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Incorporation of salinity in Water Availability Modeling

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SUMMARY

Natural salt pollution from geologic formations in the upper watersheds of several large river basins in the Southwestern United States severely constrains the use of otherwise available major water supply sources. The Water Rights Analysis Package modeling system has been routinely applied in Texas since the late 1990s in regional and statewide planning studies and administration of the state's water rights permit system, but without consideration of water quality. The modeling system was recently expanded to incorporate salinity considerations in assessments of river/reservoir system capabilities for supplying water for environmental, municipal, agricultural, and industrial needs. Salinity loads and concentrations are tracked through systems of river reaches and reservoirs to develop concentration frequency statistics that augment flow frequency and water supply reliability metrics at pertinent locations for alternative water management strategies. Flexible generalized capabilities are developed for using limited observed salinity data to model highly variable concentrations imposed upon complex river regulation infrastructure and institutional water allocation/management practices.

1. Introduction

The Texas Commission on Environmental Quality (TCEQ), in collaboration with the Texas water management community, maintains a Water Availability Modeling (WAM) System used in the administration of the state's water rights permit system, regional and statewide planning, and other activities (Wurbs, 2004). The TCEQ WAM System consists of the generalized Water Rights Analysis Package (WRAP) river/reservoir system water management simulation model and WRAP hydrology and water rights input files for the 23 river basins of Texas. The WRAP modeling system is generalized for application to river/reservoir systems located anywhere in the world, with input datasets being developed for the particular river basin of concern. For WRAP simulation studies assessing water availability and supply reliability in Texas, readily available TCEQ WAM System data files are altered as appropriate to reflect proposed water management plans of interest. These plans could involve changes in water use or reservoir system operating practices, construction of new facilities, or other water management strategies.

The WRAP/WAM modeling system, as routinely applied since the late 1990s, has not included consideration of water quality. However, natural salt pollution originating in the upper watersheds of several river basins in Texas and neighboring states severely constrains municipal, industrial, and agricultural use of large quantities of water otherwise available in major river/reservoir systems. Ecosystems are also significantly affected by salinity. The natural salt pollution motivated the recent development of a salinity tracking component of the WRAP modeling system. Salinity concentration frequency statistics are determined at locations of interest throughout a river system for alternative water use scenarios and water management plans. This paper describes the generalized salinity simulation model and its application to the Brazos River Basin of Texas.

The salinity simulation component of the WRAP modeling system and strategies for developing input data address the following complexities:

(1) Complex physical infrastructure and institutional water allocation/management practices are modeled in detail in the Texas WAM System. The added salinity features must be compatible with the WRAP/WAM framework for modeling water development and management.
(2) Salinity loads and concentrations resulting from natural salt pollution in Texas and neighboring states exhibit extreme variability both spatially and temporally.
(3) The generalized modeling system must provide flexibility to facilitate optimal use of limited observed salinity data, with data availability varying greatly between river basins, in combination with water management and hydrology datasets from the WAM system.

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2. Natural salt pollution in the Southwestern United States

The Arkansas, Brazos, Canadian, Colorado, Pecos, and Red Rivers shown in Fig. 1 and their tributaries supply agricultural, municipal, industrial, and environmental water needs in the states of Arkansas, Colorado, Kansas, Louisiana, New Mexico, Oklahoma, and Texas. Water management and use are governed largely by salinity in these river basins. The primary sources of salt loads in the rivers are geologic formations underlying portions of their upper watersheds.

This region was covered by a large inland sea during the Permian age about 230 million years ago (Rought, 1984). Thick deposits of halite were formed as evaporating seawater precipitated salts. Much of the salt loads in the rivers originate from formations at shallow depths within the Permian Basin geologic region delineated in Fig. 1. Salt flats, springs, and seeps in their upper watersheds contribute large salt loads to the rivers consisting largely of sodium chloride with moderate amounts of calcium sulfate and other minerals. Small tributary streams in some of the primary salt source areas have dissolved solids concentrations that sometimes exceed that of seawater. Salt concentrations in the downstream reaches of the rivers decrease with dilution from low-salinity tributary inflows.

The US Army Corps of Engineers (USACE), Bureau of Reclamation, US Geological Survey, state water agencies, river authorities, and university researchers have conducted extensive natural salt pollution control studies for these river systems dating back to the 1950s and continuing today. Many salinity control projects have been proposed, and some have been implemented (Wurbs, 2002).

