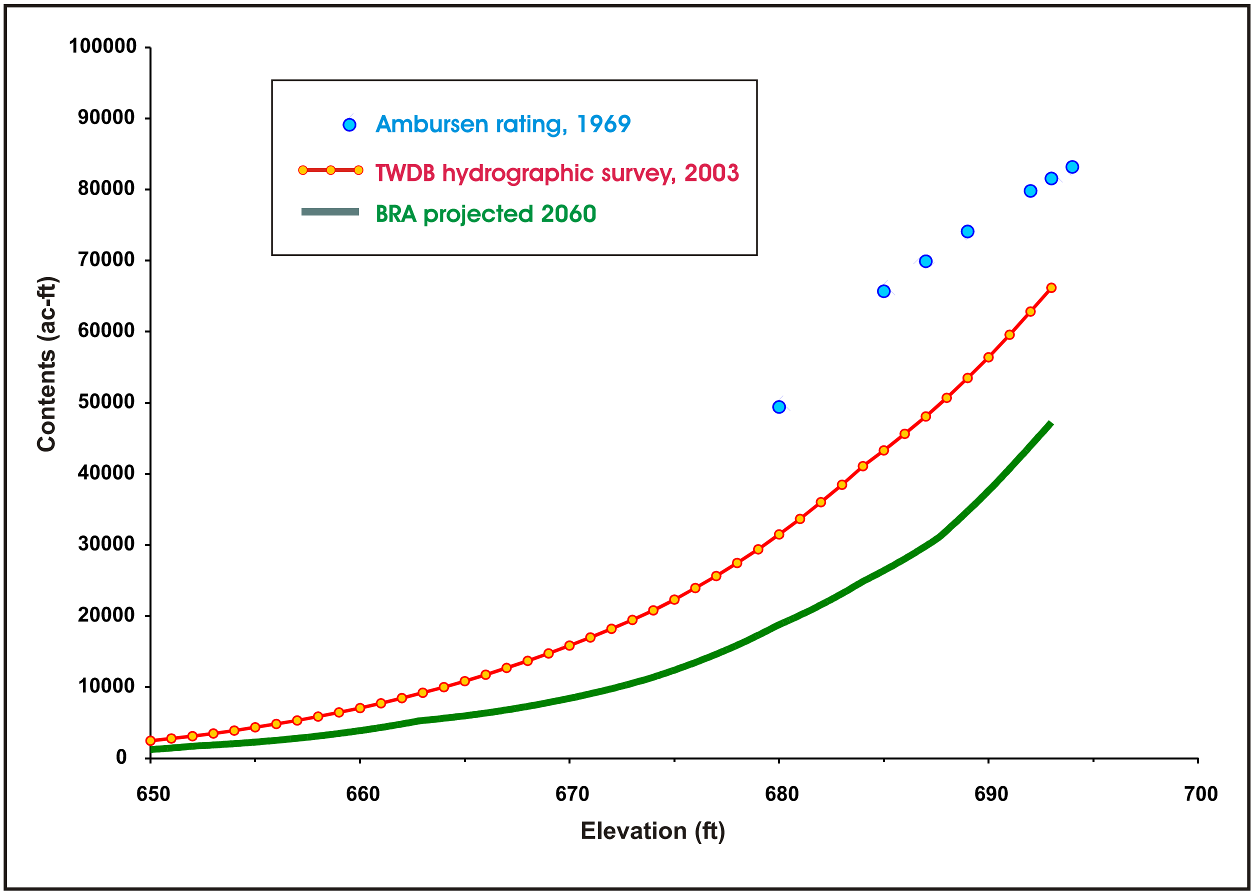

Figure 5 – Volume vs elevation ratings developed for Lower Reach of Lake Granbury

into the reservoir is almost entirely consummated when the lake throughflow enters the Lower Reach (with a minor additional dilution due to peripheral drainageways in the Lower Reach, mainly along the north shore of the lake). When this flow is high enough to raise the reservoir stage above normal, it is passed through the dam at the lower end of the reach, so that solids retained in the Lower Reach is largely the difference between the load from upstream and the mass transfer through the dam. When the reservoir is at normal stage or lower, particularly in the heat of summer, net evaporation becomes a major mechanism in concentrating the dissolved solids. The Lower Reach is subjected to the additional, or "forced", evaporation of the De Cordova cooling loop, and under the proposed tower operation will be further subjected to the evaporative loss of the cooling towers.

For these reasons, this study examined the potential impacts of the proposed tower operation on this Lower Reach of the reservoir. It was necessary to devise volume and area relations on reservoir elevation specific to this reach. At 0.5-mile intervals, the widths at key elevations were compiled from bathymetric data for both pre-lake topography and for the 2003 hydrographic survey of TWDB. For the TWDB 2003 survey, which has the greatest vertical detail, the volume beneath each key elevation was computed by quadrature, and the *proportion* of total lake volume represented in the Lower Reach at each key elevation was employed as an interpolation variable to fill out the rating curve. The same approach was used for the BRA 2060 rating elevations, except that regressions of TWDB 2003 between the rating elevations of BRA 2060 were used to fill in the intervening levels. The resulting rating curves are shown in Figure 5. Though the pre-lake rating was not used in this study, the Lower Reach values were computed for the Ambersen rating points to display the alteration in morphology of the Lower Reach since construction of the reservoir.

In 1986, Espey Huston & Associates, Inc. (EHA) performed a series of field surveys of the discharge area of the De Cordova SES (EHA, 1986), to map the extent of the thermal plume as defined by the 3°F (1.7°C) excess isotherm relative to the intake temperature. These surveys are displayed in Figure 6, cf. Fig. 4. It should be noted that in every survey, despite the downstream flow induced by the cooling-water circulation and despite the low but nonnegligible downstream transport of about 20,000 ac-ft/mo, a substantial portion of the thermal plume lies upstream from the discharge point, clearly a response to large-scale transports within the reservoir, most likely driven by the easterly and southeasterly winds of late summer.

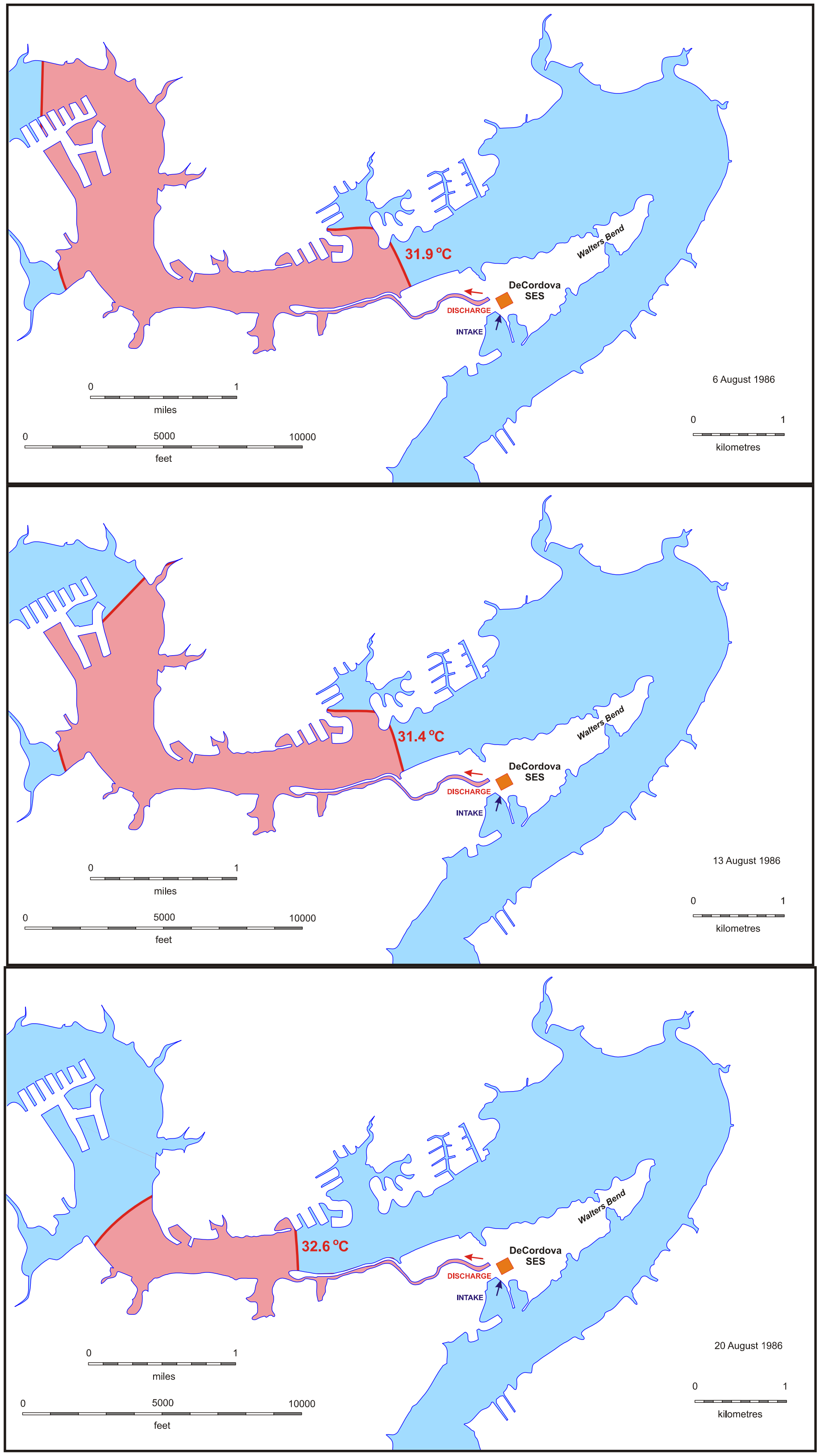

Figure 6 – Thermal plume surveys of De Cordova SES, summer 1986 (EHA, 1986)

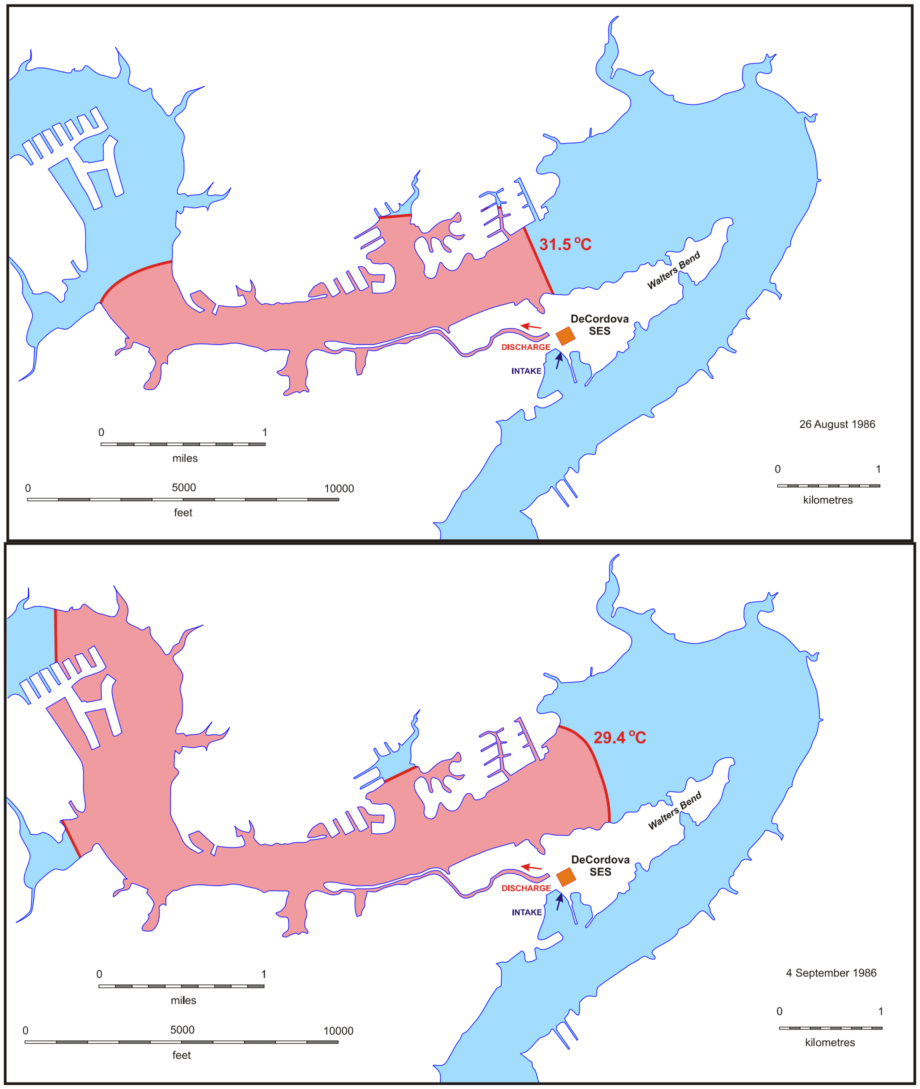

Figure 6 (continued)

2.3 Temperature structure and stability

Water quality data has been collected in Lake Granbury by the Texas Commission on Environmental Quality (TCEQ) and predecessor agencies since 1972 (see, e.g., the data compilation of Espey Consultants, 2007), and by the U.S. Geological Survey for the period 1970-97 (with a much-reduced renewal of sampling in 2006). The data of central importance to this analysis are measurements of TDS, conductivity (which can be related to TDS) and water temperature. These measurements, as well as a suite of grab-sample analytes, are routinely secured by TCEQ at three main-stem stations in the reservoir:

Station 11860	mile 0.2	just upstream from De Cordova Bend Dam
Station 11861	mile 13.7	bridge crossing U.S. Highway 377/67
Station 11862	mile 20.0	bridge crossing at State FM Highway 51

Longitudinal position in miles is measured along the reservoir longitudinal axis, upstream from De Cordova Bend Dam. These TCEQ stations are shown on the map of Fig. 1. USGS samples were taken at six (6) main-stem stations, three of which are approximately co-located with the TCEQ sites, and eleven (11) tributary, backwater, and off-axis stations. Both profiles and water-sample analyses were logged at each USGS station.

Several aspects of waters in Lake Granbury of relevance to its dissolved solids can be addressed by analysis of this data. These include the time trends of solids concentrations, their association with external parameters, notably inflow of the Brazos River, horizontal variation in solids along the length of the lake, and vertical stratification of solids. These are addressed in Section 2.4 below. First, we examine the hydrographic structure of the reservoir and its flushing by riverine throughflow, as these factors govern retention of solids in the lake and hydrodynamic mixing of solids in the water column and along the length of the lake, and will prove germane to interpreting the F&N modeling results.

Flows into the lake and out of the lake, i.e. throughflow which is dominated by the flow in the Brazos, varies widely in response to the storm-dominated climatology of North Texas. Typically, the higher annual flows are experienced in the late spring (April – June) and a secondary maximum occurs in the fall, see Figure 7, however this pattern is widely variable from year to year. This wide range in throughflow induces a Jekyll-Hyde dichotomy in the behavior of Granbury. Only when throughflow is low enough that the waters in the reservoir are quiescent and respond to the seasonal march of temperature and insolation does the reservoir behave like a subtropical lake.

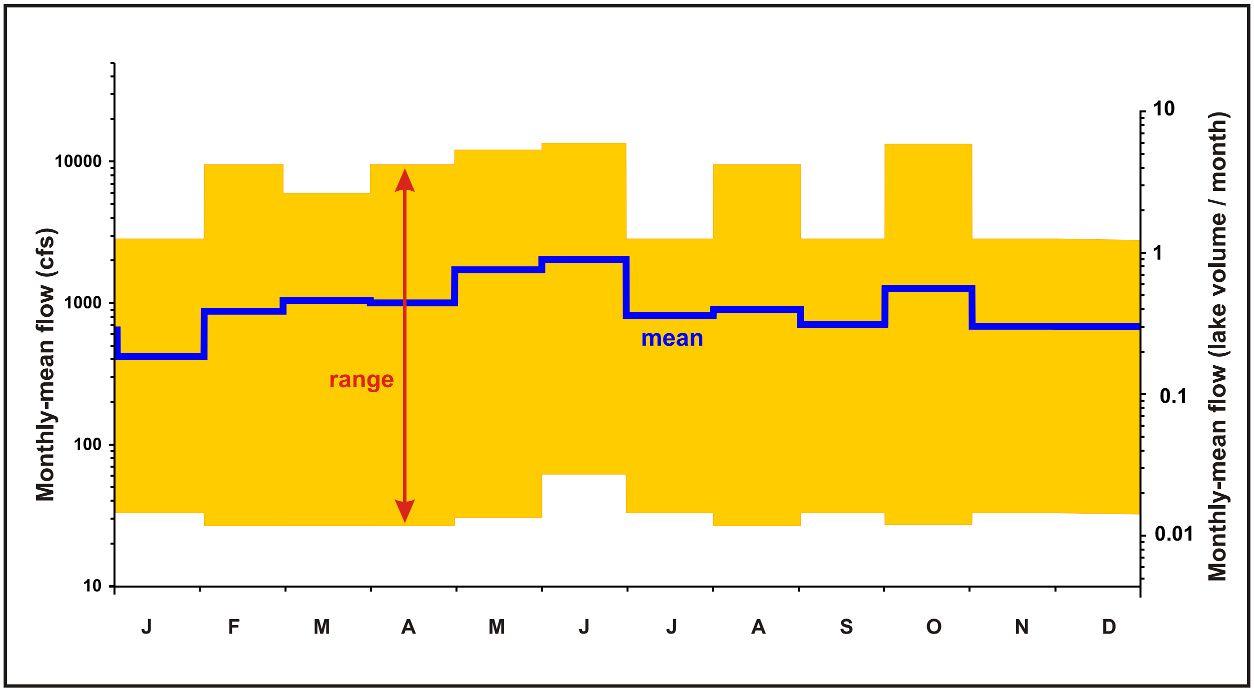

Figure 7 – Seasonal variation in reservoir throughflow based on 1968-2007 hydrology at USGS Dennis gauge (note logarithmic scale)

In such a subtropical lake, the increased heating with the advance of spring produces a buoyant surface layer, called the *epilimnion*, that continues to collect warmed water and gradually deepens into summer. The zone of fall-off in temperature with depth, the *thermocline*, is a layer of vertical density gradient. Because the warm buoyant epilimnion water lies on top of the cool dense water below the thermocline, the *hypolimnion*, this stratification opposes vertical water movement and becomes self-stabilizing, resisting the exchange of water between epilimnion and hypolimnion. As the season advances from spring to summer, and epilimnion and hypolimnion become increasingly isolated, dissolved oxygen (DO) is retained in the epilimnion due to its continuing influx from surface reaeration and from photosynthesis in the light-illuminated near-surface layer, but is no longer mixed downward into the hypolimnion. Here DO is consumed by microbiological respiration, until the hypolimnion becomes anoxic. A roll-off in DO with depth, called the *oxycline*, from high concentrations in the epilimnion to zero in the hypolimnion, occurs at, or just above the level of the thermocline.

