Impacts of Natural Salt Pollution on Water Supply Capabilities of River/Reservoir System

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1. Introduction

Salinity is a major determinant of where and how water resources are used. Natural salt pollution severely constrains the beneficial use of large amounts of water in Texas and neighboring states. The U.S. Environmental Protection Agency secondary drinking water standards suggest a maximum TDS limit of 500 mg/l set on the basis of health effects and taste preferences and because conventional treatment processes do not remove salinity. Salts also damage pipelines, equipment, household appliances, and industrial facilities. Salinity is also a major consideration in irrigated agriculture. Acceptable salt concentrations for irrigation vary greatly depending on the type of crop, soil conditions, climate, and the relative amounts and timing of rainfall versus supplemental irrigation. TDS concentrations of less than 1,000 mg/l are usually preferred for irrigation.

In Texas, natural salt pollution severely constrains the water supply capabilities of the Brazos River and other neighboring rivers shown in Figure 1 (Wurbs 2002). Geologic formations in the Permian Basin geologic region are the primary source of the salinity. Salt springs and seeps and salt flats in the upper watersheds of the Brazos, Colorado, Pecos, Red, Canadian, and Arkansas Rivers contribute large salt loads to these rivers. The salinity drastically limits the municipal, industrial, and agricultural use of water that could otherwise be supplied by a number of existing large reservoirs located on these rivers.

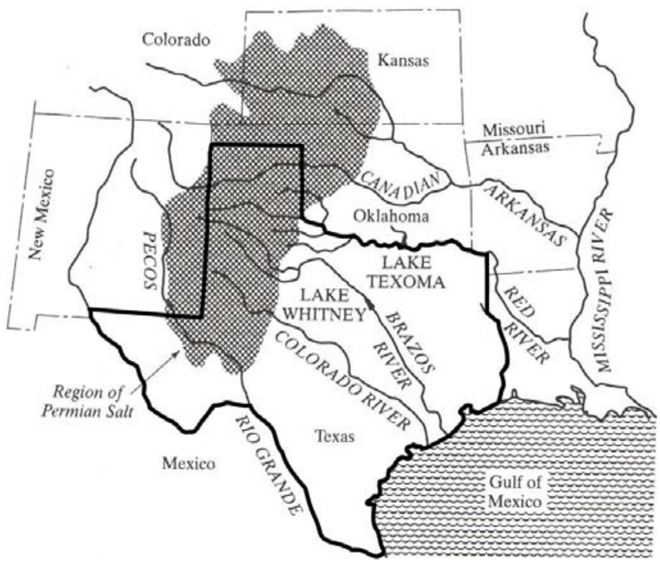

Figure 1. Major Rivers Affected by Permian Basin Salt

Desalination is very energy intensive and much more expensive than conventional municipal and industrial water treatment processes. The Brazos River Authority operates a desalination plant that allows water withdrawn from Lake Granbury to supplement municipal water supplies for the City of Granbury. However, Brazos River salinity constraints are mitigated primarily by using the water resource through water supply diversions in the lower Brazos River after dilution form low-salinity tributary inflows.

This study will examine the salinity budget related to the streamflows. From this result, a simulation modeling study will be performed to evaluate the impacts of salinity on water supply capabilities in the Brazos River Basin.

2. The Objectives of The Study

The objectives of the dissertation research are;

1. Develop an improved understanding of the occurrence and transport of salinity in river/reservoir systems to support improvements to the salinity simulation features of the Water Rights Analysis Package (WRAP) modeling system.
2. Improve, expand, test, and evaluate the capabilities of the salinity components of WRAP for assessing impacts of natural salt pollution on water availability and supply reliability.
3. Develop and implement strategies for incorporating salinity considerations into the Texas Water Availability Modeling (WAM) System.
4. Apply the modeling capabilities developed by the research to assess the impacts of natural salt pollution on water supply capabilities of river/reservoir systems in Texas and the effectiveness of alternative strategies for dealing with the salinity.

3. Study Area

3.1 Study area

The reach of the Brazos River containing Lakes Whitney, Granbury, and Possum Kingdom is divided into five sub-reaches for purposes of the water and salinity budget study. The five river reaches are defined by the USGS stream flow gauging stations listed in Table 1 with locations shown in Figure 2.