Lake Texoma on the Red River and Lake Meredith on the Canadian River are examples of the many major reservoirs for which water supplies are greatly constrained by salinity. The USACE multiple-purpose Lake Texoma, the largest reservoir in Oklahoma and Texas in terms of total flood control and conservation storage capacity, has been used primarily for hydropower and flood control, but water supply use of the project is increasing with intensifying water demands. Salinity control measures implemented in primary salt source subwatersheds upstream of Lake Texoma include a ring containment levee around a salt spring and a brine impoundment dam on a tributary stream. A shallow-well brine collection and deep-well injection system near the Texas–New Mexico border reduces salt inflows to Lake Meredith, which is operated by the Canadian River Municipal Water Authority to supply 11 member cities. Several desalination plants are in operation for municipal and industrial water supply from the Red, Brazos, and other rivers. Blending of water from different sources of low and high salinity is also common.

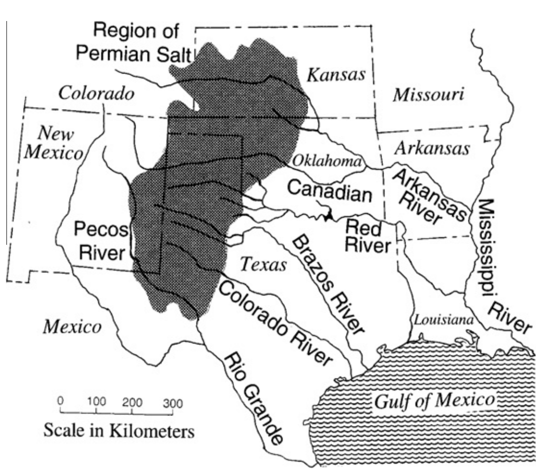

Fig. 1. Major rivers in the Southwest subject to Permian Basin salt pollution.

3. Water Rights Analysis Package (WRAP) modeling system

The WRAP modeling system simulates water resources development, management, regulation, and use in a river basin or multiple-basin region under priority-based water allocation systems. The generalized model facilitates assessments of hydrologic and institutional water availability and reliability in satisfying requirements for municipal, industrial, and agricultural water supply, hydroelectric energy generation, environmental instream flows, and reservoir storage. Basinwide impacts of water resources development projects and management practices are modeled. WRAP and its application in the TCEQ WAM System are described by Wurbs (2004). The public domain WRAP software and documentation (Wurbs, 2011) are available at http://ceprofs.tamu.edu/rwurbs/wrap.htm which connects with the TCEQ WAM website providing input datasets for Texas river basins and information regarding application of WRAP in Texas.

Recently developed WRAP salinity modeling capabilities are described by a reference and users manual (Wurbs, 2009). Concentration frequency statistics are computed for locations of interest in a river system for alternative water development and management scenarios. Though motivated primarily by natural salt pollution, WRAP water quality modeling features are applicable to essentially any conservative water quality constituent. The Brazos River studies discussed in this paper focus on total dissolved solids (TDS), though the available observed data also includes chloride and sulfate which can be modeled as individual constituents.

WRAP is a set of executable computer programs of which the following are applicable to simulating salinity. WinWRAP is a user interface for executing the programs on microcomputers within Microsoft Windows®. SIM performs the river/reservoir/use system water allocation simulation for a hydrologic period-of-analysis of any number of years using a monthly time step. Program SALT reads a SIM simulation results output file and salinity input file and tracks salt loads and concentrations through a river/reservoir system. Program TABLES organizes SIM and SALT simulation results and develops frequency relationships, reliability indices, and summary statistics. SIM and SALT simulation results are also optionally recorded in binary data storage system format for plotting or manipulation with HEC-DSSVue (USACE, 2009).

Incorporation of salinity tracking features directly into the simulation program SIM was explored. However, development of SALT as a separate program was found to be advantageous. SIM is very complex in its simulation of the details of water allocation and management. Developing SALT as a post-simulation salinity tracking model greatly simplifies the modeling system with no significant loss of modeling flexibility.

The WRAP-SIM simulation starts with sequences of monthly naturalized flows at all locations of interest, called control points, and computes regulated flows. Naturalized stream flows represent natural conditions unaffected by human water resources development and use. The regulated stream flows computed in the simulation represent actual flows which reflect the effects of water development and use.