A disturbance of sufficient strength, such as a thunderstorm or influx of flood water, can disrupt the temperature stratification and mix the waters in the lake. The stability of the thermocline is the key parameter that dictates whether the vertical structure of the lake can withstand such an event. As the season progresses into fall, cooling of the epilimnion reduces the thermocline stability to the point that fall storms begin to mix out the vertical structure. In the case of Granbury, an inspection of field data indicates that summer stratification is not manifested under high-flow conditions, even in the heat of summer.

It is necessary to have a means of differentiating the high-flow conditions, in which Granbury behaves as an enlarged river, from the low-flow conditions, in which the reservoir is quiescent and behaves like a lake. The simplest measure of the effect of throughflow Q on reservoir quality is the residence time

$$T_r = V / Q$$

where V is the volume of the lake. This is time required for a parcel of water located at the head of the lake to move to the spillway of the dam, in other words the time needed for the through-flow Q to replace the contents of the lake. For Granbury, a rule of thumb is a residence time of more than two months is indicative of a quasi-quiescent lacustrine behavior, and a residence time substantially less than one month a dynamic lotic (flowing) behavior. A related indicator with similar qualitative value is obtained by expressing the throughflow Q in units of lake volume per month (the right-hand axis of Fig. 7), which has the additional intuitive value of being proportional to flow (rather than reciprocal, as is the case with residence time). These indicators (computed assuming the conservation storage at elevation 693 ft from the TWDB 1993 survey) are superimposed in the time plots of Figure 8. In this graph are demarcated protracted low-flow periods that also encompass a summer season. These are the periods in which Granbury would be expected to most likely manifest summer stratification typical of a subtropical lake. Of the forty (40) years represented in this record, twenty-one (21) summers would fail to qualify as protracted low-flow periods.

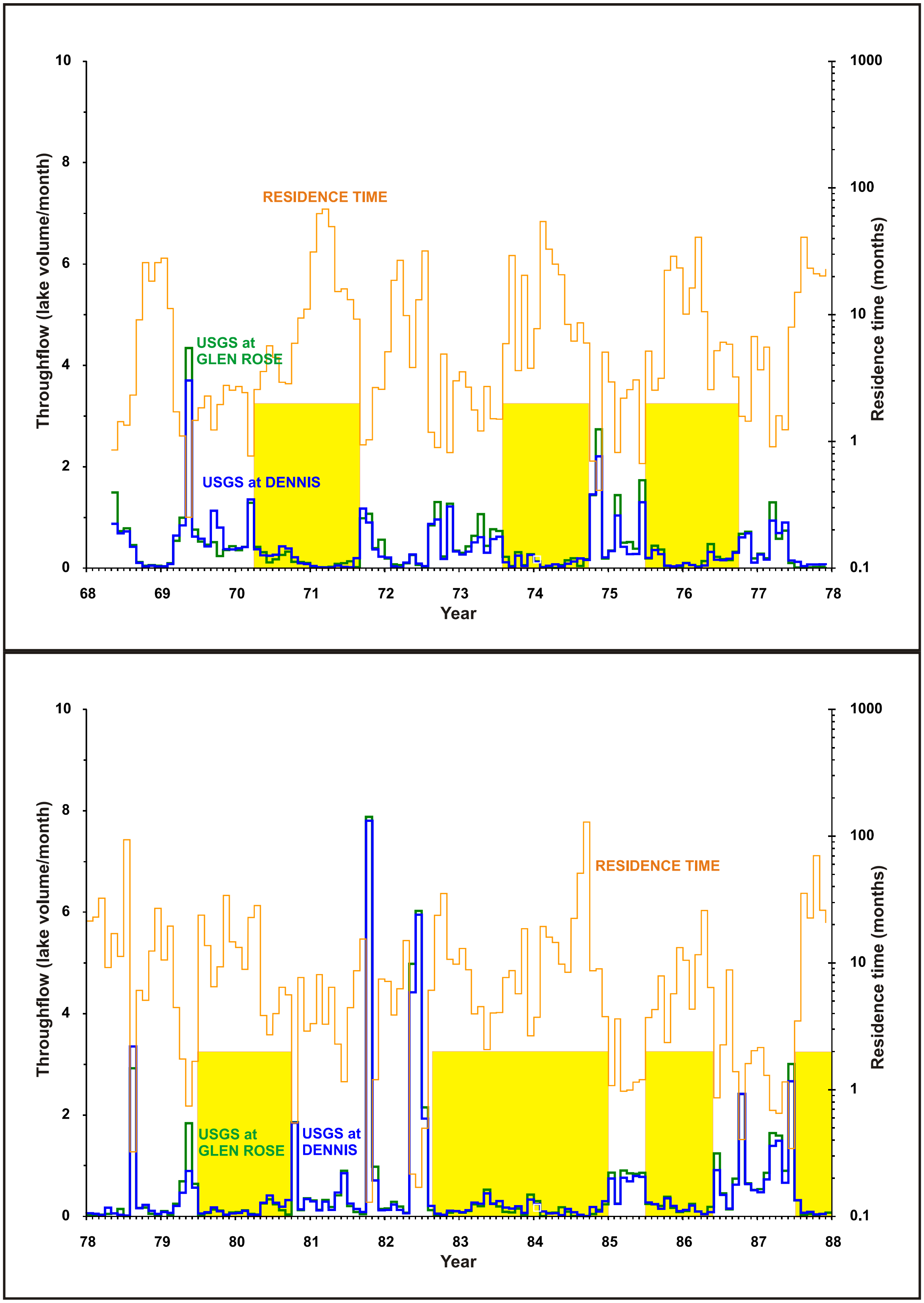

Figure 8 – Reservoir throughflow in volume of lake per month and residence time, 1968-2007. Yellow areas indicate periods of low flow encompassing at least one summer season.

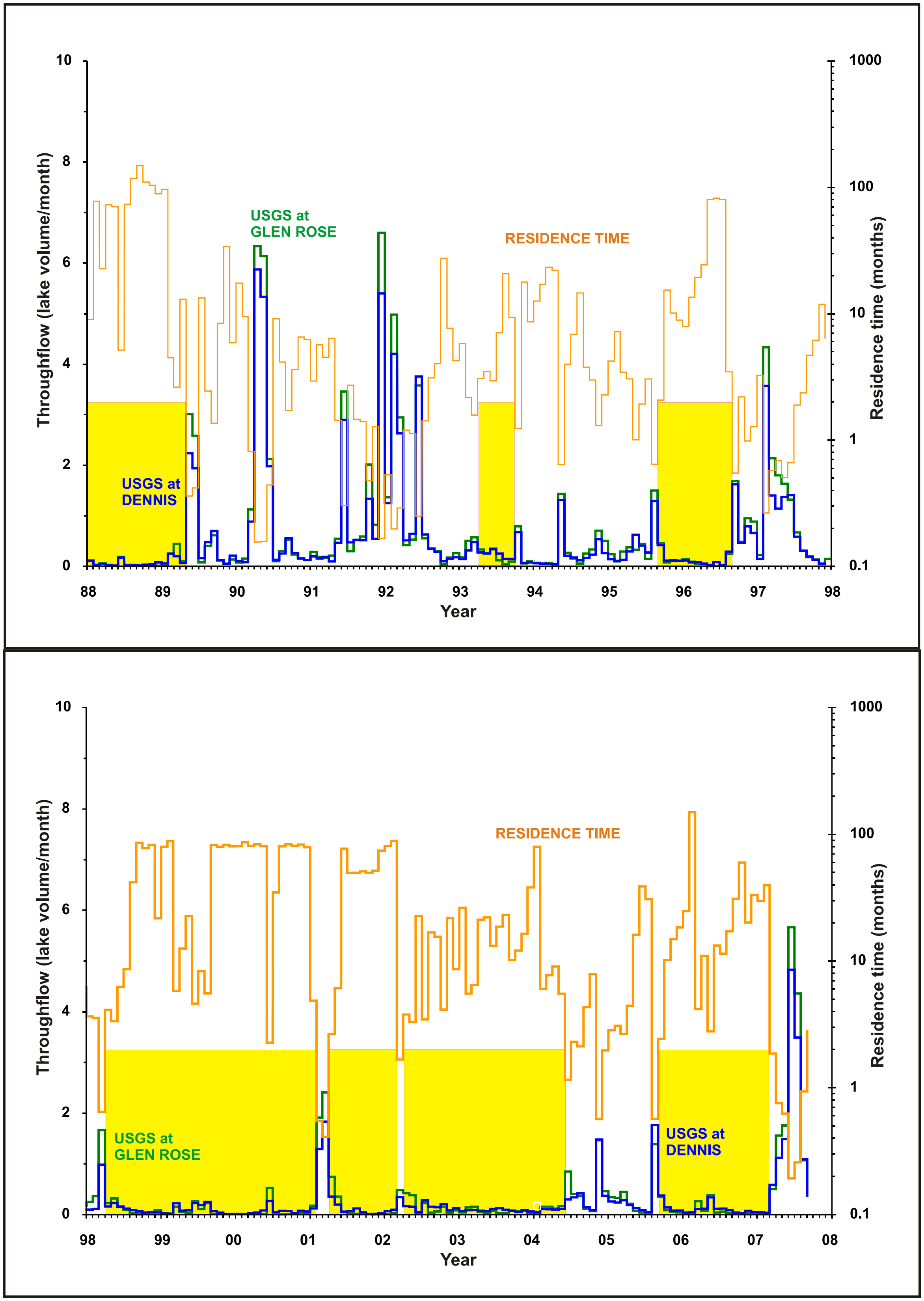

Figure 8 (continued)

One of the most important data collections from the standpoint of the present analysis is the vertical profile of electrometric parameters, *viz.* temperature, conductivity and dissolved oxygen (DO). The temperature and dissolved oxygen profiles are used to delineate vertical structure in the reservoir. Generally at least three sets of profiles during the summer stratification season are necessary to determine the stratification state of the reservoir. During its 1970-97 sampling activity, the USGS visited the reservoir only quarterly, so in each year there is at most only one set of profiles from the summer (which may be too early or too late in the summer to establish the degree of stratification). TCEQ (née TNRCC née TWC) was even more sporadic from 1973-94, generally sampling about twice a year, occasionally skipping years. Sampling was suspended 1995-96, then, inexplicably, surface and bottom measurements *only* were obtained roughly bimonthly for 1997-2000. Therefore, for the period 1970-2000, combined profile data from both agencies are inadequate to define the summer stratification cycle. In 2001, vertical profiling was re-instituted by TCEQ (by then, of course, USGS had suspended data collection), but even then the summer was inadequately sampled. By combining the available profiles and plotting by season of year (measured as a fraction of the year after 1 January), the profiles from the 2001-04 period can be combined, limited to those taken under the protracted low-flow periods indicated in Fig. 8, to construct a time-depth cross-section. A similar cross-section was constructed for the 2004-07 period, though in this case large sections of the early and late summer lacked representation in the profiles. These time depth-cross sections are shown in Figure 9.

These figures illustrate the seasonal pattern in stratification exhibited by Granbury in the absence of high inflows. In winter there is vertical homogeneity in the temperature structure, then stratification develops through the spring. The vertical stratification is more apparent in DO, because the near-surface source combined with the DO consumption through the water column and at the lake bed enhances the vertical gradient. The stratification in Granbury is relatively weak. This is quantified by the density gradient at the thermocline, measured by the square Brunt-Väisälä frequency (see, e.g., Pedlosky, 1982, Kundu, 1990; Williams, 2006):

$$N^2 = -\frac{g}{\rho}\frac{\partial \rho}{\partial z}$$

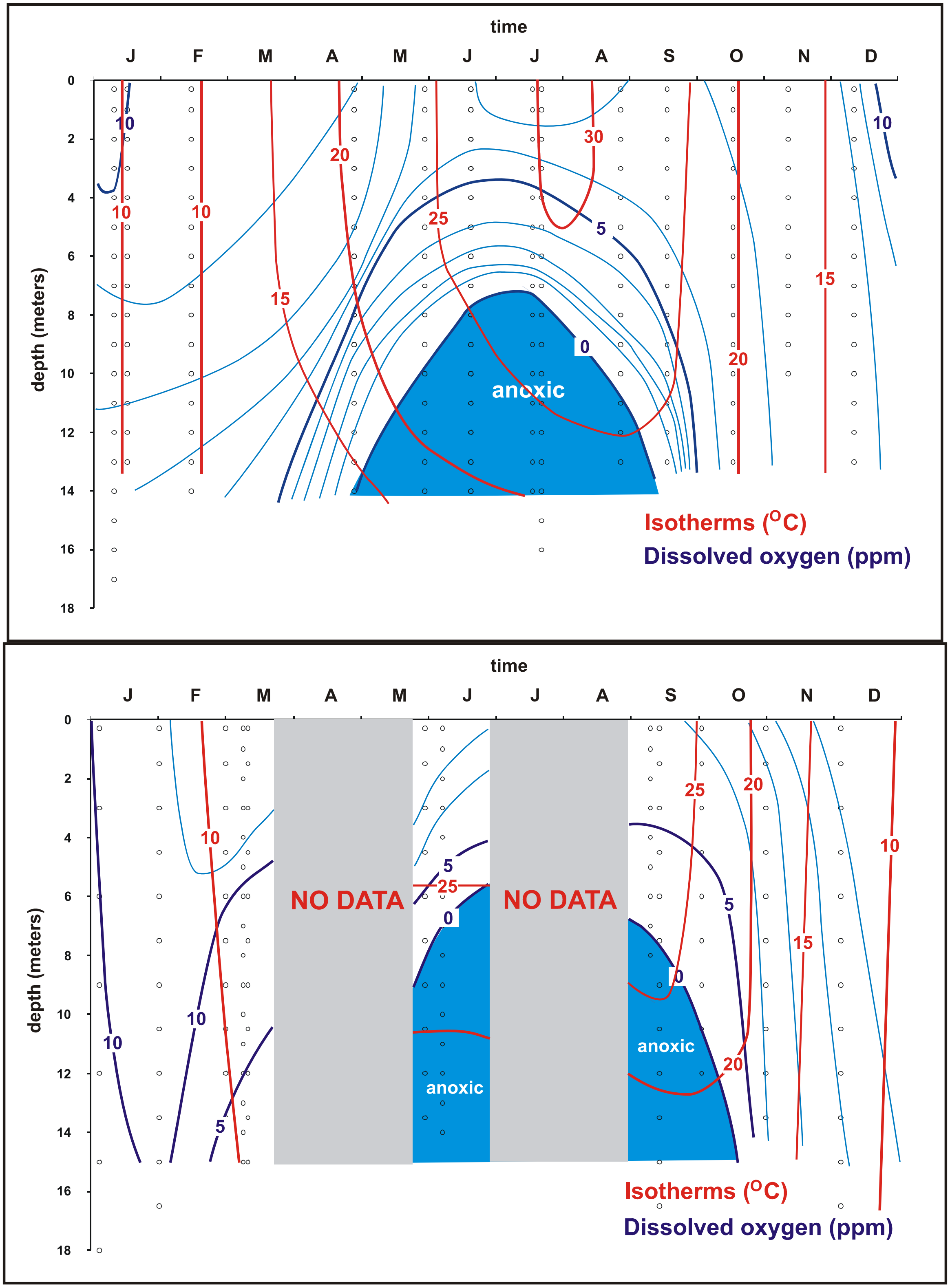

Figure 9 – Time-depth cross sections (combined) for temperature and dissolved oxygen. Low-flow profiles from 2001-04 period (above) and 2004-07 period (below).

N is the frequency of natural oscillation of a parcel of water about its equilibrium level after being displaced vertically. The higher the frequency, the greater the stability of the density stratification. Calculations of various parameters relating to stratification at each of the mainstem TCEQ stations are given in Appendix A. The frequency distributions of the maximum N^2 in the vertical profile, for all data and for low-flow conditions only, respectively, are shown in Figure 10. Many of the higher N^2 values are not associated with the thermocline of the lake, but are the base of a shallow "radiation thermocline" that often forms due to solar radiation under calm conditions. (This is diagnosed by the depth of the layer of maximum N^2, which is quite shallow, less than 2 or 3 m, for a radiation thermocline, see Appendix A.) The important conclusion to be drawn from this figure is that, even with radiation thermoclines in the mix, the occurrences of substantial density stratification (N^2 greater than 40×10^{-4} s^{-2}, say) are relatively rare, cumulatively about 12% of the data, both for all flow conditions and for low-flows only.