Table 1. Gaging Stations Defining Volume and Load Balance Reaches

Station	USGS Number	River Mile	Drainage Area ($mile^2$)
Seymour	08082500	847.0	15,538
South Bend	08088000	686.5	22,673
Graford at PK	08088600	687.5	27,190
Dennis	08090800	571.0	25,237
Glen Rose	08091000	523.6	25,818
Whitney	08092600	442.4	27,189

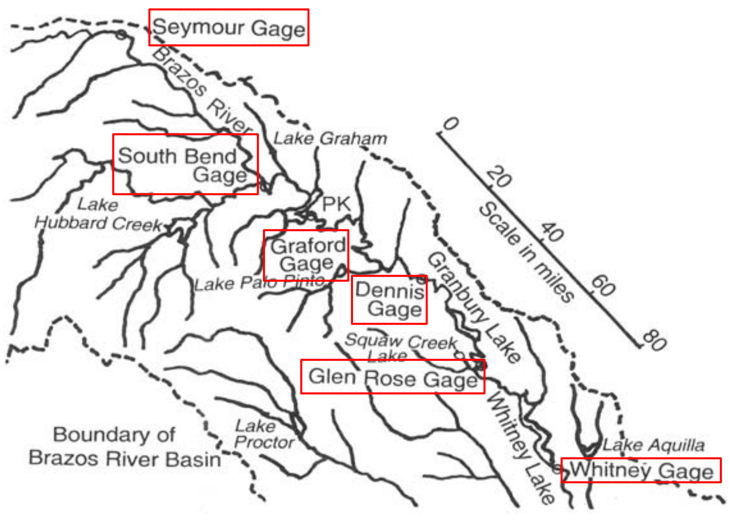

Figure 2. Map of Study Reach and Vicinity

3.2 Dataset from USACE/USGS Natural Salt Pollution Studies

The Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) in collaboration with the U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA), and other agencies conducted extensive Brazos River Basin natural salt pollution studies during the 1970's-1980's (Wurbs 2002). The USGS conducted an extensive water quality data collection program during October 1963 – September 1986 in support of the USACE salt pollution control studies. The USACE-sponsored USGS salinity measurement program was discontinued in 1986. The USACE later contracted with Texas

A&M University to compile the USGS salinity data into a more conveniently usable format and to perform various analyses (Wurbs et al. 1993).

The water years (Oct-Sep) 1964-1986 USGS/USACE observed data described by Wurbs et al (1993) will be used to develop the basin-wide salinity input required for the WRAP modeling studies. The 1964-1986 USGS data will be also used to develop the volume and load budgets. Analyses of the volume and load budgets also will contribute to the development of WRAP salinity input data.

The USGS aggregated daily flow and concentration observations into mean monthly flows and monthly concentrations and loads of total dissolved solids (TDS), chloride, and sulfate. Chloride and sulfate are major constituents of total dissolved solids (salinity) in the Brazos River. Discharges and salt loads are cited by the USGS in units of cubic feet per second (cfs) and tons/day, respectively. Salt concentrations are cited in units of milligrams of salt solute per liter of water (mg/l). Assuming a liter of water has a mass of one kilogram, the units mg/l and parts of salt solute per million parts of water (ppm) are equivalent.

4. Summary and Conclusion for Each of the Study Plans

4.1 Volume and Load Budget Study

Water and salinity budget studies were performed for five sub-reaches of a 405 mile long reach of the Brazos River between the USGS stream gaging stations near Seymour and Whitney, which includes Lakes Possum Kingdom, Granbury, and Whitney. The studies were based primarily upon water year 1964-1986 monthly flow volumes and TDS loads from the USACE-sponsored USGS water quality sampling program supplemented as needed by other observed or synthesized (computed) water quantity and quality data.

The budgets consist of Microsoft Excel spreadsheets of October 1963 through September 1986 sequences of 276 monthly inflow, outflow, and storage volumes and the corresponding inflow, outflow, and storage TDS loads for each of the 5 reaches. The inflows and outflows are subdivided into components. Component inflow and outflow quantities and storage changes sum to zero as appropriate to balance the budgets. Some components such as monthly stream flow volumes and loads and end-of-month reservoir storage volumes are observed data, with only gaps in the records synthesized (computed) as part of the study. Other components such as end-of-month reservoir storage loads were computed in conjunction with the study since observed data are not available. Concentrations were computed by combining volumes and loads. Summaries of means of the quantities for the 276 months are also included in this report along with plots of the 276-month (1964-1986) sequences.