The WRAP program SALT reads a salinity input file along with simulation results from an output file created by the WRAP program SIM. The SIM simulation results provided to SALT are organized by control point locations and consist of monthly time series covering the multiple-year hydrologic period-of-analysis. These SIM simulation results include monthly volumes of naturalized flows, regulated flows, water supply diversions, return flows, channel losses, channel loss credits, and net reservoir surface evaporation less precipitation. Beginning-of-simulation storage volumes and storage volumes at the end of each month of the simulation are also provided for reservoirs. Channel losses are the portions of upstream inflows that are loss in the reach below a control point as computed within SIM. Channel loss credits are reductions in downstream channel losses associated with diversions and refilling of reservoir storage.

4. Salinity simulation features of the WRAP modeling system

4.1. WRAP-SALT input datasets

The WRAP program SALT is designed to provide flexibility in combining the simulation results from Texas WAM System or other SIM input datasets, which may be large and complex, with available salinity data which varies in format and quantity between different river basins. The spatial configuration of a system of river reaches and reservoirs is modeled as a set of control points. Either concentrations or loads are specified for either incremental inflows or total flows at each control point as monthly time series spanning the hydrologic period-of-analysis, or alternatively a constant concentration is applied to all months of the period-of-analysis.

The salinity input file contains loads or concentrations of inflows during each month of the hydrologic period-of-analysis and reservoir storage at the beginning of the simulation. WRAP-SALT tracks the loads and concentrations of TDS or constituents thereof through a system of river reaches and reservoirs subject to water supply diversions and return flows and reservoir system operations. Salt loads associated with various components of inflow, outflow, and storage are mixed and transported along with the water. Load losses and gains can also be specified as a percentage of stream flow loads and reservoir storage loads.

Salinity inflow data may be limited to a subset of the control points included in the SIM model, depending on data availability and study scope. The SIM simulation may include any number of control points located downstream of the control point defining a SALT upstream salinity boundary on a main-stem river or tributary, above which the salinity tracking computations are not performed. Another key option allows concentrations input for a control point to be repeated for any number of other control points automatically within the model.

A salinity input dataset includes: beginning-of-simulation storage concentration for each reservoir; salinity concentrations or loads associated with incremental stream inflows at pertinent control points for each month of the hydrologic period-of-analysis; specifications for alternative options for assigning concentrations to water supply diversions, return flows, and channel losses and loss credits; specification of additional load losses not associated with volume losses as a function of either inflow or storage loads; and specifications for routing salt through reservoirs.

4.2. Salinity routing options

WRAP-SALT computes salt loads and concentrations for each control point of a river/reservoir system for inflows and outflows and end-of-month reservoir storage for each month of the hydrologic period-of-analysis, for given loads entering the system. River reaches connect control points. The mass balance algorithms proceed from upstream to downstream, with outflow from one river reach contributing to inflow to the next downstream reach. In a given month, for each control point in sequence, the inflow loads are first computed. Loads and concentrations of outflows and reservoir storage at the control point are then determined. Complete mixing during the month is assumed at locations without reservoir storage. A set of options is provided in the model for routing salinity through reservoirs.

Hendrick (1973) and Tanji (1981) summarize general approaches for modeling mixing and movement of salinity in reservoirs that range from assuming complete mixing during the computational time step to various methods for simulating stratification and transport. Prairie and Rajagopalan (2007) review models dealing with interactions between salinity and water management in major river basins in the western United States and present methods for stochastically generating salinity loads. Imberger (1981) modeled salinity transport through a single reservoir at a daily time step considering thermal stratification. Zhang et al. (2010) coupled daily time step water quantity and quality models to analyze the impact of various pollutants on water allocation in a river system. After comparing methods for modeling salinity transport through three large reservoirs on the Rio Grande based alternatively on (1) assuming complete mixing, (2) a two layer model with the top layer subject to evaporation and precipitation and the bottom layer subject to percolation, and (3) variations thereof, Inosako et al. (2006) conclude that any of the models can adequately simulate reservoir salinity with the choice between methods depending largely on the availability of data.

WRAP-SALT provides flexibility for applying the options outlined below for routing salinity through reservoirs. However, detailed calibration analyses for the Brazos River Basin study resulted in the conclusion that the more complex options provided little or no improvement over the default option based on complete mixing during the monthly time step.