2.4 Time and space variation of dissolved solids

There is a close relationship between conductivity and dissolved solids in a water sample, since the solids are the major contributor to enhanced electrical conductance of the water. However, the coefficient of that relationship depends upon the specific salts in solution and their relative proportions; for salts common in surface waters, literature values range 0.4 – 1.0. It is best, therefore, to determine the relationship from direct measurement of both parameters. From the TCEQ data base, the coefficient of TDS on conductivity proves to be 0.525 for Lake Granbury, with a correlation of 0.97, see Figure 11. The vast majority of measurements from Granbury are of conductivity. While conductivity and TDS are discussed interchangeably in this section, the interconversion between the two is used when specific values are required, in which case the regression relation of Fig. 11 is employed. We also use the term "salts" interchangeably with "dissolved solids," such as in the title of this chapter, because almost the entirety of the dissolved solids are in fact salts.

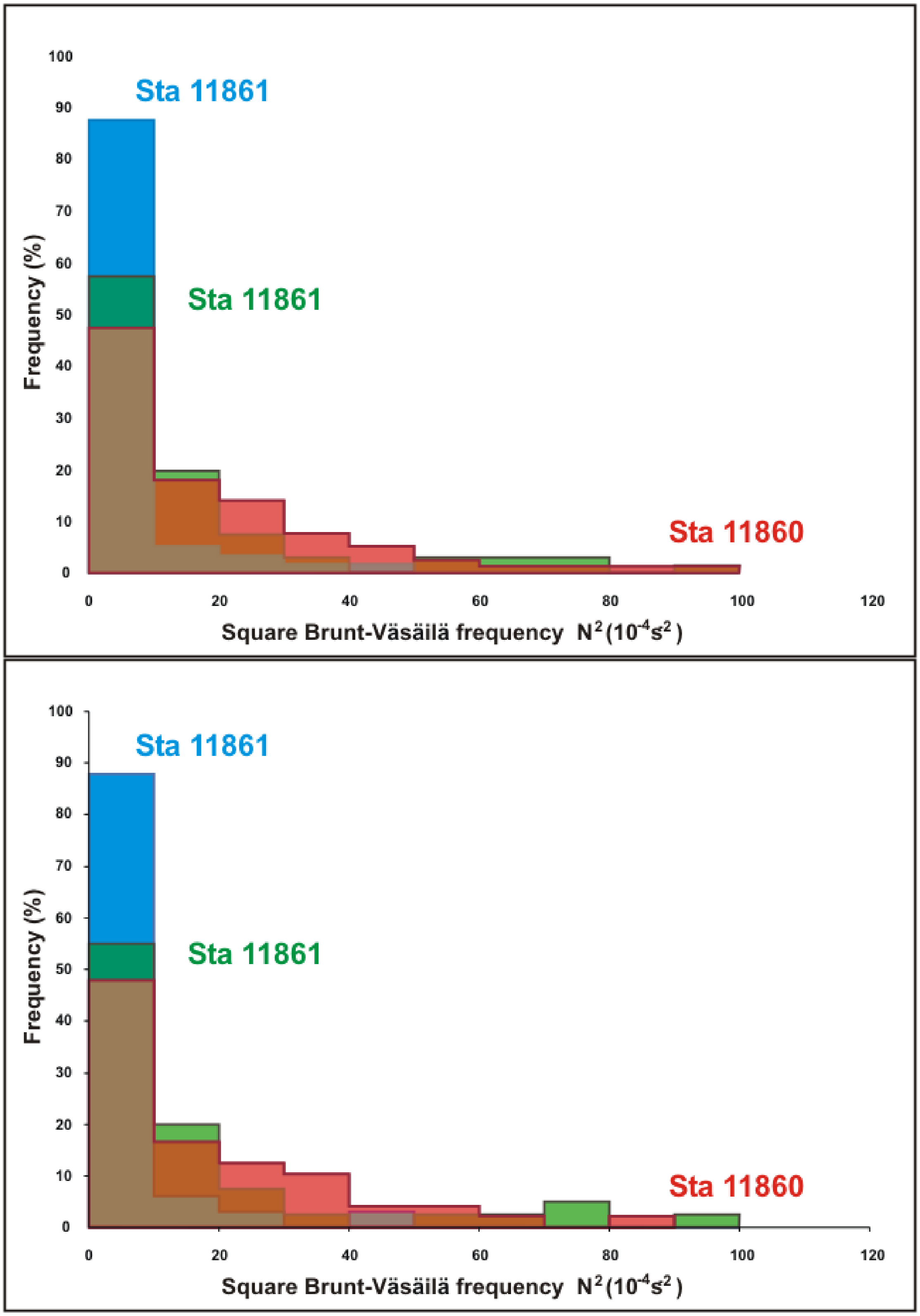

Figure 10 – Frequency distribution of N2 at three stations in Lake Granbury, all data (above) and low-flows only (below)

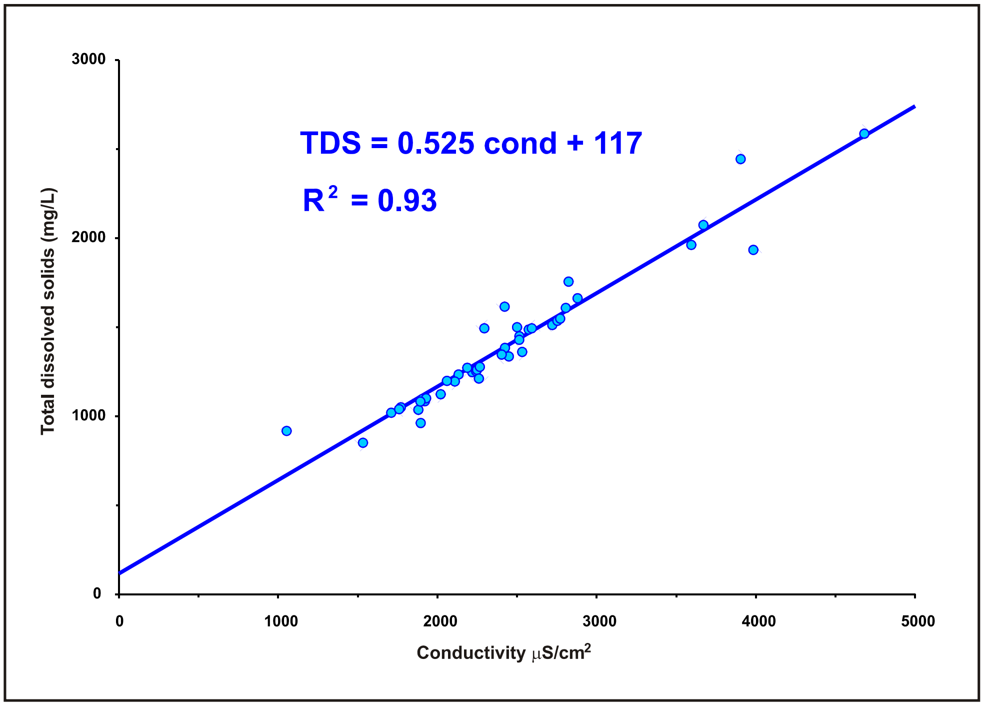

Figure 11 – Paired measurements of conductivity and TDS from TCEQ data base for Lake Granbury

TDS has varied since the early 1970's from low values around 500 mg/L to nearly 3000 mg/L, the highest values being logged during the protracted low flow of 2005-6, see Figure 12. While these high values occurred during this period, they cannot be unequivocally attributed to the low flow of the river, because over time the conductivity of the lake has been remarkably uncorrelated with flow, see Appendix B. Considering that the main salt load to the lake is carried by the Brazos, also the predominant source of inflow, it is probable that the controls on salt concentration are: (1) the component of inflow from peripheral runoff (diluting the salt concentration of the Brazos), and (2) the rate of evaporation from the reservoir surface, which is strongly governed by water temperature. Generally, no trend is apparent in the over-30-years of record.

While solids increase the density of water, in Granbury temperature dominates the density structure. There is a tendency for higher TDS to occur near the bottom (see Appendix B), but the average [surface – bottom] difference in conductivity is only about -120 µS/cm^2 per meter (recall

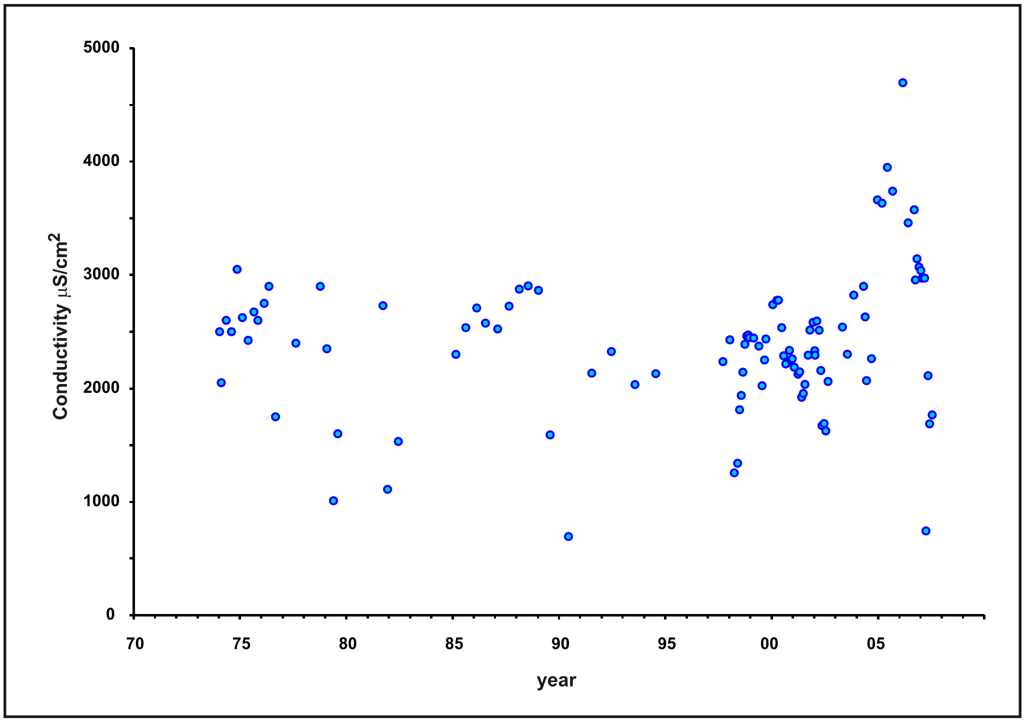

Figure 12 – Time history of surface-and-bottom-mean conductivity at Station 11860, reservoir mainstem near dam

that the corresponding TDS difference is about half this value), which results in the same density change as a mere 0.15 °C difference in temperature. Put another way, even the relatively average weak vertical gradient in temperature of 0.25 °C/m represents nearly ten times the density change resulting from the average vertical gradient in TDS of 0.45 mg/L/m. (We speculate that the slightly lower conductivity values in the upper layer of Granbury may be due to the diluting effect of peripheral runoff into the lake.)

Perhaps the most important attribute of the spatial structure of solids in Lake Granbury (for reasons that will emerge in Chapter 3) is the longitudinal gradient, i.e. the change in solids along the main axis of the reservoir. While detailed statistical data on this are presented in Appendix B, the situation is nicely summarized by Figures 13 and 14. Figure 13 demonstrates that, while there is a slight tendency for higher conductivities to occur at the upstream end of the lake, i.e.

somewhat more than half (about 58%) of the data have a negative [downstream – upstream] difference, the distribution is fairly equal. Moreover, only a small fraction of the differences exceed ± 500 mg/L TDS (corresponding approximately to the ± 1000 μS/cm^2 points on the axis of Fig. 13). We conclude that the solids concentration is practically homogeneous in the reach below SH 51. When a difference occurs, it tends to be linearly distributed along the axis of the lake, as demonstrated by the regression of Fig. 14. (Perfect linearity would scale exactly with the distance along the reservoir axis, in which case the expected slope of the regression would be 1.46, tolerably close to the regression slope of 1.36 in the data.) A linear distribution is an additional indicator of energetic longitudinal mixing, in that curvature of the concentration distribution has been eliminated.

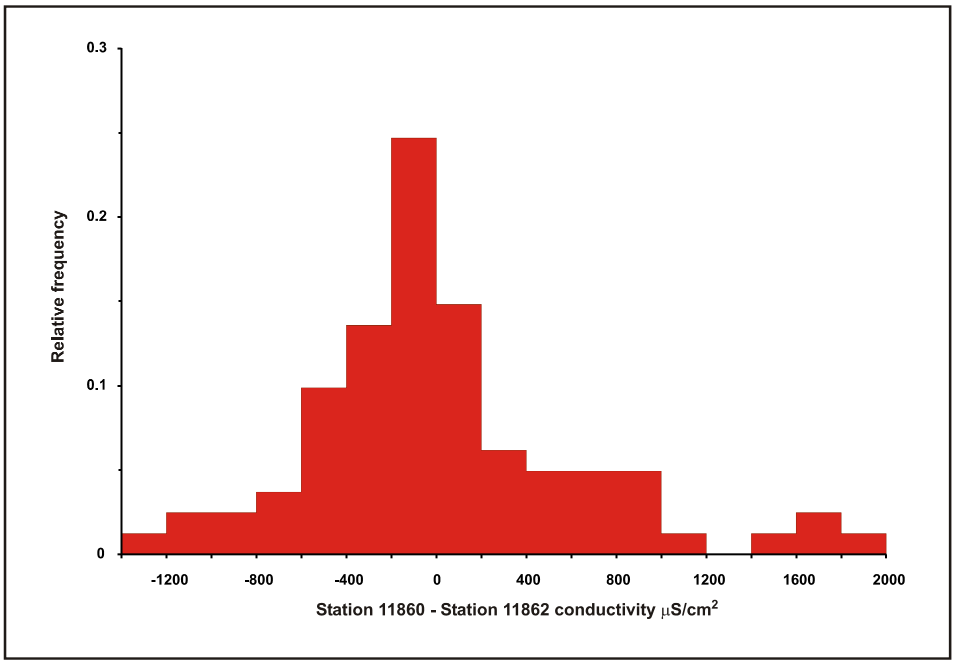

Figure 13 – Frequency distribution of longitudinal difference in surface-and-bottom mean conductivity between Station 11860 at dam and Station 11862 at SH 51 bridge

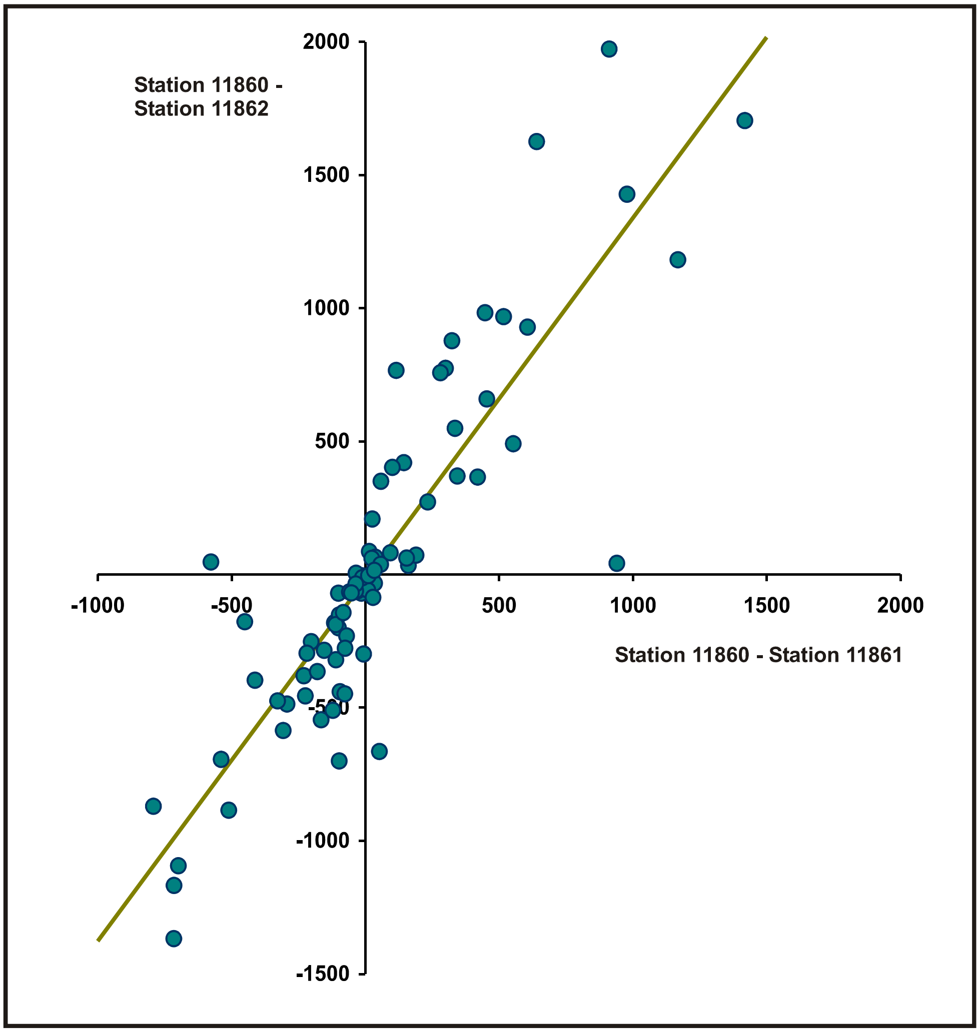

Figure 14 – Regression of downstream change in conductivity measured from 11862 (mile 20.0) versus that measured from 11861 (mile 13.7), slope of regression = 1.36 with R^2 = 0.77

3. Lake Granbury Projected Solids Concentrations

3.1 Assessment of the F&N TDS modeling

Two models were employed by F&N in its simulation study of Lake Granbury. The first is an application of the Brazos Water Availability Model (WAM), based upon the TCEQ Water Rights Analysis Program (WRAP), which is a simulation of the entire basin (Albright, 2007a, Wurbs, 2003). This is a monthly accounting of flows and water retention through the drainage system, including human demands, discharges and hydraulic operations. A run-of-the-river reservoir such as Granbury is treated by closing a volume budget:

$$\frac{V(t+\Delta t)-V(t)}{\Delta t} = Q_r + \Sigma Q_i - \Sigma Q_w - Q_o + (P-E)\,A(V) + [Q_b - Q_m] \quad (1)$$

where

	$V(t)$	=	reservoir contents (volume) at time t
	Q_r	=	river inflow (volume per unit time), for Granbury the Brazos at Dennis
	Q_i	=	inflow other than the river or the proposed cooling tower blow-down, such as tributaries, local runoff,and wastewater returns
	Q_w	=	withdrawal other than the proposed cooling tower make-up, such as municipal water-supply diversion or industrial water supply intake
	Q_o	=	outflow through the dam, the sum of spills and releases
	$(P-E)$	=	net precipitation (precipitation minus evaporation) on lake surface (depth of water per unit time)
	$A(V)$	=	lake surface area, a function of reservoir contents (through the rating relation)
	Q_b	=	cooling tower blowdown returned to the lake
	Q_m	=	cooling tower make-up withdrawn from the lake

and where Δt = 1 month. Each term in (1) is an average over the timestep interval Δt (in the WRAP WAM, one month) so the equation is *exact*, except for the slight error entailed by representing the average surface flux $\int\iint[p(\mathbf{x}) - e(\mathbf{x})]\, dA\, dt/\Delta t$ by the product of the average values $(P - E)$ and $A(V)$, and except for the error due to the implicit assumption that the water-surface elevation is level, so that A can be related to V through the rating curve. Thus the major source of error in (1) is not the approximation but the imprecision in measurement or estimation of the individual inflow or outflow terms.