Components of the Volume and Load Budgets

Most of the inflow and outflow for each reach is reflected in the river flows at the upstream and downstream gages defining the upper and lower ends of the reach. The 1964-1986 mean flow at the Glen Rose gage upstream of Lake Whitney and the Whitney gage downstream of Lake Whitney are 61,670 acre-feet/month and 74,193 acre-feet/month. The mean TDS loads at the upstream and downstream ends of the Glen Rose to Whitney reach are 90,017 and 93,538 tons/month. The corresponding concentrations are 1,073 mg/l and 927 mg/l.

The other inflow volume (F_{OI}) and other outflow volume (F_{OO}) are monthly amounts required to balance the volume budget each month. The other flow volume differences are the summation of all other components of the volume budget and are positive in some months and negative in other months. This volume difference was assigned to the variable F_{OI} if positive in a particular month and F_{OO} if negative. Of course, the volume difference required to balance the volume budget in a particular month is probably the net of both other inflows and outflows. Thus, the procedure adopted here of assigning the monthly volume differences as being either totally inflow (F_{OI}) or totally outflow (F_{OO}) is an approximation. The other inflows (F_{OI}) may include rainfall runoff from the incremental watersheds, stream underflow not measured by the upstream gage, water supply diversions, and water supply return flows. The other outflows (F_{OO}) may be stream underflow not measured by the downstream gage, seepage from the river and reservoir into the ground, evapotranspiration not accounted for by the reservoir surface evaporation term, and water supply diversions. The other flows (F_{OI} and F_{OO}) terms may also reflect timing effects of flows passing through the reach and inaccuracies in the other components of the water budget.

The 1964-1986 means of the other inflow volume (F_{OI}) and other outflow volume (F_{OO}) for the Glen Rose to Whitney reach are 19,447 and 2,233 acre-feet/month, respectively. The other inflow volume (F_{OI}) should consist largely of rainfall runoff from the local incremental watersheds draining to the reaches between their upstream and downstream gages. The mean other inflow volume (F_{OI}) of 19,447 acre-feet/month is equivalent to a depth of 3.2 inches for the 1,371 square mile incremental watershed, which is a reasonable rainfall runoff depth for this region. The other outflow volumes (F_{OO}) reflecting diversions and losses are a relatively small component of the volume budget.

For the three reaches containing Possum Kingdom, Granbury, and Whitney Reservoirs, the other inflow load (L_{OI}) was estimated by applying a concentration of 270 mg/l to the other inflow volume (F_{OI}). This concentration is representative of other similar watersheds in the vicinity for which salinity measurements are available. The other outflow load (L_{OO}) was estimated by applying the monthly concentration at the downstream gage each month. The 1964-1986 means of the other inflow load (L_{OI}) and other outflow load (L_{OO}) for the Glen Rose to Whitney reach are 7,139 and 3,103 tons/month.

The other load (L_X) term is the additional load difference required to balance the load budget for the South Bend to Graford (Lake Possum Kingdom) and Glen Rose to Whitney (Lake Whitney) reaches. The 1964-1986 mean load difference was calculated by summing the 1964-1986 means of the other components and then distributing to the 276 individual months. The load balances are achieved automatically in the computational algorithms for the other two reaches. The other loads (L_X) required to balance the load budgets for the South Bend to Graford and Glen Rose to Whitney reaches are additional outflows of 12,787 and inflows of 1,298 tons/month, respectively. Ideally L_X should be zero. The L_X term represents inaccuracies in the other terms or additional loads not reflected in the other terms. There are no outflow volumes in the volume budget corresponding to the L_X load losses.

The salinity budget for Lake Whitney was further adjusted to match the volume-weighted storage concentration determined by the USGS based on lake water quality surveys performed at 30 points in time between September 1970 and May 1980. The adjustments involved changing the timing of load inflows and outflows as necessary to match the observed storage concentrations.

Reservoir Storage Volumes, Loads, and Concentrations

The computed reservoir storage concentrations are volume-weighted mean end-of-month concentrations. Impoundment of water Lakes Possum Kingdom, Granbury, and Whitney began in 1941, 1970, and 1951, respectively. A sediment survey in 1974 indicated that the storage capacity of Possum Kingdom Lake had decreased significantly since initial impoundment in 1941.

End-of-month storage loads and volume-weighted storage concentrations were computed for the three reservoirs. The computations for Lake Granbury are very different than for Lake Possum Kingdom and Lake Whitney due primarily to differences in data availability but also due to the smaller size and later construction of Lake Granbury.