SALT computes end-of-month reservoir storage concentrations as total salt storage divided by total volume in storage. In reality, concentrations vary spatially, both horizontally and vertically, throughout a reservoir. Streams carry salt loads into the upper reaches of a large reservoir, and mixing occurs over time. The lag features outlined below facilitate modeling spatially varying concentrations with a monthly model based on volume-weighted concentrations.

With optional lag features activated, the WRAP-SALT strategy for routing salinity through a reservoir is based on maintaining two load budgets. The regular load budget reflects the actual total salt mass in storage. The second conceptual computational mass budget based on lagged load inflows is maintained solely for the purpose of determining the outflow concentration each month. The timing of the load inflow to this computational mass-budget reservoir is controlled by a lag parameter with units of months. The lag may be a user-specified constant or alternatively computed within the model each month based on retention time.

Two different reservoir outflow concentrations for downstream releases and lakeside diversions are computed using the following equation.

$$\mathrm{OC_M} = \mathrm{SC_{M-L}} \times F_1\left[1.0 + \left(\frac{V}{V_C}\right)(F_2 - 1.0)\right] \quad (1)$$

$\mathrm{OC_M}$ denotes the mean outflow concentration in month M, and $\mathrm{SC_{M-L}}$ is the volume-weighted storage concentration in month $\mathrm{M-L}$ which is L lag months before month M. V is the average storage volume contents of the reservoir during the current month. V_C is the storage capacity. Input parameters F_1 and F_2 may vary for lakeside diversions versus downstream releases. F_1 and F_2 are optional calibration parameters, with defaults of 1.0 designed to remove terms in Eq. (1), that allow for variations between outflow and lagged storage concentrations.

With F_1 and F_2 defaults of 1.0 and a lag L default of zero, Eq. (1) reduces to Eq. (2) where the outflow concentration in month M equals the storage concentration. Calibration studies resulted in adoption of Eq. (2) for the Brazos River reservoirs.

$$\mathrm{OC_M} = \mathrm{SC_M} \quad (2)$$

5. Brazos River Basin hydrology, water rights, and salinity datasets

The Brazos River Basin served as a case study for developing and testing the new salinity modeling capabilities (Wurbs and Lee, 2009; Lee, 2010). Further applications to the Brazos River Basin are continuing. The following discussion addresses compilation and analyses of available observed salinity data, development of a SALT salinity input dataset, adoption of alternative versions of SIM input datasets, and simulations for alternative water development and use scenarios. The simulation study includes assessments of the impacts of multiple-reservoir system operations and proposed salt control impoundments on downstream salinity concentrations. A key modeling consideration was flexibility for combining the same salinity input dataset with both the full TCEQ WAM System WRAP-SIM datasets and alternative condensed versions that focus on a reservoir system operated by the Brazos River Authority (BRA).

5.1. WRAP-SIM input datasets for the Brazos River Basin

The 118,000 km^2 Brazos River Basin extends from New Mexico southeasterly across Texas to the Gulf of Mexico. Climate, vegetation, topography, land use, and water use vary greatly across the basin. Mean annual precipitation varies from 48 cm in the upper basin which lies in the High Plains to 115 cm in the lower basin in the Gulf Coast Region.

Over a thousand water districts, cities, companies, and individuals hold water right permits to use the waters of the Brazos River and its tributaries. The BRA owns and operates Possum Kingdom, Granbury, and Limestone Reservoirs and has contracted with the Corps of Engineers for the conservation storage capacity of nine federal multiple-purpose reservoirs listed in Table 1. Water rights associated with the 14 reservoirs listed in Table 1 account for 75% of the conservation storage capacity of the 711 permitted reservoirs and 33% of the permitted annual water supply diversion volume in the basin.

The TCEQ WAM System contains WRAP input datasets for each of the river basins of Texas for two alternative water use scenarios, authorized and current. The authorized use scenario is based on the premise that all permanent water right permit holders appropriate the full amount of water legally authorized by their permits each year. The current use scenario represents a best estimate of actual water use in recent years which, for the Brazos River Basin, is significantly less than authorized use.

The authorized and current use scenario WAM System datasets for the Brazos River Basin and adjoining coastal basin contain 77 primary control points for which naturalized flows are provided

Table 1
Reservoirs in the BRAC2008 dataset.