Freese and Nichols (Albright, 2007a) has performed an excellent application of the WAM in examining the Brazos water budget for a number of future water-use scenarios, including the system operation of Possum Kingdom, Granbury and Squaw Creek. For the purpose of evaluating the impacts of the proposed cooling tower operation, this review focused on Scenario 3C, detailed by Albright (2007a), in which the tower bleedstream flow is returned to the lake. This scenario employs the BRA 2060 rating curve, see Fig. 2. The cooling water circuit of the existing De Cordova SES would be represented by a pair of withdrawal Q_w and return flow Q_i, but from a volumetric viewpoint, only the difference is operative in the volume budget. This difference is equal to the forced evaporation of the cooling circuit, which is included in the F&N model as a single demand Q_w based upon assumed power generation (Albright, pers. comm., 2007). Precipitation and evaporation were obtained from the 1^o x 1^o quadrant compilations of the TWDB. The river and tributary flow volumes were developed as part of the WAM modeling process for the Brazos basin. The effect of the cooling tower operation is represented in the last terms in brackets in (1), which in the F&N work are Q_m = 109,000 ac-ft/yr and Q_b = 48,000 ac-ft/yr.

Key variables in the water budget simulation are summarized in Table 3 and displayed in Figure 15 from the F&N Scenario 3C model. Over the 58-year simulation period, the annual spills and releases from Granbury average abour eight times the volume of the reservoir, and the annual evapora-tive deficit averages one-fifth (20%) of the volume of the reservoir, see Table 4. This of course reflects a smaller available storage due to the assumed siltation rate (see Fig. 2), two-

Table 3
Summary of annual water budget for Lake Granbury at year-end (ac-ft)
From F&N WAM simulation Scenario 3C (Albright, pers. comm., 2007)

year	*volume*	*spills &*	*P - E*	*year*	*volume*	*spills &*	*P – E*
end releases				*end releases*			
40 9	2,129	767,807	-22,141	69 8	9,331	978,301	-12,044
41 9	2,129	3,508,085	-15,200	70 8	4,605	390,499	-16,648
42 9	2,129	1,852,101	-19,269	71 9	2,129	353,526	-14,653
43 8	2,632	171,012	-31,297	72 9	2,129	392,847	-22,183
44 8	6,109	146,752	-23,123	73 8	9,245	389,377	-3,289
45 8	9,450	628,592	-19,602	74 9	2,129	569,722	-14,330
46 9	2,129	614,033	-21,998	75 9	0,865	498,967	-13,465
47 9	2,129	460,014	-30,746	76 9	2,037	168,769	-11,292
48 8	5,019	257,310	-35,169	77 8	4,597	359,411	-24,370
49 9	2,037	636,921	-17,364	78 8	9,594	287,292	-24,912
50 8	7,106	585,664	-26,613	79 8	7,999	289,208	-12,012
51 8	1,765	220,180	-31,062	80 8	7,646	393,918	-28,038
52 2	6,976	108,640	-21,797	81 9	2,037	1,141,594	-12,827
53 8	3,594	142,094	-10,527	82 8	8,748	1,721,023	-15,858
54 6	7,935	450,356	-35,982	83 9	1,978	109,198	-20,298
55 8	6,865	861,212	-22,734	84 9	2,129	83,853	-22,373
56 2	7,537	329,855	-30,527	85 9	2,037	583,362	-18,781
57 9	2,129	3,409,300	-4,960	86 9	2,129	630,276	-12,882
58 8	7,561	753,742	-13,458	87 8	9,333	847,390	-16,448
59 9	2,037	562,901	-14,567	88 8	4,634	73,640	-25,902
60 9	2,036	400,202	-20,730	89 8	9,928	764,356	-12,040
61 9	2,037	500,792	-14,328	90 8	7,362	2,076,409	-8,784
62 9	2,129	951,604	-16,640	91 9	2,129	1,723,993	-3,050
63 8	4,630	433,849	-28,774	92 9	2,129	1,664,964	-8,371
64 8	5,903	115,591	-17,693	93 8	6,835	272,440	-19,302
65 8	8,093	368,725	-15,106	94 9	2,129	319,933	-12,077
66 8	8,924	1,057,983	-12,937	95 8	9,442	365,659	-8,154
67 8	5,176	279,384	-20,131	96 9	2,129	432,024	-14,775
68 9	1,549	792,493	-7,317	97 8	7,242	1,281,134	-8,710

thirds (0.67) of the conservation storage of the 1993 TWDB survey, which increases the flushing rate of the reservoir. In the simulation, as in reality, it is the intervals between the pulses of throughflow that the evaporative deficit can potentially exacerbate the accumulation of dissolved solids. The greatest surface evaporative flux was recorded during the drought of the 1950's, especially 1951, 1954 and 1956, see Figure 16. The years with greatest evaporative loss after the drought of record are 1963, 1980 and 1988, whose rate approach those of the 1950's drought.

Table 4
Annual throughflow of Lake Granbury in volumes of lake per year,
from flow measurements at Dennis and Glen Rose,
and from F&N model simulation Scenario 3C

year	*data[1] mo*	*del[2] year*	*data[1] mo*	*del[2] year*	*data[1] mo*	*del[2]*
40		8.3 63		4.7 86	6.3	6.8
41		38.1 64		1.3 87	8.1	9.2
42		20.1 65		4.0 88	0.6	0.8
43		1.9 66		11.5 89	6.5	8.3
44		1.6 67		3.0 90	15.8	22.5
45		6.8 68		8.6 91	12.8	18.7
46		6.7 69	9.6	10.6 92	14.7	18.1
47		5.0 70	4.5	4.2 93	3.2	3.0
48		2.8 71	3.0	3.8 94	3.2	3.5
49		6.9 72	4.3	4.3 95	4.0	4.0
50		6.4 73	3.9	4.2 96	4.3	4.7
51		2.4 74	4.8	6.2 97	10.4	13.9
52		1.2 75	4.6	5.4 98	2.1	
53		1.5 76	2.8	1.8 99	1.2	
54		4.9 77	3.6	3.9 00	0.8	
55		9.3 78	4.3	3.1 01	4.2	
56		3.6 79	2.8	3.1 02	1.9	
57		37.0 80	4.0	4.3 03	1.0	
58		8.2 81	11.3	12.4 04	3.6	
59		6.1 82	13.4	18.7 05	3.7	
60		4.3 83	2.7	1.2 06	1.2	
61		5.4 84	1.3	0.9		
62		10.3 85	5.4	6.3 m ean	5.2	7.6

[1] 1993 volume 136823 ac-ft *[2] BRA 2060 projected volume 92169 ac-ft*

The high evaporative rates in the 1940's are questionable, because this older data was based upon non-standard pans, and no revision of pan-to-lake coefficients has been applied by TWDB. (The record high evaporative loss in 1948, Table 3, in particular, may be exaggerated.)

The TDS model was developed by F&N for specific use in addressing the solids problem, and employs the WAM-generated volume budget in a mass-budget accounting of TDS concentration for the Brazos *system*. The basic model equation is analogous to the volume budget (1), except applying to the mass of solids dissolved in that water budget, *viz*.

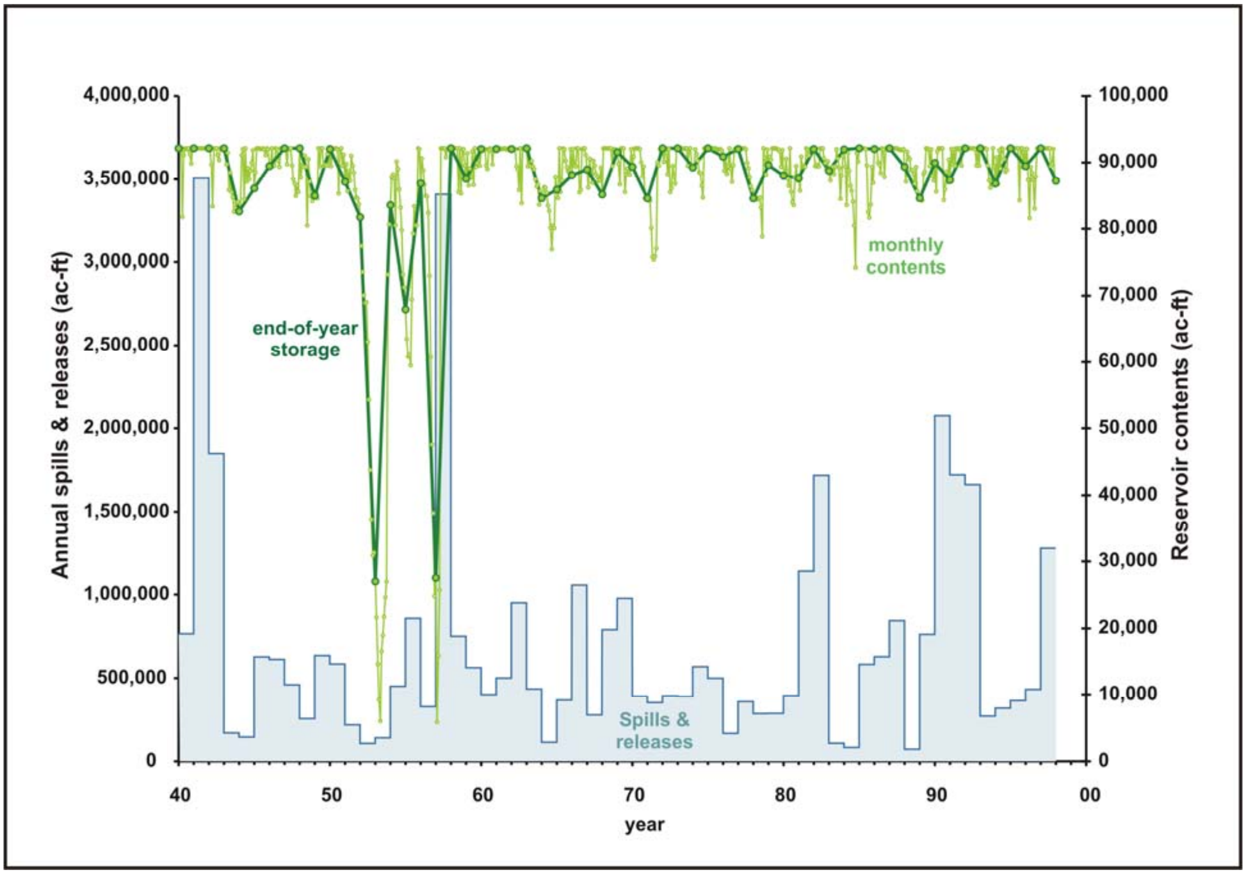

Figure 15 – Lake Granbury releases and storage from F&N WAM Scenario 3C simulation

$$\frac{\Delta(sV)}{\Delta t} \equiv \frac{s(t+\Delta t)V(t+\Delta t) - s(t)V(t)}{\Delta t} = s_r Q_r - \sum s(t)Q_w - s(t)Q_o \quad (2)$$

where

$s(t)V(t)$ = mass of salt in reservoir at time t

$s_r Q_r$ = river salt load, for Granbury basically the salt load from Possum Kingdom

$s(t)Q_w$ = withdrawal other than the proposed cooling tower make-up, such as municipal water-supply diversion or industrial water supply intake

$s(t)Q_o$ = salt removal in outflow through the dam

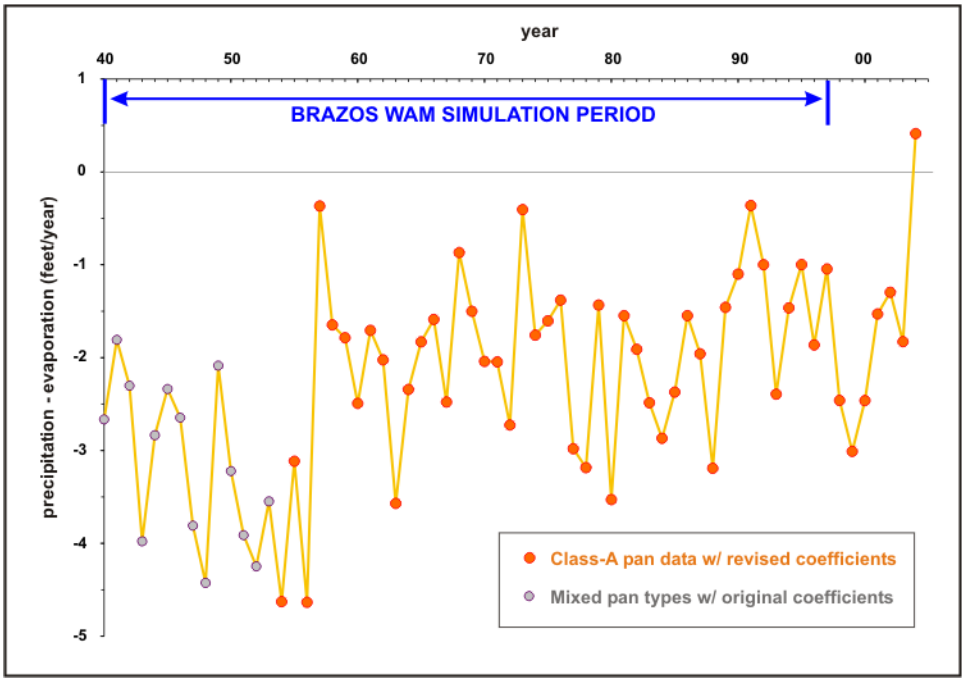

Figure 16 – [Precipitation – evaporation] for Lake Granbury area (TWDB data)

All of the above terms represent volume loads of salt, or, assuming unit density of water, mass loads. Neither net precipitation ($P - E$) nor the tower operation appears in (2) because neither entails a transfer of salt, in the case of the cooling tower because the blowdown returns the same salt to the reservoir that was removed in the make-up water. However, because both of these involve net losses of water, they are included in the volume budget (1) and therefore are implicit in the volume and outflow terms of (2).

The resulting simulation of TDS over the WAM time period is shown in Figure 17, along with the simulated annual-mean volume. The highest TDS concentrations occur during the 1950's drought, in association with the very low reservoir volume (which increases the concentration of the mass of salt in the water), but there are other high-salt events that are not so clearly associated with low lake volumes, notably in the 1970's and 1980's.