The unknown concentrations of water stored in Lakes Possum Kingdom and Whitney at the beginning and the end of the October 1963 to September 1986 period-of-analysis were set based on the corresponding observed outflow concentrations. This is the storage concentration at the beginning of October 1963 and the end of September 1986. The October 1963 beginning concentration in Possum Kingdom Reservoir was set equal to the mean outflow concentration during the first 21 months beginning in October 1963. The first 21 months represent the retention period during which the outflows sum to approximately the storage volume at the beginning of October 1963. Likewise, the October 1963 beginning concentration in Whitney Reservoir was set equal to the mean outflow concentration during the first 11 months beginning in October 1963. The September 1986 storage concentrations of both reservoirs were set equal to the September 1986 outflow concentrations.

Volume-weighted mean dissolved solids concentrations of storage in Lake Whitney and Lake Granbury are available from USGS reports as follows. Water quality surveys of Lake Whitney were performed on 30 dates between 1970 and 1980. Measurements were made in Lake Granbury on 28 dates between 1970 and 1979. Detailed information of salinity budget study are provided by the Texas Water Resources Institute (Wurbs et al., 2009).

4.2 Salinity Routing Calibration Study

WRAP-SALT Reservoir Salinity Routing Methodology

Salinity routing consists basically of computing the concentrations of the outflows from a reservoir. Reservoir outflow concentration refers to the monthly concentration of the regulated stream flow in the river downstream of the dam and the monthly concentration of the water withdrawn from the reservoir as lakeside diversions. The computed downstream river flows and lakeside diversions may have either the same or different concentrations.

Reservoir storage concentration is the volume-weighted concentration of the water stored in the reservoir either at the end of a month or the average of the beginning-of-month and end-of-month concentrations.

The WRAP-SALT salinity simulation methodology is summarized as follows. The outflow concentration (OC_M) in month M is computed as a function of storage concentration (SC_{M-L}) in month M-L (L months before month M). Lag L is an integer number of months.

$$OC_M = SC_{M-L} \tag{1}$$

$$OC_M = SC_{M-L} \times F_1 \left[1.0 + \left(\frac{V}{V_C} \right) (F_2 - 1.0) \right] \tag{2}$$

Equation 2 is an expanded version of Equation 1 with SC_{M-L} multiplied by a factor computed as a function of the two input parameters F_1 and F_2. With F_1 and F_2 defaults of 1.0, Equation 2 reduces to Equation 9. V_C in Eq. 2 is a storage volume entered as an input parameter which is typically the storage capacity of the reservoir. V is the average storage contents of the reservoir during the current month computed within WRAP-SALT. The ratio V/V_C represents storage contents as a fraction of capacity or other specified volume.

The lag (L) in months may be entered directly as an input parameter. Alternatively, the lag L may be computed internally within WRAP-SALT based on the concept of retention time.

$$\text{retention time } T_R \text{ in months} = \frac{\text{reservoir storage volume}}{\text{outflow volume per month}}$$

WRAP-SALT includes an algorithm for summing reservoir storage volume and outflow volume over multiple months for use in computing a retention time T_R. The lag time L is computed by WRAP-SALT as the following function of retention time T_R. L is truncated to an integer number of months. The multiplier factor F_L is an input parameter with a default of 1.0.

$$L = T_R\,(F_L) \tag{3}$$

Salinity routing in WRAP-SALT is based on Eq. 1 which can optionally be expanded to Eq. 2. Two approaches are available for setting the lag parameter L. The first option is for L to be a constant integer provided by the model-user as an input parameter. The second option is for L to be computed within WRAP-SALT based on Equation 3 with the parameter F_L provided by the user as an input parameter. With the second option, the lag is allowed to vary from month to month. Another option provides additional flexibility for using mean monthly versus beginning-of-month storage concentrations in the computation of outflow concentrations.

With a zero for the lag L, and 1.0 for F_1 and F_2, the reservoir outflow concentration equals the storage concentration. The parameters F_1 and F_2 allow the outflow concentration to differ from the storage concentration. The optionally either constant or variable lag L accounts for the time required for salinity entering a reservoir to be mixed and transported through the reservoir.

Summary and Conclusions of the Salinity Routing Parameter Calibration Studies

A WRAP-SIM and SALT input dataset was created based on the water and salinity budget data. The dataset is designed for the sole purpose of testing the salinity routing methods and calibrating the salinity routing parameters. The salinity input dataset serves a completely different purpose and is totally different from the salinity dataset.