Reservoir	Stream	Watershed area (km^2)	Storage capacity	
			Conservation (Mm^3)	Flood Cont (Mm^3)
Brazos river authority and corps of engineers				
Possum Kingdom	Brazos River	61,700	681	–
Granbury	Brazos River	66,900	164	–
Whitney	Brazos River	70,600	692	1693
Aquilla	Aquilla Creek	2510	51.4	107
Waco	Bosque River	4290	255	683
Proctor	Leon River	3270	67.5	383
Belton	Leon River	9170	534	790
Stillhouse Hollow	Lampasas River	3420	277	482
Georgetown	San Gabriel R.	642	45.6	108
Granger	San Gabriel R.	1910	62.3	200
Limestone	Navasota River	1750	257	–
Somerville	Yequa Creek	2610	190	417
West Central Texas municipal water district				
Hubbard Creek	Hubbard Creek	2820	392	–
Comanche Peak nuclear power plant				
Squaw Creek	Squaw Creek	–	186	–

Table 2
BRAC2008 water supply diversions.

Water supply diversion location	Water supply diversions (1000 m^3/year)				
	Industrial	Irrigation	Mining	Municipal	Total
Diversions sites on Brazos River					
Lake Possum Kingdom	1250	396	1520	1730	4900
Between Lakes P.K. and Granbury	0	138	2870	0	3000
Lake Granbury	63,200	3810	133	853	76,800
Between Lakes Granbury and Whitney	0	127	1240	0	1360
Lake Whitney	1290	970	37	16	2310
Between Lake Whitney and Hempstead	0	2850	0	401	3250
Brazos River at Hempstead gauge	44,300	37	0	0	44,400
Brazos River below Hempstead gauge	0	286	0	0	286
Diversion sites on tributaries					
Lake Hubbard Creek on Hubbard Creek	1270	916	1250	8810	12,250
Lake Aquilla on Aquilla Creek	0	0	0	7050	7050
Lake Proctor on Leon River	0	5480	0	3330	8800
Leon River between Proctor and Belton	0	252	0	7740	7990
Lake Belton on Leon River	0	0	0	53,300	53,300
Lake Stillhouse Hollow on Lampasas R.	0	69	0	33,000	33,100
Lake Georgetown on San Gabriel River	0	0	0	16,600	16,600
Lake Granger on San Gabriel River	0	1	0	3460	3460
Sites on Little River Below Lakes	3220	263	26	0	3510
Lake Somerville on Yequa Creek	0	0	0	4320	4320
Lake Limestone on Navasota River	40,000	0	6	223	40,200
Navasota River below Lake Limestone	4520	0	0	0	4520
Totals	159,000	15,600	8270	149,000	331,000

as an input file and over 3000 secondary control points at which naturalized flows are synthesized as the WRAP-SIM simulation model is executed. Most of the 77 primary control points are sites of gauging stations. The secondary control points are locations of dams, diversions, return flows, instream flow requirements, stream confluences, and other sites of potential interest. The current use scenario version of the Brazos WAM contains 711 reservoirs, 1725 diversion targets, numerous return flow sites, and 144 sets of environmental instream flow requirements. The hydrologic period-of-analysis for the official Brazos WRAP input dataset in the TCEQ WAM System is 1940–1997, but has been extended to 1940–2007 in the condensed dataset described next.

The large complex Brazos model is necessary for the planning and water right permitting applications for which the WAM System was developed. However, a much simpler model focused on the BRA reservoir system facilitates BRA operational planning studies. Wurbs and Kim (2011) developed and applied a methodology for simplifying WAM System datasets to focus on management of a particular reservoir system. Selected water rights, control points, and reservoirs are removed with their effects retained in the stream inflow input data file for the condensed dataset. The Brazos River Authority Condensed (BRAC) datasets developed based on modifying the Brazos WAM authorized use scenario and current use scenario datasets contain 48 primary control points and no secondary control points. The stream inflows at the 48 control points reflect the effects of the numerous water rights, reservoirs, and control points removed from the Brazos WAM dataset. Wurbs and Kim (2011) also developed and applied a methodology for extending the simulation period from 1940–1997 to 1940–2007.

A single salinity input file was developed which is applicable with any version of either the full TCEQ WAM System or condensed BRAC datasets. The majority of the simulations were performed with a version of the BRAC current use dataset, labeled BRAC2008, which reflects actual water use during the year 2008 which was a representative though drier than normal year.