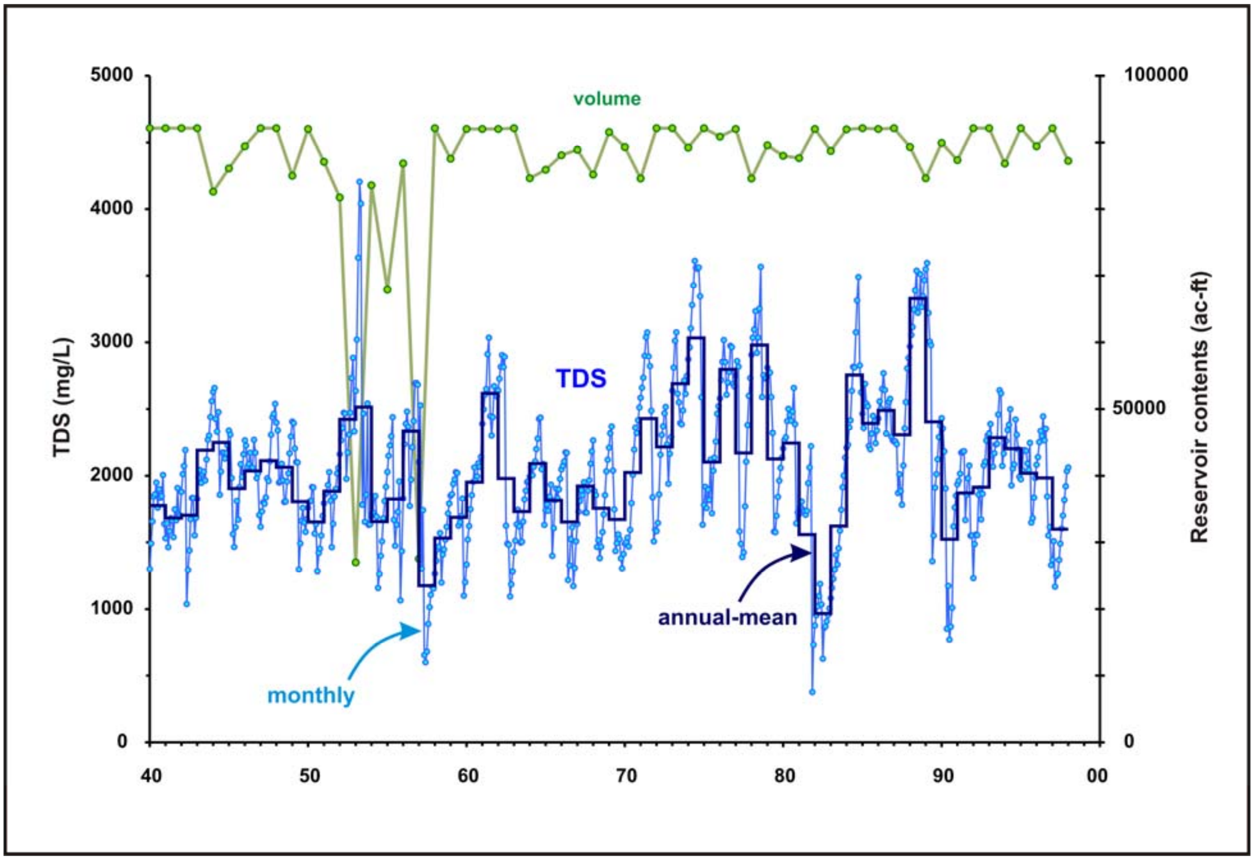

Figure 17 – Lake Granbury TDS and annual-mean storage from F&N model simulation

To quantify the effect of the proposed cooling towers, these model results need to be compared to a reference condition. For this purpose, F&N defined a *Base Scenario* without the new units at Comanche Peak. This is not simply a with/without exercise, however. The Base Scenario is intended to be a realistic future operation, so F&N adopted the 2060 Brazos G Water Plan, with some slight adjustments, in which all of the system yield is used, including surplus TxU contract water (Albright, pers. comm., 2008). F&N (Albright, 2007b) determined that the new-units scenario (Scenario 3C) raises TDS about 400 mg/L on average above the Base Scenario, and that the maximum predicted TDS values are about 60% higher than historical measurements in Lake Granbury.

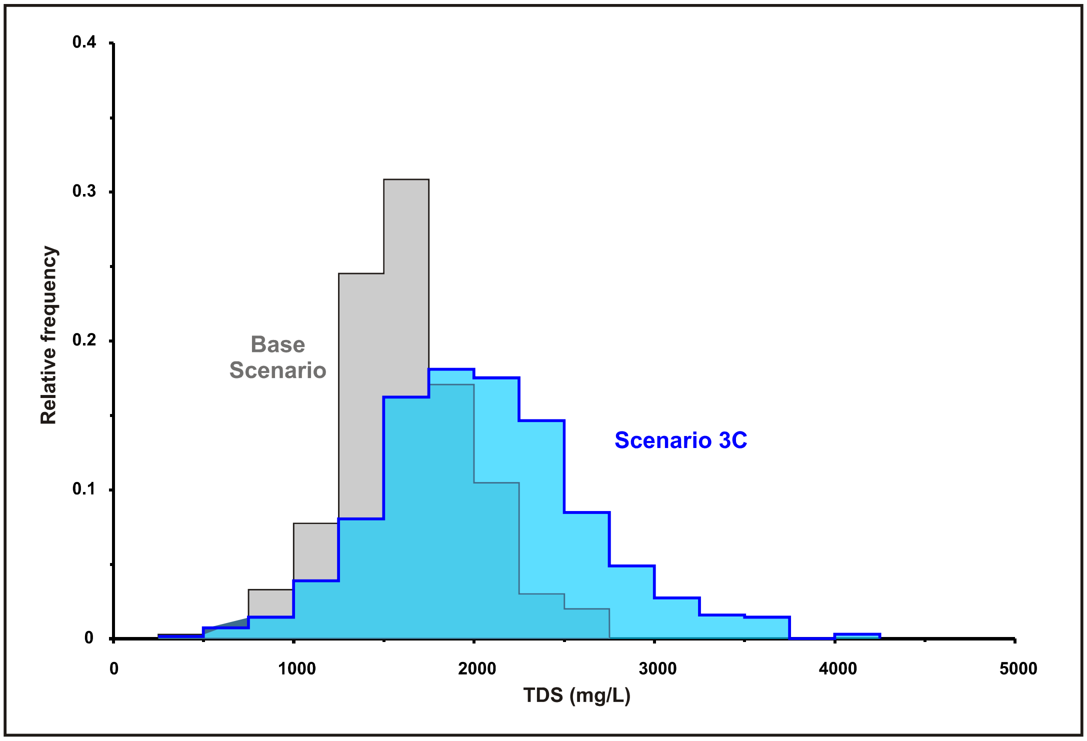

Figure 18 – Frequency distribution of modeled monthly TDS concentrations, Base Scenario (without new units) and Scenario 3 C, from model data provided by F&N (Albright, pers. comm., 2008)

The frequency distribution of the (monthly) TDS for both scenarios are shown in Figure 18. Not only does the addition of the new units increase the average TDS (from 1629 mg/L to 2058 mg/L), it also increases the spread of the distribution. Under the Base Scenario, 2% of the monthly TDS values exceed 2500 mg/L, while under Scenario 3C, this frequency is increased to 26%.

The TDS standard for Lake Granbury is 2500 mg/L, to be applied to an annual average (see TCEQ, 2000). Figure 19 displays the same frequency distributions as Fig. 18, but for the 58 annual averages in the F&N simulation. Under the Base Scenario, there are no violations of the standard, but under Scenario 3C, the standard is violated in 14% of the years of simulation.

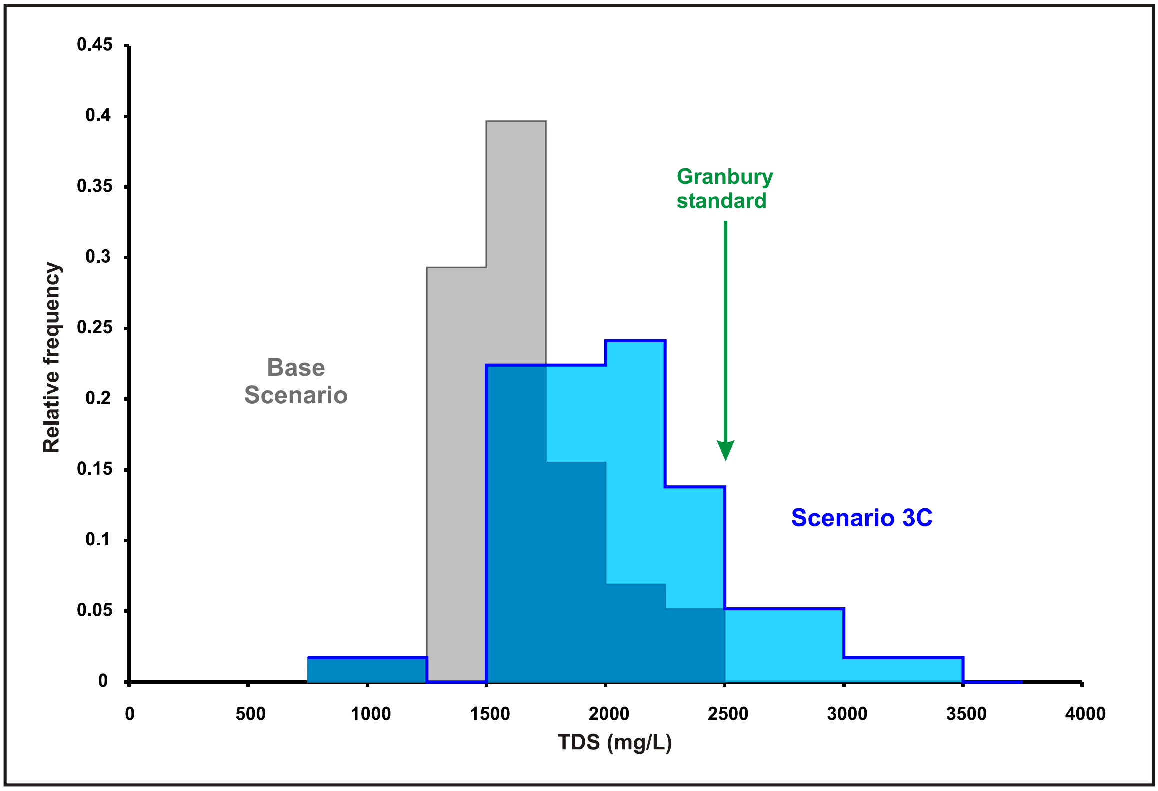

Figure 19 – Frequency distribution of modeled annual-average TDS concentrations, Base Scenario (without new units) and Scenario 3 C, from model data provided by F&N (Albright, pers. comm., 2008)

Both (1) and (2) treat the reservoir as a uniform, homogeneous waterbody. As noted before, this is a good approximation for the volume budget, in effect assuming that the water surface is level. Water transfers raise or lower the water-surface elevation immediately in the model, which accords well with reality, where hydraulic adjustment takes place very quickly compared to the monthly timestep of the volume budget. A water influx into the head of the reservoir can be drawn from any point in the reservoir: it is not necessary to wait for the individual water parcels to travel to the point of diversion. For this reason, the volume budget (1) was described as nearly exact. The same is not necessarily true for the salt budget. Transfer of salt in the reservoir operates relatively slowly, by the advection of water mass and by turbulent diffusion. This much slower response to influxes and effluxes of salt mass can induce a gradient both in the vertical and along the longitudinal axis of the reservoir. The immediate consequence of this is that the

TDS values in the solids-efflux loads $s(t)Q_w$ and $s(t)Q_o$ of (2) should in fact be the concentrations at the respective points of withdrawal from the reservoir. The latter, representing the removal of solids from the reservoir through releases to downstream, is particularly sensitive to the correct value of solids, given the large magnitude of the associated flow Q_o.

The analysis of field data in the preceding chapter demonstrates that the assumption of vertical and longitudinal homogeneity is not a bad one for Granbury, so the F&N modeling approach is reasonable. The high frequency of replacement of the reservoir volume by inflow and the weak vertical stability in the density structure, in those low-flow periods when it is allowed to stratify, together with an apparent high intensity of longitudinal mixing, all support the approximation of the lake as a well-mixed waterbody. But it is also true that most of the hydraulic and salt budget "action" is confined to the Lower Reach, cf. Fig. 4. The imposition of the forced evaporation from both the existing De Cordova SES and the tower exchange of the proposed new units opens the possibility of increasing dissolved solids in the Lower Reach. On the other hand, the dam release is also drawn from this same area, which opens the possibility that whatever increase in concentration might result from the evaporative loss may be evacuated from the reservoir by spills and releases. These concerns mandated a closer examination of this reach of the reservoir.

3.2 Model projections of TDS in the Lower Reach

The volume and TDS modeling of Lake Granbury has been capably prosecuted by F&N (Albright, 2007a, 2007b). The assumption that the lake is well-mixed is basically supported by hydrological and water quality field data analyzed in Chapter 2, but the peculiar fact that the majority of the salt fluxes are concentrated in the Lower Reach raises the possibility that the impact of the proposed cooling-tower operation may be underestimated. Therefore, we seek a method of applying the excellent work of F&N to an improved estimate of the effect of the proposed cooling tower operation on TDS in the Lower Reach of the reservoir. We postulate that (1) the TDS concentration in the Lower Reach is homogeneous through this reach (but may

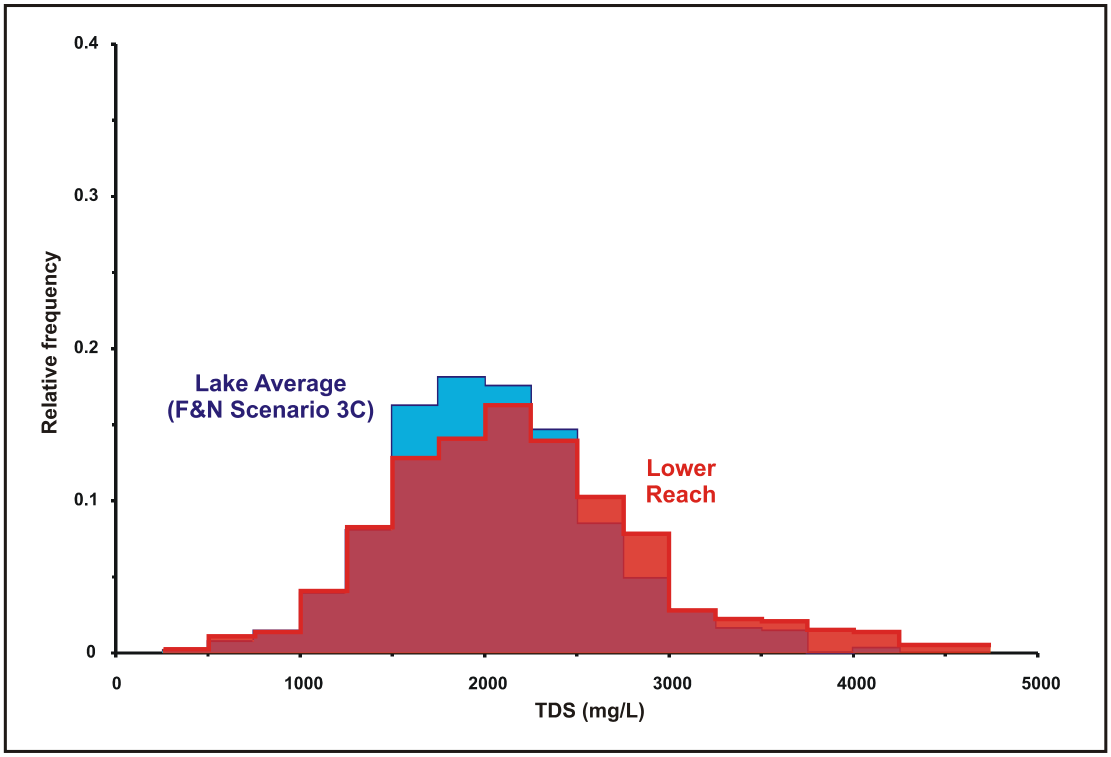

Figure 20 – Frequency distribution of modeled *monthly* TDS concentrations, F&N lake-average model (see Fig. 18) and estimated Lower Reach

differ from the concentration elsewhere in the lake) and (2) all diversions from the reservoir are imposed upon the lower reach. Continuing to assume that the surface of the lake is level allows us to write the volume of the Lower Reach as a function of the volume of the entire lake, $V_L = f(V)$ (solving the rating relation of Fig. 2 for elevation h and substituting into the relation shown in Fig. 5). Then the TDS budget for the Lower Reach only can be shown to reduce to:

$$\frac{\Delta(s_L V_L)}{\Delta t} \equiv \frac{s_L(t+\Delta t)V_L(t+\Delta t) - s_L(t)V_L(t)}{\Delta t} = \frac{\Delta(sV)}{\Delta t} + (s - s_L)Q_o \quad (3)$$

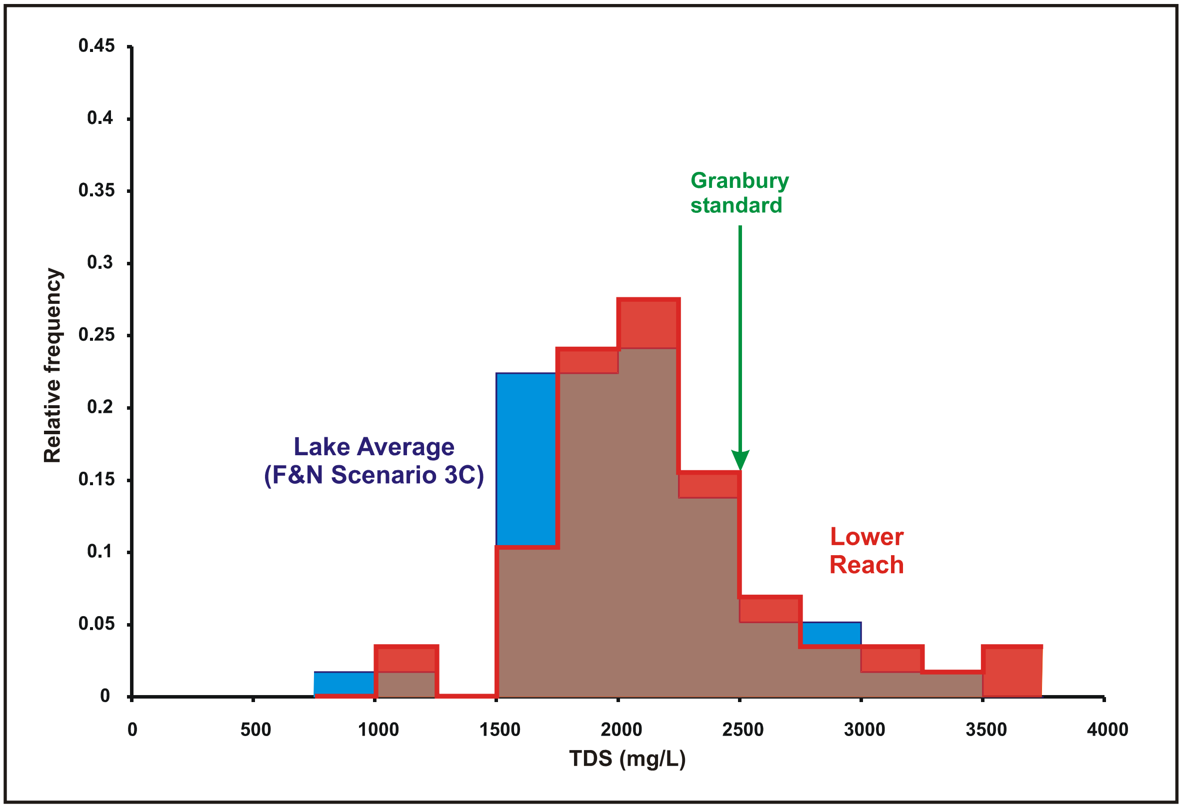

Figure 21 – Frequency distribution of modeled annual-average TDS concentrations, F&N lake-average model (see Fig. 19) and estimated Lower Reach

where V_L and s_L denote the Lower Reach volume and TDS concentration, resp., and $\Delta(sV)/\Delta t$ is given by (2), i.e. the increment in time of the *average lake* TDS from the F&N model. This equation (3) therefore provides a means of applying a "correction" to the F&N model results to estimate the TDS in the Lower Reach. Details of the method and some of the numerical subtleties are provided in Appendix C.