The dataset for investigating computational methods and input parameters for routing salinity through reservoirs incorporates the volume and salinity budget results for six reaches of the Brazos River between the Seymour and Whitney gaging stations. These reaches contain Lakes Possum Kingdom, Granbury, and Whitney. The volume budget data are converted into a WRAP-SIM simulation results output file and WRAP-SALT salinity input file. The program SIM output file read by program SALT precisely reproduces the volume budget. All TDS load and flow volume inflows and outflows other than the flows in the river below the dams are aggregated together in the SIM output and salinity input files read by SALT. Thus, SALT computes volume-weighted storage loads and concentrations and the loads and concentrations of the river flows below the dams with all other variables fixed to perfectly match the results of the volume and load budget study. Computed storage and outflow concentrations from the WRAP-SALT simulation results can be compared with the measurement-based data from the salinity budget study.

The WRAP-SALT reservoir salinity routing procedure is based on Equations 1, 2, and 3 and associated input parameters. There are two different aspects of salinity routing with one aspect represented by the lag options and the other represented by the factors F_1

and F_2 in Equation 2. The lag parameter and lag options control the timing (lag time) features of the WRAP-SALT algorithms for routing salinity through reservoirs. The parameters F_1 and F_2 address differences between the long-term levels of volume-weighted outflow concentrations versus volume-weighted storage concentrations reflecting losses or gains of salinity load in the reservoir.

The concept of lag time addresses the issue of the time required for entering salt loads to be transported through a large reservoir. Lag options have been extensively investigated in this study based on the initial premise that lag time is an important key consideration in salinity routing. However, this was found to not be the case for the two reservoirs analyzed. Lag times of zero or one month were found to be optimal for Possum Kingdom and Whitney Reservoirs. These reservoirs can probably be best simulated without activation of the lag options (zero lag). If the lag option is activated, the optimal lag is one month. A reasonable approach is to adopt the beginning-of-month option combined with zero lag.

4.3 Simulation of the Brazos River/Reservoir System

The Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System consists of the generalized Water Rights Analysis Package (WRAP) river/reservoir system simulation model and input datasets for the 23 river basins of Texas. The WAM System is routinely applied by agencies and consulting firms in regional and statewide planning studies and administration of the water rights permit system, but without consideration of salinity.

The simulation model provides capabilities for computing frequency statistics of salinity concentrations and water supply reliability indices for alternative scenarios of water management and use.

The computer program WRAP-SALT is the salinity simulation component of the WRAP modeling system. SIM is the basic simulation model that simulates river basin hydrology, water control infrastructure, river/reservoir system operations, water allocation systems, water use scenarios, and water management strategies. SALT reads a SIM simulation results output file and salinity input file and tracks salt loads and concentrations through a river/reservoir system. The WRAP program TABLES is used to develop frequency tables and reliability indices and otherwise organize the simulation results from SIM and SALT. The software is documented in detail by a set of reference and users manuals.

The TCEQ WAM System includes variations of WRAP input datasets for the Brazos River Basin for authorized use and current use scenarios. The TCEQ WAM System current use dataset contains 3,834 control points and 711 reservoirs. A condensed WRAP input dataset focusing on the Brazos River Authority System was recently developed at Texas A&M University that contains 48 control points and 14 reservoirs. The impacts of all other water users and water management activities on the Brazos River Authority System are reflected in the stream flow input data in the condensed dataset. Another version of the condensed dataset was developed for this study which incorporated actual recorded water use of Brazos River Authority customers during 2008.

WRAP-SALT combines a SIM simulation results output file and salinity input SIN file. A single salinity input file was developed which is applicable with any of the SIM input datasets. Developing WRAP-SALT simulation algorithms and a Brazos River Basin salinity input dataset that can be combined with variations of any of the available WRAP-SIM datasets was a key objective of the study which was successfully accomplished. The same SIN file is applied with a complete Brazos WAM (Bwam8) dataset with 3,834 control points and 711 reservoirs and the Brazos River Authority Condensed (BRAC8) dataset with 48 control points and 14 reservoirs.

Table 2. Ten alternative simulations

Simulation	WRAP-SIM Input Data	Simulation Period	Description
1	Bwam8	1940-2007	TCEQ WAM current use dataset.
2	Bwam8	1900-2007	TCEQ WAM current use dataset.
3	BRAC8	1940-2007	BRA Condensed BRAC8 current use dataset.
4	BRAC2008	1940-2007	BRAC2008 dataset with 2008 water use.
5, 6, 7, 8, 9	BRAC2008	1940-2007	Multiple-reservoir system operations.
10	BRAC2008	1940-2007	Natural salt pollution control impoundments.