The BRAC2008 SIM input dataset includes the 14 reservoirs and 2008 annual water supply diversions in Tables 1 and 2. Diversions vary seasonally over the year. The BRA operates a desalination plant to treat water from Lake Granbury to supply the City of Granbury and vicinity. The BRA also transports by pipeline diversions from Lake Granbury to Squaw Creek Reservoir which provides cooling water for the Comanche Peak nuclear power plant. Most of the other water supply diversions supplied by the BRA multiple-reservoir system are from the lower Brazos River near the city of Houston or from low-salinity tributaries.

5.2. United States Geological Survey (USGS) salinity data

The USGS conducted an extensive salinity data collection program during October 1963 through September 1986 (water years 1964–1986) in support of natural salt pollution control studies performed by the USACE. USGS water quality sampling activities in the Brazos River Basin date back to 1906 and continue to the present. However, the salinity data collection program during 1964–1986 was much more extensive than salinity measurement activities before or since. The USGS compiled monthly TDS, chloride, and sulfate data for at least three years during 1964–1986 for 39 stations and for the entire 276 months of 1964–1986 for six of the sites, which include the Cameron, Seymour, Graford, Whitney, and Richmond gauges listed in Table 3 and shown in Fig. 2 and the Aspermont gauge located upstream of the Seymour gauge. Observed flows at these six stations extend from before 1940 to the present.

The 1964–1986 mean flows and TDS, chloride, and sulfate loads and concentrations at the Cameron gauge on the Little River and four Brazos River gauges are listed in Table 3. For comparison, the US Environmental Protection Agency secondary drinking water standards include a recommended maximum TDS limit of 500 mg/L. Mean 1964–1986 TDS concentrations in the Brazos River decrease from 3590 mg/L at the Seymour gauge to 339 mg/L at the Richmond gauge with dilution from tributary inflows. The flow and TDS load at the Seymour gauge are 3.9% and 41.3% as large as the flow and load at the Richmond gauge. The concentrations vary dramatically temporally as well as spatially as illustrated by the 1964–1986 mean monthly TDS concentrations at the Seymour gauge plotted in Fig. 3.

Table 3
Observed 1964–1986 mean flows, loads, and concentrations.

		TDS		Chloride		Sulfate	
USGS Gauge near City of	Flow (m^3/s)	Load (kg/s)	Conc. (mg/L)	Load (kg/s)	Conc. (mg/L)	Load (kg/s)	Conc. (mg/L)
Cameron	43.7	11.6	256	1.37	31	1.33	30
Seymour	7.62	27.5	3590	11.4	1480	5.33	696
Graford	20.2	31.2	1534	11.9	601	6.05	309
Whitney	34.8	32.6	928	12.0	342	6.26	178
Richmond	195	66.4	339	15.5	79	10.9	56

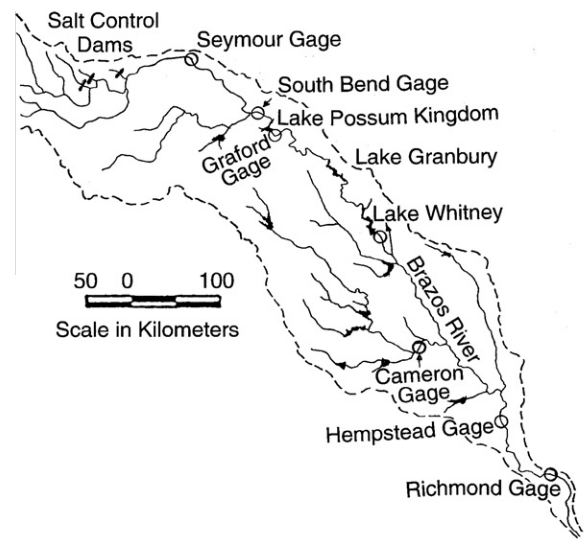

Fig. 2. Reservoirs, stream gauging stations, and proposed salt control dams.

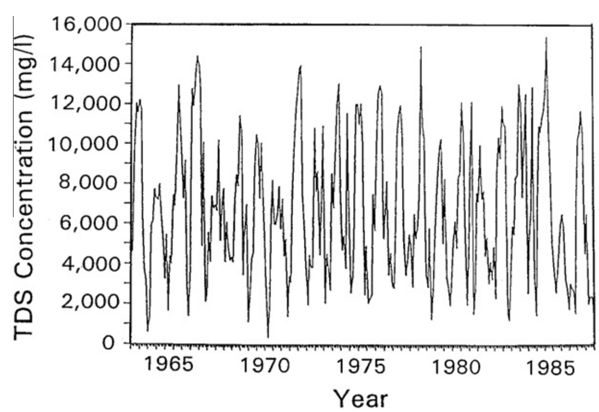

Fig. 3. Observed 1964–1986 monthly TDS concentrations at Seymour gauge.