The results, summarized in Table 5, indicate a further increase in TDS, the 58-year average increasing from 2058 mg/L of the F&N model to 2190 mg/L in the Lower Reach. The resulting frequency distribution of monthly TDS values is shown in Figure 20, analogous to Fig. 18. The frequency distribution of annual-mean TDS is given in Figure 21, analogous to Fig. 19. The rate of standards violation increases from 14% to 19% in the 58 years of simulation.

Table 5
Summary of annual-mean TDS for Lake Granbury at year-end (mg/L)
F&N model simulations Base and Scenario 3C, and estimated Lower Reach

year end	*well-mixed lake F&N Base*	*well-mixed lake F&N 3C*	*Lower Reach*	*year end*	*well-mixed lake F&N Base*	*well-mixed lake F&N 3C*	*Lower Reach*
40	1558 1	776 1	897	69	1400 1	673	1802
41	1533 1	683 1	693	70	1653 2	024	2183
42	1509 1	704 1	760	71	1786 2	429	2658
43	1755 2	192 2	346	72	1824 2	216	2429
44	1672 2	249 2	405	73	2112 2	690	2787
45	1524 1	903 1	985	74	2252 3	034	3399
46	1582 2	036 2	067	75	1693 2	102	2224
47	1777 2	113 2	246	76	2003 2	798	3117
48	1674 2	063 2	105	77	1673 2	171	2454
49	1493 1	806 1	870	78	2285 2	981	3576
50	1345 1	654 1	749	79	1584 2	126	2214
51	1539 1	882 2	037	80	1726 2	245	2503
52	1513 2	423 2	187	81	1353 1	559	1625
53	1499 2	514 1	995	82	856	967	1049
54	1405 1	655 1	832	83	1304 1	622	1981
55	1395 1	825 1	885	84	2056 2	756	3222
56	1901 2	335 2	291	85	1999 2	393	2413
57	1022 1	176 1	182	86	1993 2	490	2657
58	1262 1	533 1	656	87	1938 2	307	2539
59	1329 1	688 1	894	88	2447 3	331	4053
60	1573 1	951 2	113	89	1890 2	404	2470
61	2027 2	618 2	758	90	1329 1	523	1618
62	1535 1	978 2	043	91	1589 1	869	2058
63	1494 1	732 1	855	92	1656 1	914	2012
64	1559 2	091 2	189	93	1703 2	286	2364
65	1434 1	814 1	899	94	1659 2	204	2267
66	1380 1	653 1	791	95	1460 2	018	2075
67	1622 1	923 2	107	96	1542 1	983	2102
68	1451 1	756 1	900	97	1376 1	599	1687

4. Discussion and conclusions

Lake Granbury is proposed as source and receiving water for cooling towers, the diversion point and the return discharge both in the Lower Reach of the reservoir, lying within two miles of the dam. Lake Granbury is a narrow run-of-the-river reservoir dominated by the flow of the Brazos River, and has historically exhibited elevated concentrations of TDS, due to the salt load in the Brazos, in turn derived from brine aquifers in contact with gypsum strata upstream from Possum Kingdom. There is concern that the additional evaporative loss associated with the proposed cooling towers has the potential to further increase these TDS levels.

Freese and Nichols has carried out model simulations of a reservoir volume budget and a dissolved solids budget for Lake Granbury to evaluate this potential. The model scenario of greatest concern is F&N's Scenario 3C, based upon: (1) system operation of the upper Brazos reservoirs, with full utilization of the yield; (2) new units for Comanche Peak and the associated tower operation, in which the blowdown is returned to the reservoir just upstream from the dam; (3) 1940-97 hydroclimatology, including the 1950's drought of record; (4) BRA 2060 projected reservoir volume, about two-thirds of the present reservoir volume. F&N compared this to a Base Scenario, basically the Brazos G water plan without the water commitment to the new Comanche Peak units but still assuming full utilization of the system yield, and determined that the effect of the addition of the tower operation was to increase the average TDS concentration by about 400 mg/L. In the present review, the F&N results were further compared to the Texas Surface Water Standard for TDS in Lake Granbury, and determined that, while no violations occur under the Base Scenario, the TDS standard is violated in 14% of the years under Scenario 3C.

The F&N volume-budget model is an application of the Brazos WRAP water availability model, and the TDS is a numerical mass-budget accounting for dissolved solids based upon the WAM output and implemented in an EXCEL workbook. Both have been applied competently by F&N, and this review finds no technical fault in their implementation. The fundamental assumptions of this model application are:

(1) the input data can be extracted from historical hydrometeorological data for the upper Brazos, and/or projections of future reservoir morphology and water demands in the basin;

(2) time resolution of one month is sufficiently accurate for volume- and mass-budgeting purposes;

(3) the reservoir can be treated as a well-mixed (homogeneous) watercourse

Assumptions (1) and (2) are, of course, common to the WAM methodology employed in all of the river basins of Texas. Some of the water-budget terms can be rendered more precise with detailed study, such as run-off or lake evaporation, and can be improved by finer time resolution (perhaps coupled with more accurate hydraulic formulae), but the remaining error latent in the other terms such as future water-demand projections makes such improvements moot, and the departure from interbasin consistency makes them undesirable. The assumption of greatest concern is (3), that Lake Granbury is a well-mixed system. For the volume budget, this assumption, which boils down to a level water surface, has little effect (since water flowing into the reservoir anywhere is potentially available for a withdrawal anywhere). However, for the TDS budget, this assumption may serious undermine the accuracy of the simulation, because there is a possibility of substantial spatial variation in TDS, either variation in the vertical, i.e. stratification, or variation along the longitudinal axis of the reservoir. The former is most likely in the Lower Reach because the greatest water depths are found here, hence the greatest potential for seasonal stratification. The latter is especially an issue because the Lower Reach of the reservoir will be affected by the forced evaporation of the existing De Cordova SES cooling-water circuit and by the evaporation from the cooling towers. Moreover, the predominant transfer of salt out of the reservoir through releases at De Cordova Bend Dam is also imposed on this segment of the reservoir.

In order to evaluate the threat posed by these factors, historical data from the reservoir were compiled and analyzed. The possibility of stratification in the TDS was examined first. Any subtropical lake is prone to the development of summer stratification, with the increased insolation and accumulation of buoyant, heated water. This stratification is disrupted by intense mixing, especially that deriving from storms and from lake throughflow. An important hydrographic feature of Granbury is its high throughflow-to-volume ratio, dominated by the flow in the Brazos. On average the waters of the lake are evacuated and replaced 7 – 8 times per year. Only under protracted low-flow conditions is it possible for seasonal stratification to develop. The available temperature data indicate that seasonal stratification in the lake is relatively weak, substantial stratification occurring in only about 12% of the profile data (some of which is attributable to near-surface solar heating rather than seasonal stratification). Moreover, the profile data for conductivity indicate that the very slight stratification evidenced is too weak to be attributed to density differences.

Longitudinal variation in conductivity/TDS below the SH 51 bridge crossing proves to be slight, and about equally distributed between positive (increasing downstream) and negative (decreasing downstream). This indicates that the Lower Reach of the lake is in fact rather well-mixed, not a surprising conclusion given the rate of throughflow replacement. This conclusion is reinforced by the summer field surveys of the De Cordova SES thermal plume, which lies generally upstream from the discharge point, suggestive that the effect of wind and other external hydrographic factors is sufficient to overbalance the downstream net circulation involved in the cooling-water circuit.

These conclusions serve to justify the F&N assumption that the TDS distribution is quasi-homogeneous. However, the fact that the tower make-up diversion and blowdown return will be placed about a mile apart in the Lower Reach of the reservoir means that a longitudinal gradient may be created by the proposed tower operation, which in turn could undermine the accuracy of the TDS modeling. In order to evaluate this, a supplementary TDS-budget model was developed for the Lower Reach of the reservoir. In order to exploit the modeling work already performed by F&N, this supplementary model was based upon the volume-budget and TDS-budget model results of F&N, resulting in a "correction" to the well-mixed lake model appropriate for the Lower Reach alone.

Application of this Lower Reach model for the same future scenarios addressed by F&N indicates that the imposition of the cooling-tower operation will further increase the TDS in the

Lower Reach on average about 130 mg/L (above the 400 mg/L increase predicted by F&N throughout the lake), so the total projected increase above the Base Scenario would be about 530 mg/L. The rate of violation of the surface water standard for Granbury would increase to 19% of the years in the 58-year simulation period.

While a review of the surface water standard for TDS is beyond the scope of the present analysis, it is worth noting that the corresponding standard for Possum Kingdom is 3500 mg/L annual average, compared to 2500 mg/L for Lake Granbury. Given that the outflow from Possum Kingdom is the main salt load to Granbury, and that the flow in the Brazos dominates the hydrology of the lake, the basis for such a large difference between the standards might be questioned. Were the standard for Granbury equal to that of Possum Kingdom, the projected frequency of violations would become 0% for the well-mixed lake model, and 3% for the Lower Reach alone.

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APPENDIX A

Stratification parameters: 1974-2007 TCEQ profile data

The levels of maximum stratification, i.e. the depths of the thermocline (if it occurs) and of the oxycline (if it occurs), provide an index to the extent of separation into two layers exhibited by Granbury, and, more importantly, its statistical consistency. The *thermocline* is defined to be the level of the *maximum* change in temperature $\partial T/\partial z$, where z is elevation measured positive upward. Because density ρ is dominated by temperature in a freshwater system, this also represents a maximum rate of decline in density $\partial \rho/\partial z$. An associated measure is the Brunt-Väisälä frequency

$$N = \sqrt{-\frac{g}{\rho}\frac{\partial \rho}{\partial z}}$$

The higher the value of N, the greater the rate of decline in density, and the more stable the water column, i.e. the greater resistance to vertical perturbations. A stable thermocline therefore resists mixing in the vertical and hydrodynamically separates the lake into two layers.

Dissolved oxygen (DO) acts as a tracer in the water column. Its concentration is normally greatest in a shallow surface layer, where oxygen is transferred into the water by mechanical aeration and photosynthesis, and lowest near the bottom, where oxygen is lost to respiration both in the water column and in the bed sediments. The only source of oxygen to waters below the level of light penetration is vertical mixing. With a stable thermocline, this vertical mixing is attenuated, or even eliminated at the thermocline, so the lower layer of the reservoir becomes anoxic, and there is a pronounced decline in DO from the surface down to the thermocline. The level of maximum rate of decline $\partial DO/\partial z$ is the oxycline, and typically occurs at or just above the level of the thermocline.

In the case of Granbury, salts (TDS) are naturally elevated, so the level of maximum vertical variation in TDS concentration $\partial c/\partial z$ is also of concern, from two standpoints: as a tracer to further reinforce the natural stratification of the water column, and to diagnose whether the vertical gradient is sufficient that it further alters the density stratification.

Several reservoirs in Texas exhibit very stable thermoclines, e.g. Lake Buchanan on the Colorado, Toledo Bend on the Sabine, and Amistad on the Rio Grande. Most reservoirs in Texas are moderately stable, though capable of being overturned by wind. For example, Lake Calaveras near San Antonio routinely stratifies around 10-15 m, reinforced by the surface circulation of a power plant cooling-water circuit, yet can be overturned in a matter of hours by a strong sustained wind.

In order to quantify all of these aspects of stratification in Lake Granbury, the profile data of TCEQ was subjected to detailed analysis in which each of the above vertical gradients were computed, along with their level of occurrence in the water column (measured as depth below the surface) and along with associated parameters such as *N* (given here as a squared value). Some of these profile extrema are not true thermoclines/oxyclines, but rather result from intermittent turbulent variation of the parameters that just happened to occur when the profile was taken, or are near-surface stratifications, such as solar-radiation "thermoclines" that occur under calm conditions. Which is which must be determined by the conditions under which the data were taken, and by comparison to profiles taken earlier or later in the year. In temperature lake stratification, the thermocline surface can sometimes coincide with an isothermal surface in a time-depth cross section, (i.e., the thermocline behaves as a material surface). Whether that obtains in Granbury is indicated by consistency of the temperature at thermocline level, also evaluated in these computations. The following tables present all of these stratification parameters for the three principal main-stem stations in Granbury (see Figure1). The flow prevailing at the date of the profile is indicated by the residence time in the final column.

Table A-1
Vertical-profile parameters, Station 11860, near dam

date	*season*	*vertical-mean*	*th*	*ermocline*			*oxycline*		*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	N^2 *dept*	*h*	*∂DO/∂z dept*	*h*	*∂C/∂z time*	
(yr)	*(yr)*	*(µS/cm²) (m*	*g/L)*	*(m)*	*(°C)*	*($10^{-4}/s^2$) (m*	*)*	*(ppm/m)*	*(m)*	*(µS/m cm²) (m*	*o)*
74.04315	0.04315	2500 1	.0	7.6 6	.5 0	.0	7.6	0.00	1.7 0	.0	7.75
74.11932	0.11932	2020 0	.7	7.6 8	.9 1	.4	7.6	0.13	10.7	-32.8	6.78
74.35180	0.35180	2600	3.0	10.7 1	9.0 1	2.6	10.7 0	.89	1.7	0.0	11.34
74.44557	0.44557		3.4	13.0 21	.2 50	.6	10.7 1.	57			5.96
74.60201	0.60201	2514	6.4	13.7 2	2.0 2	9.2	7.6 0	.99	4.6	-65.6	3.61
74.86494	0.86494	2583 1	.6	1.7	16.0 0	.0	13.7	0.13	7.6	-921.1	0.26
75.11423	0.11423	2620 1	.8	7.6 8	.5 0	.0	4.6	0.00	1.7	-18.2	0.64
75.38559	0.38559	2343	4.0	13.7 1	8.0 2	3.8	10.7 1	.51	10.7	-32.8	1.40
75.65361	0.65361	2579	5.6	16.8 2	3.8 3	5.4	7.6 0	.43	10.7	-16.4	1.70
75.84510	0.84510	2600 0	.0	1.7	19.0 0	.0	7.6	0.03	1.7 0	.0	12.61
76.13605	0.13605	2783 2	.1	10.7	11.3 8	.4	10.7	0.49	1.7	-36.4	6.23
76.36316	0.36316	2900 0	.4	7.6	19.8 3	.3	13.7	0.95	1.7 0	.0	2.06
76.66995	0.66995	1750	0.0	10.7 2	6.3 1	3.0	10.7 2	.07	1.7	0.0	2.08
77.62663	0.62663	2440	4.6	10.7 2	6.3 2	1.6	7.6 1	.28	1.7	0.0	10.98
78.77974	0.77974	2900 1	.9	7.6	23.3 3	.9	13.7	0.30	1.7 0	.0	2.76
79.08659	0.08659	2333	-2.8	11.4 5	.0 1	.0	3.8	0.79	15.5	-163.9	7.58
79.39592	0.39592	939	1.7	5.3 24	.0 47	.5	13.0 1.	24	14.0	-180.3	0.52
79.59907	0.59907	1670	2.3	9.9 2	7.0 1	7.7	9.9 3	.40	0.9	0.0	8.71
81.72726	0.72726	2724	4.4	19.1 2	2.1 4	1.2	17.5 2	.29	17.5	-26.1	5.55
81.94126	0.94126	1109 1	.6	3.8	14.1 0	.9	18.7	0.33	0.9	-2.5	1.03
82.21239	0.21239	1424	0.6	8.4 1	3.4 3	0.5	3.8 0	.59	0.9	-77.0	2.40
82.44271	0.44271	1531	1.5	9.9 2	5.7 1	3.5	19.1 1	.32	14.5	-12.5	0.09
85.15751	0.15751	2289 1	.2	11.4 7	.4 8	.0	11.4	0.39	11.4	-203.9	0.83
85.62312	0.62312	2972	3.8	13.0 2	7.8 2	7.2	11.4 1	.91	0.9	-841.8	1.99
86.13559	0.13559	2708 0	.9	6.9	10.6 5	.5	18.9	0.74	18.9	-8.2	3.06
86.54384	0.54384	2483	3.5	16.0 2	4.5 4	0.6	11.4 3	.49	11.4	-197.4	0.62
87.11648	0.11648	2506 1	.1	11.4 9	.6 5	.8	11.4	0.99	11.4	-59.2	0.81
87.65334	0.65334	2707	5.5	17.2 2	5.3 3	3.2	8.4 2	.43	11.4	-52.6	3.17
88.13008	0.13008	2881 0	.5	5.3 8	.3 0	.4	19.1	0.20	11.4	-6.6	8.08
88.55485	0.55485	2916	4.2	8.4 2	7.1 8	0.2	8.4 4	.61	8.4	-39.5	4.80
89.03151	0.03151	2868 0	.0	9.9	11.3 0	.7	17.5	0.33	2.3	-6.5	46.18