Simulations 1 and 2 demonstrate that WRAP-SALT can be effectively applied with a complex TCEQ WAM System dataset for a large river basin. Simulations with 1900-2007 and 1940-2007 hydrologic periods-of-analysis yield similar results. Results for both simulations appear to be reasonable. The 1940-2007 simulation was adopted for the remaining simulations since the naturalized flows for 1900-1939 are based on fewer stream gaging stations than the later flows.

Simulation 3 confirms that the model works fine with a condensed dataset. The results for simulations 2 and 3 with the Bwam8 and BRAC8 dataset match closely.

Simulation 4 with the BRAC2008 dataset is designed to combine actual current water resources development, management, and use with historical 1940-2007 natural river basin hydrology. The discharge-weighted 1940-2007 mean regulated flow concentration at the Richmond gage on the lower Brazos River is 358 mg/l in the BRAC2008 simulation 4 as compared to a 1964-1986 mean of 339 mg/l for observed concentrations. The current conditions simulated concentrations are expected to be somewhat greater than the 1964-1986 observed concentrations due to increased water supply diversions from the low-salinity tributaries and increased reservoir surface evaporation with the construction of additional reservoirs during and after the 1964-1986 period of the USGS water quality sampling program. The 1940-2007 hydrologic period-of-analysis also includes the 1950-1957 drought. Simulation results show a significant increase in concentrations during the 1950-1957 drought and other extended periods of low flows.

Simulations 5, 6, 7, 8, and 9 were performed to explore the effects on salinity concentrations of multiple-reservoir system operations. The concentrations of water supply diversions and stream flows along the lower Brazos River should be dependent on whether reservoir releases for the downstream diversions are from the reservoirs on the low-salinity tributaries or Lakes Possum Kingdom, Granbury, and Whitney on the upper Brazos River. The BRAC2008 simulations indicated little difference in lower Brazos River salinity concentration statistics with different multiple-reservoir system operating strategies. Reservoir releases for lower basin water supply diversions are a relatively small portion of the flow of the lower Brazos River most of the time. The sensitivity of lower Brazos River concentrations to different multiple-reservoir system operating strategies was demonstrated in increase with a large increase in diversions from the lower Brazos.

The Corps of Engineers during the 1970's−1980's performed investigations of alternative measures for controlling natural salt pollution in the Brazos River Basin. Primary salt source areas were identified. The studies resulted in a recommendation to construct a system of three dams on small tributaries of the Salt Fork and Double Mountain Forks of the Brazos River to impound runoff from key salt source watersheds. The salt control plan was never implemented due to economic, financial, and other constraints.

Simulation 10 consists of adding the three salt control impoundments to the

BRAC2008 model. The simulation is based on the premise that all flows and loads at gaging stations near the sites of the salt dams are permanently prevented from entering the Brazos River. Simulation results indicate that reductions in salt concentration could potentially be significant. Of course, simulation results always reflect the premises and approximations incorporated in the model. The question of natural loss of portions of the salt load even without the salt dams is pertinent. Model estimates of losses of salt load along the length of the river and in the reservoirs are uncertain.

TDS concentrations with and without the proposed salt control impoundments are compared as follows.

Simulation	4	4	10	10
Without or With Salt Dams	without	Without	with	with
Exceedance Frequency	50%	10%	50%	10%
		Concentration (mg/l)		
Seymour Gage on Brazos River	5,932	11,123	3,689	6,849
Possum Kingdom Reservoir	1,675	2,133	1,210	1,540
Granbury Reservoir	1,239	1,994	938	1,468
Whitney Reservoir	890	1,468	715	1,106
Bryan Gage on Brazos River	414	905	372	741
Hempstead Gage on Brazos River	369	790	336	639
Richmond Gage on Brazos River	354	763	325	627

The table compares the concentrations of reservoir storage and stream flows that are equaled or exceeded during 50 percent (median) and 10 percent of the 816 months of the 1940-2007 hydrologic period-of-analysis for the two alternative simulations without and with the proposed salt control dams. The table also illustrates the decrease of TDS concentrations in a downstream direction. Without the system of three salt control impoundments, the estimated median storage concentration of Possum Kingdom Lake is 1,675 mg/l compared with an estimated 1,210 mg/l with the proposed salt control project.

The median concentration of the flow at the Richmond gage is estimated to be 354 mg/l and 325 mg/l without and with construction of the proposed project.

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