(continued)

Table A-1
(continued)

date	*season*	*vertical-mean*	*th*	*ermocline*		*oxycline*			*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	N^2 *dept*	*h*	*dDO/dz*	*depth*	*dC/dz*	*time*
(yr)	*(yr)*	*(µS/cm²) (m*	*g/L)*	*(m)*	*(°C)*	*(10⁻⁴/s²) (m*	*)*	*(ppm/m)*	*(m)*	*(µS/m cm²) (m*	*o)*
89.58499	0.58499	1588	5.1	9.9 2	5.9 1	7.0	6.9 2	.24	6.9	-197.4	2.06
90.44821	0.44821	694 2.	5	11.0	25.4 3.	8	17.0	0.85	17.0	-2.5	0.12
91.53866	0.53866	2200	2.1	11.4 2	7.7 2	5.5	11.4 2	.17	5.3	-208.5	0.27
92.46175	0.46175	2322 1	.0	9.0	26.1 3	.9	9.0	0.35	11.0	-15.0	0.20
93.57406	0.57406	2046	3.1	15.0 2	6.2 2	1.1	9.0 1	.65	3.0	0.0	2.07
94.54917	0.54917	1961	4.6	14.5 2	4.9 2	3.1	5.3 2	.61	14.5	-243.4	2.52
101.24110	0.24110	2116 1	.6	9.5	13.5 0	.7	3.5	0.05	13.5	-8.0	0.23
101.31507	0.31507	2002	2.3	11.5 1	7.1 7	7.3	11.5 4	.69	11.5	-349.0	0.36
101.41096	0.41096	1917	5.2	10.5 2	2.2 2	0.7	8.5 1	.14	12.5	-20.0	1.85
101.48493	0.48493	1934	4.5	11.5 2	3.4 3	5.3	7.5 2	.18	13.5	-25.0	5.65
101.71233	0.71233	2375	5.4	12.5 2	4.4 1	9.7	8.5 1	.80	3.5	-5.0	25.15
101.79452	0.79452	2515 1	.9	11.5	20.6 4	.2	8.5	0.40	4.5	-3.0	25.18
101.94521	0.94521	2578 2	.3	12.5	13.2 2	.5	12.5	1.30	12.5	-10.0	30.45
102.02466	0.02466	2387 3	.1	2.5	11.1 4	.6	14.5	5.13	1.5	-4.0	38.72
102.04110	0.04110	2294 1	.5	2.5 9	.5 0	.8	8.5	0.20	2.5	-2.0	38.72
102.12055	0.12055	2595 1	.3	12.5 9	.6 0	.1	6.5	0.10	2.5	-4.0	42.32
102.23288	0.23288	2538 0	.8	13.5	13.6 1	.2	3.5	0.05	11.5	-399.0	1.64
102.30959	0.30959	2124	4.0	8.5 1	7.5 2	9.1	7.5 1	.29	8.5	-82.0	1.16
102.36712	0.36712	1690	2.9	11.5 1	9.1 9	5.5	11.5 3	.40	0.7	-854.3	1.77
102.46849	0.46849	1596	5.5	7.5 2	4.4 3	0.5	5.5 2	.44	13.5	-93.0	2.89
102.54521	0.54521	1557	5.6	11.5 2	3.9 4	6.7	6.5 2	.19	13.5	-92.0	3.01
102.65479	0.65479	2067	3.6	11.5 2	6.2 3	3.1	8.5 1	.95	10.5	-120.0	2.88
103.32329	0.32329	2538	4.6	9.5 1	7.5 1	7.8	9.5 1	.69	13.5	-6.0	4.95
103.55616	0.55616	2680	4.5	9.5 2	4.4 6	5.5	6.5 4	.01	0.7	0.0	7.72
103.86301	0.86301	2822 3	.1	2.5	18.1 0	.2	2.5	0.07	8.5	-1.0	6.97
104.32329	0.32329	2878	0.2	8.5 1	9.8 1	8.1	8.5 1	.63	8.5	-30.0	4.17
104.39726	0.39726	2600	3.3	9.5 2	1.5 1	3.9	9.5 1	.37	8.5	-44.0	3.43
104.46027	0.46027	2052 2	.3	6.5	25.9 9	.6	6.5	1.24	1.5	-29.0	0.96
104.69315	0.69315	2257 2	.2	7.5	26.7 2	.9	7.5	0.37	7.5	-9.0	1.43
104.97534	0.97534	3664 0	.5	2.5	11.6 1	.0	8.5	0.31	12.5	-10.0	0.44

(continued)

Table A-1
(continued)

date	*season*	*vertical-mean*	*th*		*ermocline*	*oxycline*			*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	*N^2 dept*	*h*	*dDO/dz*	*depth*	*dC/dz*	*time*
(yr)	*(yr)*	*(μS/cm^2) (m*	*g/L)*	*(m)*	*(^{o}C)*	*(10^{-4}/s^2) (m*	*)*	*(ppm/m)*	*(m)*	*(μS/m cm^2) (m*	*o)*
105.18904	0.18904	3603	1.7	12.5 1	2.3 1	2.0	12.5 3	.79	14.5	-63.0	1.43
105.43562	0.43562	3971		7.5 2	3.0 2	6.5			3.5	-14.0	11.38
105.68219	0.68219	3713	3.9	10.5 2	5.1 1	9.8	5.5 5	.80	5.5 1	1.0	0.46
106.16712	0.16712	4691 0	.8	5.3	11.2 2	.8	5.3	0.45	0.9	-7.5	4.18
106.41370	0.41370	3248		12.8 1	9.5 2	9.3			9.8	-245.3	2.22
106.70411	0.70411	3274		11.3 2	3.8 5	7.9			11.3	-362.0	11.06
106.75616	0.75616	2938 3	.6	3.8	24.2 6	.5	11.3	1.75	11.3	-29.3	20.39
106.83562	0.83562	3128 2	.7	12.8	18.5 0	.4	12.8	0.14	11.3	-2.7	15.06
106.92877	0.92877	3067 1	.7	6.8	12.5 0	.7	15.8	0.24	9.8	-2.0	12.54
107.01096	0.01096	3034 1	.4	1.7	10.9 0	.0	13.5	0.29	13.5	-3.7	15.68
107.08493	0.08493	2970 1	.0	3.8 7	.8 0	.2	5.3	0.09	6.8	-2.0	15.68
107.19452	0.19452	2969 1	.6	6.8	12.3 9	.1	11.3	0.90	8.3	-6.0	1.78
107.25479	0.25479	725 5	.8	8.3	18.5 1	.7	5.3	0.16	12.8	-42.0	0.54
107.35342	0.35342	2018		12.0 2	0.6 1	6.9			12.0	-243.7	0.34
107.42740	0.42740	1622	1.9	6.8 2	4.9 1	0.0	6.8 1	.02	6.8	-56.7	0.15
107.54521	0.54521	1761		8.3 2	7.5 1	0.1			12.8	-12.7	0.11

Table A-2
Vertical-profile parameters, Station 11861, US 377/67 bridge crossing

date	*season*	*vertical-mean*	*th*	*ermocline*		*oxycline*			*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	*N^2 dept*	*h*	*dDO/dz*	*depth*	*dC/dz*	*time*
(yr)	*(yr)*	*(μS/cm^2) (m*	*g/L)*	*(m)*	*(^{o}C)*	*(10^{-4}/s^2) (m*	*)*	*(ppm/m)*	*(m)*	*(μS/m cm^2) (m*	*o)*
78.77983	0.779833	3075 1	.1	7.6	22.5 0	.0	7.6	0.26	7.6	-32.9	2.76
79.08666	0.086663	2200	-3.8	0.9 4	.0 0	.0	5.3	0.13	0.9 0	.0	7.58
79.39601	0.396014	1561 1	.8	0.9	22.5 0	.0	11.4	0.20	6.9	-32.9	0.52
79.59914	0.599144	1700	-0.2	3.8 2	9.0 1	9.0	5.2 1	.39	0.9	0.0	8.71
81.72735	0.72735	2740 2	.5	9.9	23.8 7	.8	9.9	0.85	0.9 0	.0	5.55
81.94134	0.941343	1369 1	.3	8.4	13.0 3	.3	11.4	0.07	11.4	-5.3	1.03
82.21249	0.21249	1440	0.4	9.9 1	3.8 1	4.0	8.4 0	.99	8.4	-111.2	2.40
82.44281	0.442808	1488 1	.2	9.9	26.1 8	.6	3.8	0.53	3.8	-23.7	0.09
85.15762	0.15762	2383 1	.1	11.4 9	.9 5	.0	3.8	0.39	5.3	-124.2	0.83
85.6232	0.623202	2391	2.3	12.8 2	7.9 2	7.4	11.4 2	.37	8.4	-613.2	1.99
86.13567	0.135674	2456 1	.5	3.8	10.7 1	.9	12.7	0.43	0.9	-49.2	3.06
86.54393	0.543931	2619 1	.1	8.4	28.5 9	.3	6.9	1.12	0.9 8	.2	0.62
87.11655	0.116553	2629 0	.0	3.8	11.0 2	.6	11.4	0.99	3.8	-19.7	0.81
87.65344	0.653444	2771 3	.0	8.4	30.3 9	.8	8.4	2.30	8.4	-32.9	3.17
88.13026	0.130261	2892 0	.1	6.9 8	.9 1	.4	11.4	0.26	6.9	-6.6	8.08
88.55497	0.554966	2722	3.2	8.4 2	5.2 7	5.0	6.9 4	.41	8.4	-184.2	4.80
89.0316	0.031602	2913 0	.2	9.9	11.4 2	.0	11.4	1.45	11.4	-19.7	46.18
89.58506	0.585063	1844	2.7	12.7 2	6.4 6	9.1	5.3 2	.94	11.4	157.9	2.06
90.448	0.448002	726	1.2	5.0 2	6.1 1	0.4	5.0 0	.35	3.0	-7.6	0.12
91.53885	0.538845	2349	1.6	14.5 2	6.2 3	4.6	6.9 1	.91	9.9	-71.9	0.27
92.46194	0.461939	2366 0	.7	7.0	26.2 1	.3	11.0	0.05	1.2	-5.9	0.20
93.57412	0.574119	2231 2	.1	7.0	29.4 4	.4	9.0	1.00	9.0	-70.0	2.07
94.54932	0.549315	2130	3.0	3.8 3	0.4 1	5.8	3.8 2	.30	5.3	-183.0	2.52
101.2411	0.241096	2797 1	.3	2.5	10.6 0	.0	7.5	0.05	8.5 1	.0	0.23
101.3151	0.315068	1836	2.8	8.5 1	9.4 2	1.2	8.5 1	.08	5.5	-169.0	0.36
101.411	0.410959	1869	1.8	8.5 2	5.2 1	0.4	8.5 1	.75	7.5	-1.0	1.85
101.4849	0.484932	2066	2.4	2.5 2	8.4 1	3.9	8.5 1	.67	9.5	-68.0	5.65
101.5671	0.567123	2303	2.9	9.5 2	9.1 7	6.3	6.5 2	.33	6.5	-204.0	30.16
101.6356	0.635616	2542	2.5	3.5 3	0.4 2	3.8	3.5 1	.86	6.5	-129.0	24.81

(continued)

Table A-2
(continued)

date	*season*	*vertical-mean*	*th*	*ermocline*		*oxycline*			*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	*N^2 dept*	*h*	*dDO/dz*	*depth*	*dC/dz*	*time*
(yr)	*(yr)*	*(μS/cm^2) (m*	*g/L)*	*(m)*	*(^{o}C)*	*(10^{-4}/s^2) (m*	*)*	*(ppm/m)*	*(m)*	*(μS/m cm^2) (m*	*o)*
101.7123	0.712329	2646	2.7	7.5 2	7.1 1	6.3	7.5 3	.20	1.5	5.0	25.15
101.7945	0.794521	2627 2	.6	8.5	19.9 2	.0	9.5	1.90	5.5	-2.0	25.18
101.9452	0.945205	2602 2	.7	8.5	12.9 8	.6	7.5	2.60	8.5	-26.0	30.45
102.0247	0.024658	2389 1	.1	4.5	10.0 3	.3	8.5	0.61	8.5	-40.0	38.72
102.0411	0.041096	2306 1	.0	0.7 8	.8 0	.0	5.5	0.20	6.5	-2.0	38.72
102.1205	0.120548	2558 1	.3	6.5 9	.1 0	.2	6.5	0.94	8.5	-9.0	42.32
102.2329	0.232877	1471	3.4	2.5 1	3.4	1.3	6.5 1	.32	2.5 1	1.3	1.64
102.3096	0.309589	1308	4.5	8.5 1	7.7 6	6.6	7.5 2	.37	8.5	-564.0	1.16
102.3671	0.367123	1697	3.4	9.5 2	1.2 5	4.9	8.5 2	.79	9.5	-62.0	1.77
102.4685	0.468493	1529	0.4	2.5 2	8.0 1	2.0	2.5 0	.79	5.5	-17.0	2.89
102.5452	0.545205	2061	2.3	7.5 2	8.7 1	4.8	6.5 2	.08	6.5	-448.0	3.01
102.6548	0.654795	2149 0	.3	3.5	30.2 6	.0	4.5	-0.06	1.5	-33.0	2.88
103.3233	0.323288	2644	2.5	9.5 1	9.2 2	0.7	9.5 1	.85	9.5 6	0.0	4.95
103.5562	0.556164	2877	3.0	9.5 2	4.9	100.0	7.5 4	.58	7.5	-87.0	7.72
103.863	0.863014	2823 2	.7	2.5	18.2 0	.4	3.5	0.13	2.5	-4.0	6.97
104.1178	0.117808	3186 1	.2	3.5 7	.7 0	.1	5.5	0.04	7.5	-7.0	5.58
104.3233	0.323288	2233	4.3	6.5 1	9.6 2	1.8	6.5 1	.59	5.5	-206.0	4.17
104.3973	0.39726	2155	3.3	9.5 2	1.5 5	6.2	8.5 3	.88	9.5	-252.0	3.43
104.4603	0.460274	798	4.8	7.5 24	.7 18	.9	5.5 1.	25	0.7	155.7	0.96
104.6932	0.693151	2438 2	.7	2.5	26.8 3	.8	9.5	2.08	9.5	-299.0	1.43
104.9753	0.975342	3630 0	.5	2.5	10.2 0	.6	2.5	0.11	5.5	-3.0	0.44
105.189	0.189041	3953 1	.5	6.5	14.0 6	.7	6.5	1.32	6.5	-41.0	1.43
105.4356	0.435616	4157		8.5 2	3.5 9	6.9			7.5	-110.0	11.38
105.6822	0.682192	4538	2.5	5.5 2	8.0 1	2.6	6.5 2	.18	3.5	-91.0	0.46
106.1671	0.167123	4326 0	.8	5.3	11.9 8	.2	8.3	1.07	5.3	-1.3	4.18
106.4137	0.413699	2150		8.3 2	5.5 3	4.0			6.8	-248.0	2.22
106.7041	0.70411	3013 3	.0	6.8	26.5 3	.2	6.8	2.43	6.8	-18.0	11.06
106.7562	0.756164	3000	2.7	8.3 2	4.1 1	2.8	8.3 2	.19	8.3	-22.7	20.39
106.8356	0.835616	3049 0	.8	6.8	17.8 0	.0	6.8	0.10	2.3	-2.0	15.06

(continued)

Table A-2
(continued)

date	*season*	*vertical-mean*	*th*		*ermocline*	*oxycline*			*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	*N^2 dept*	*h*	*dDO/dz*	*depth*	*dC/dz*	*time*
(yr)	*(yr)*	*(μS/cm^2) (m*	*g/L)*	*(m)*	*(^{o}C)*	*($10^{-4}/s^2$) (m*	*)*	*(ppm/m)*	*(m)*	*(μS/m cm^2) (m*	*o)*
106.9288	0.928767	2614 1	.6	6.8	11.5 0	.1	3.8	0.06	5.3	-13.3	12.54
107.011	0.010959	2618	1.8	3.8 1	0.3	-0.1	3.8 0	.15	2.3	0.7	15.68
107.0849	0.084932	2600 1	.0	6.8 7	.1 0	.0	8.3	1.51	8.3	-51.3	15.68
107.1945	0.194521	2719	-0.2	5.3 1	4.5 1	2.1	8.3 1	.96	8.3	-35.3	1.78
107.2548	0.254795	1504 2	.8	3.8	18.3 7	.4	8.3	0.03	3.8	-240.0	0.54
107.3534	0.353425	1127 2	.7	5.3	23.7 4	.8	6.8	-0.01	3.8	-172.7	0.34
107.4274	0.427397	2496 2	.3	6.8	23.6 3	.7	8.3	0.05	0.9	-212.5	0.15
107.5452	0.545205	1839 2	.5	3.8	29.5 4	.9	3.8	1.22	2.3	-34.7	0.11

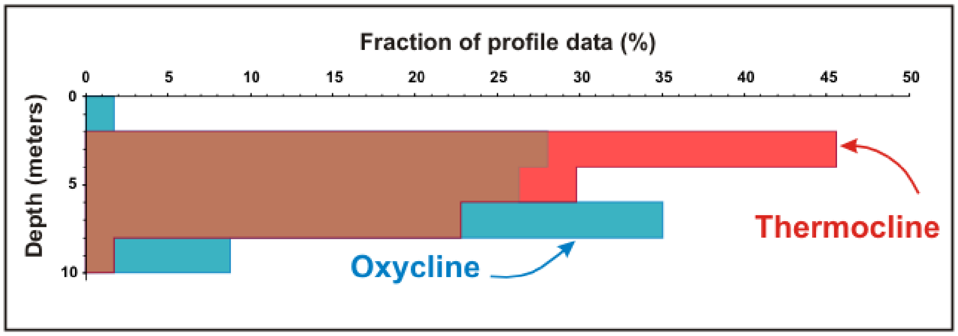
Table A-3
Vertical-profile parameters, Station 11862, SH 51 bridge crossing

date	*season*	*vertical-mean*	*th*	*ermocline*		*oxycline*			*min grad cond*		*residence*
co		*nd*	*deficit*	*depth*	*temp*	*N^2 dept*	*h*	*dDO/dz*	*depth*	*dC/dz*	*time*
(yr)	*(yr)*	*(µS/cm^2) (m*	*g/L)*	*(m)*	*(^{o}C)*	*(10^{-4}/s^2) (m*	*)*	*(ppm/m)*	*(m)*	*(µS/m cm^2) (m*	*o)*
81.72741	0.72741	2739	2.0	3.8 2	3.5 1	0.9	6.9 0	.39	0.9	-8.2	5.55
81.94140	0.94140	1595 0	.3	3.8	13.4 5	.9	3.8	0.53	3.8	-132.9	1.03
82.21260	0.21260	1648 2	.2	3.8	18.1 9	.6	3.8	0.46	0.9	-19.7	2.40
82.44295	0.44295	1563	-0.6	3.8 2	7.2	3.6	8.4 0	.99	0.9	-28.7	0.09
85.15769	0.15769	2737 0	.4	6.9	12.5 2	.3	6.9	0.79	6.9	-39.5	0.83
85.62325	0.62325	2861 1	.0	3.8	28.7 3	.8	8.4	1.05	0.9	-32.8	1.99
86.13572	0.13572	1916 0	.9	5.3 9	.9 3	.9	5.3	0.39	5.3	-248.4	3.06
86.54398	0.54398	3146 0	.6	3.8	28.1 1	.8	8.4	0.92	3.8	-105.3	0.62
87.11661	0.11661	2583 0	.9	6.9	10.6 1	.8	8.4	1.32	6.9	-13.2	0.81
87.65349	0.65349	2783 2	.0	3.8	29.9 1	.9	6.9	1.32	6.9	-13.2	3.17
88.13031	0.13031	2951 0	.3	3.8 7	.9 1	.9	5.3	0.26	0.9	-16.4	8.08
88.55501	0.55501	1916	3.9	6.9 2	7.1 4	1.0	3.8 3	.29	6.9	-246.1	4.80
89.03165	0.03165	3101 0	.5	3.8	10.3 1	.2	6.9	0.66	5.3	-19.6	46.18
89.58511	0.58511	1859	2.6						0.9	-295.1	2.06
90.44795	0.44795	757	2.0	8.2 25	.3 18	.2	8.2 2.	62	8.2	-11.9	0.12
91.53878	0.53878	2461 0	.8	5.3	29.4 9	.5	5.3	1.31	3.8	-72.4	0.27
92.46200	0.46200	2314 0	.7	7.0	25.7 1	.3	7.0	0.05	7.0	-5.0	0.20
93.57416	0.57416	2406 1	.2	7.0	28.8 2	.9	7.0	1.10	7.0	-60.0	2.07
94.54926	0.54926	2128 2	.5	3.8	30.6 9	.9	3.8	1.78	6.9	-197.4	2.52
101.31507	0.31507	1376 2	.8	4.5	20.2 6	.6	6.5	1.12	4.5	-250.0	0.36
101.41096	0.41096	1886 2	.8	6.5	25.2 7	.4	6.5	1.38	7.5	-4.0	1.85
101.48493	0.48493	2199 2	.3	6.5	27.8 4	.7	5.5	1.81	6.5	-142.0	5.65
101.56712	0.56712	2551 2	.9	5.5	30.9 4	.0	5.5	1.56	4.5	-165.0	30.16
101.63562	0.63562	2776	1.1	2.5 3	0.2 2	0.0	2.5 1	.52	2.5	-328.0	24.81
101.71233	0.71233	2626 0	.9	7.5	26.9 5	.4	7.5	2.70	7.5	-113.0	25.15
101.79452	0.79452	2700	0.7	2.5 1	9.2	-1.9	2.5 0	.10	1.5	-14.0	25.18
101.94521	0.94521	2641 1	.2	5.5	12.2 2	.3	4.5	0.30	4.5	-12.0	30.45
102.02466	0.02466	2468 1	.4	4.5 9	.4 6	.5	5.5	1.17	5.5	-52.0	38.72
102.04110	0.04110	2309 1	.0	6.5 8	.5 0	.7	1.5	0.50	4.5	-5.0	38.72
102.12055	0.12055	2674 0	.2	4.5 8	.6 3	.3	5.5	0.13	4.5	-57.0	42.32

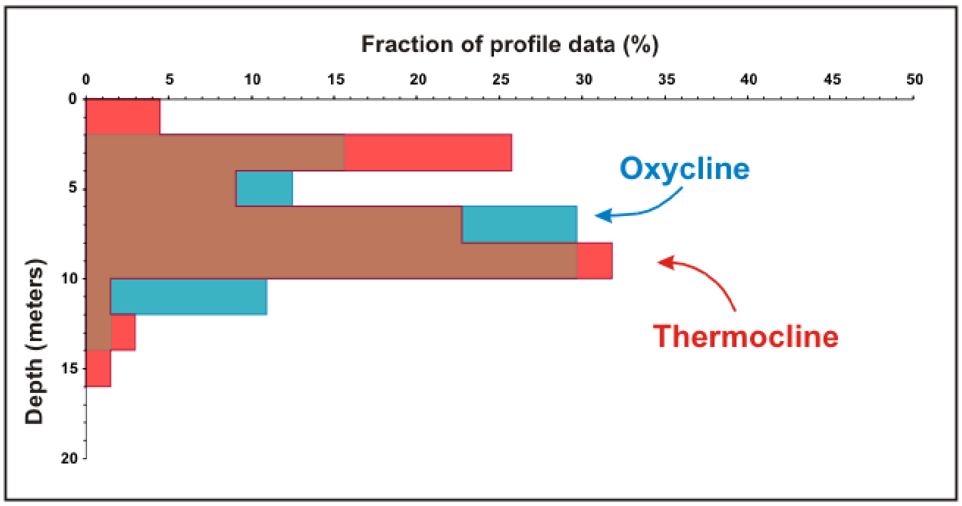
(continued)

Table A-3
(continued)

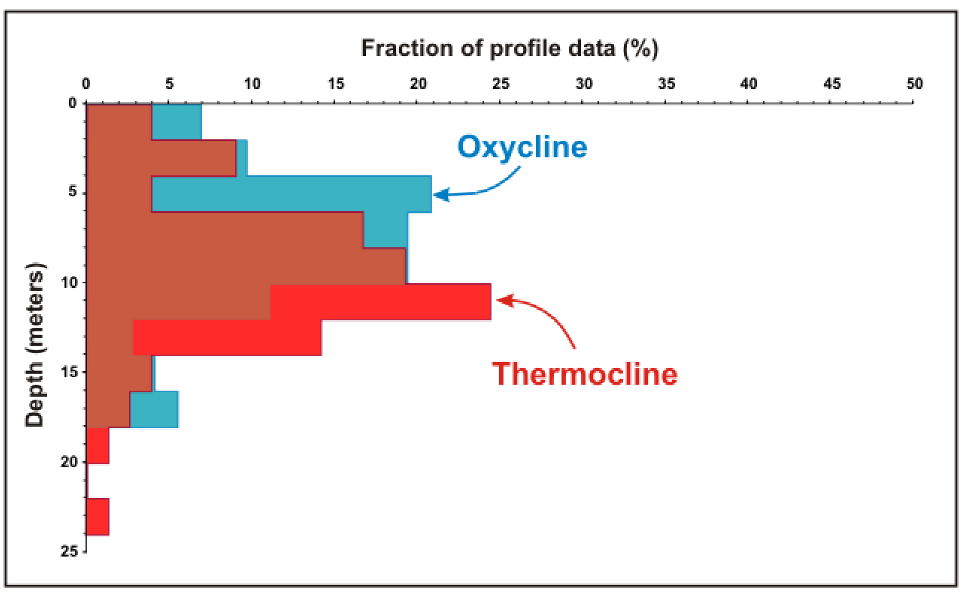
date	season	vertical-mean	th	ermocline		oxycline			min grad cond		residence
co		nd	deficit	depth	temp	N^2 dept	h	dDO/dz	depth	dC/dz	time
(yr)	(yr)	(μS/cm^2) (m	g/L)	(m)	(^{o}C)	(10^{-4}/s^2) (m	)	(ppm/m)	(m)	(μS/m cm^2) (m	o)
102.23288	0.23288	529 2	.3	5.5	13.4 0	.5	7.5	1.11	7.5	-24.5	1.64
102.30959	0.30959	958	3.1	7.5 2	0.9 3	4.7	6.5 2	.81	6.5	-43.0	1.16
102.36712	0.36712	1717 0	.8	3.5	23.2 3	.3	7.5	1.47	3.5	-94.0	1.77
102.46849	0.46849	1624 2	.4	6.5	27.4 6	.6	5.5	2.19	5.5	-10.0	2.89
102.54521	0.54521	2820 1	.5	3.5	28.3 5	.9	5.5	0.96	2.5	-241.0	3.01
102.65479	0.65479	2468 1	.1	2.5	29.8 0	.9	6.5	0.68	6.5	-76.0	2.88
103.32329	0.32329	2809	1.4	5.5 2	1.6 1	1.2	6.5 2	.75	5.5	-25.0	4.95
103.55616	0.55616	2243 2	.8	7.5	30.2 6	.6	6.5	2.24	2.5	-16.0	7.72
103.86301	0.86301	2828 2	.9	2.5	18.2 0	.2	5.5	0.26	1.5	-2.0	6.97
104.11781	0.11781	3089 1	.4	3.5 8	.3 0	.1	7.5	0.34	3.5	-3.0	5.58
104.32329	0.32329	2010	-0.8	2.5 2	2.4	8.4	2.5 2	.73	0.7	-38.6	4.17
104.39726	0.39726	2079 1	.6	2.5	25.6 1	.8	2.5	0.12	2.5	-14.0	3.43
104.46027	0.46027	642 2	.4	2.5	27.4 0	.8	2.5	0.27	0.7	-2.9	0.96
104.69315	0.69315	2433 0	.5	2.5	26.2 2	.9	2.5	0.21	1.5	-64.0	1.43
104.97534	0.97534	3647 0	.2	3.5 9	.3 0	.1	6.5	0.01	4.5	-2.0	0.44
105.18904	0.18904	4108	-0.2	5.5 1	4.7	0.1	2.5 0	.04	3.5	-5.0	1.43
105.43562	0.43562	4312 1	.1	4.5	27.9 1	.1	3.5	0.23	4.5	-2.0	11.38
105.68219	0.68219	4631 1	.0	2.5	28.2 0	.8	3.5	0.76	0.7	-77.1	0.46
106.16712	0.16712	3822	-1.7	3.8	13.1	1.3 3	.8	-0.03 0	.9	-14.2	4.18
106.41370	0.41370	2270 1	.3	5.3	27.2 5	.3	5.3	1.45	2.3	-75.3	2.22
106.70411	0.70411	3067 3	.1	3.8	26.6 4	.8	3.8	0.97	5.3	-33.3	11.06
106.75616	0.75616	3025	1.5						2.3	-4.7	20.39
106.83562	0.83562	3058 1	.4	5.3	17.1 2	.3	3.8	0.09	2.3 0	.0	15.06
106.92877	0.92877	2410	1.3						2.2	-1.4	12.54
107.01096	0.01096	2656 0	.6	5.3 9	.4 2	.7	5.3	0.88	5.3	-35.3	15.68
107.08493	0.08493	2601	-0.2						0.9	0.0	15.68
107.19452	0.19452	2699	0.0	5.3 1	5.7 2	1.6	6.8 2	.21	5.3	-6.0	1.78
107.25479	0.25479	2123 2	.0	5.3	18.4 0	.2	6.8	0.11	0.9	-52.5	0.54
107.35342	0.35342	1969 1	.7	5.3	24.6 8	.1	5.3	0.75	5.3	-390.7	0.34
107.42740	0.42740	2793 1	.9	3.8	23.3 3	.1	5.3	0.05	2.3	-24.7	0.15
107.54521	0.54521	2438 2	.0	6.8	29.7 9	.8	6.8	1.23	5.3	-82.7	0.11



(a) Station 11862, SH 51 bridge crossing

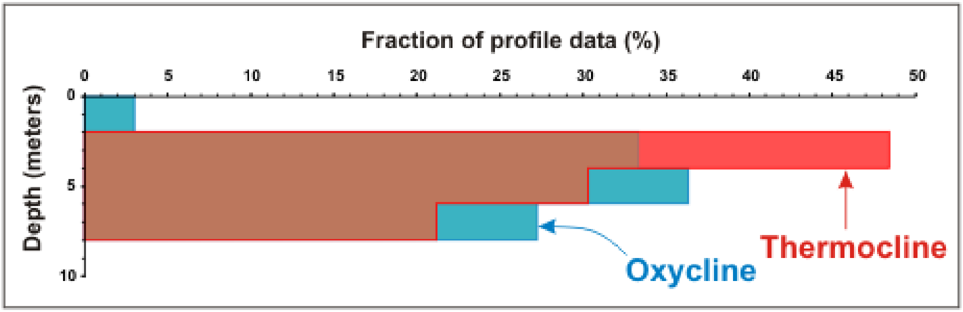


(b) Station 11861, US 377/67 bridge crossing

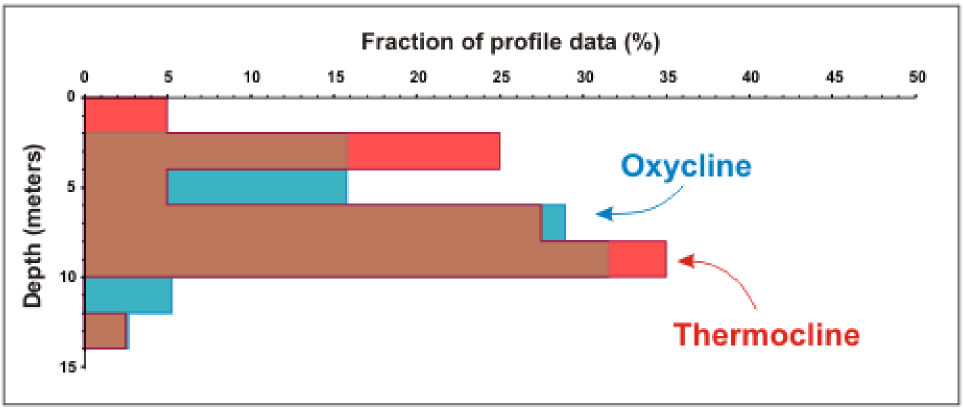


(c) Station 11860, Lake centerline upstream from dam

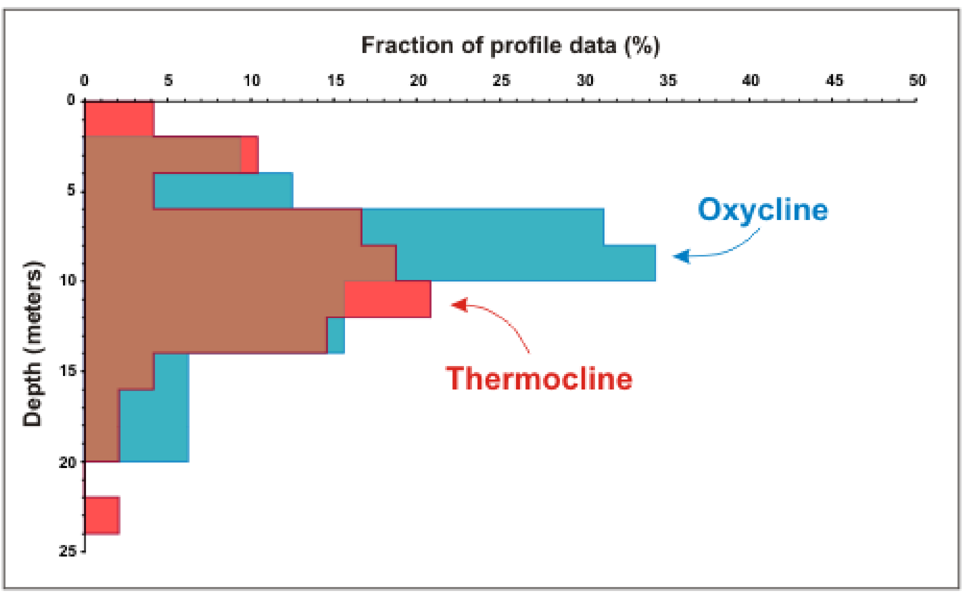
Figure A-1 – Frequency distribution of stability of maximum vertical density gradient in temperature profile



(a) Station 11862, SH 51 bridge crossing



(b) Station 11861, US 377/67 bridge crossing



(c) Station 11860, Lake centerline upstream from dam

Figure A-2 – Frequency distribution of stability of maximum vertical density gradient in temperature profile, in profiles taken under low-flow conditions

APPENDIX B

Dissolved Solids Variation in Lake Granbury

1974-2007 TCEQ profile data