5.3. WRAP-SALT salinity input file

Wurbs and Lee (2009) and Lee (2010) used USGS salinity data consisting of 276-month 1964–1986 sequences of observed

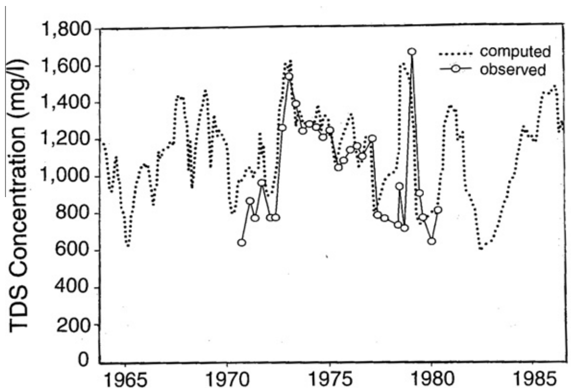

Fig. 4. Synthesized and observed mean TDS concentration in Lake Whitney.

monthly flows and monthly TDS loads and concentrations at a number of stations for two purposes. Firstly, a salinity budget analysis was performed for five sub-reaches of the 652 km long reach of the Brazos River extending from the Seymour gauge downstream to the Whitney gauge shown in Fig. 2. Secondly, a WRAP-SALT salinity inflow dataset was developed for the simulation period January 1940 through December 2007. This WRAP-SALT salinity input file is designed for use with either the complete TCEQ WAM System datasets for the Brazos River Basin or the BRA condensed datasets.

Volume and TDS load budgets for the 276 months of 1964–1986 were developed for five reaches of the Brazos River between the following gauging stations: Seymour–South Bend, South Bend–Graford, Graford–Dennis (upstream of Lake Granbury), Dennis–Glen Rose (below Lake Granbury), and Glen Rose–Whitney (below Whitney Dam). TDS loads and concentrations missing from the observed record at the gauges were synthesized by regression. Volume-weighted end-of-month salt contents and concentrations were computed for the three reservoirs. Computed mean monthly concentrations for Lake Whitney are plotted in Fig. 4 along with volume-weighted concentrations at 30 instances in time derived from reservoir salinity surveys performed by the USGS (Strause and Andrews, 1983). TDS concentrations in the lakes change dramatically as major rainfall events occur in different regions of their upstream watersheds that are and are not primary sources of salt.

The storage and flow concentrations were used in calibration analyses to determine values for the routing parameters in Eq. (1). However, the defaults reflected in Eq. (2) were ultimately concluded to represent the best approach for routing salinity through the Brazos River reservoirs. Concentrations simulated with WRAP using the defaults reflected in Eq. (2) are compared with observed concentrations at two USGS stream gauging stations in Figs. 5 and 6.

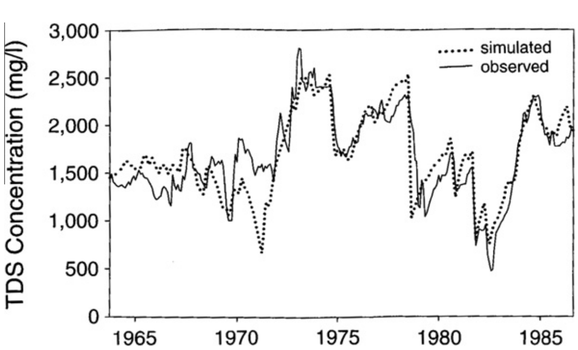

Fig. 5. Simulated and observed TDS concentrations at the Graford gauge.

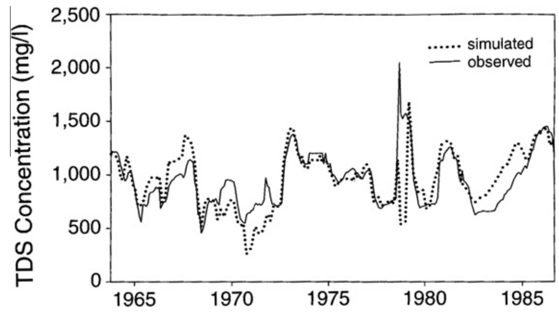

Fig. 6. Simulated and observed TDS concentrations at the Whitney gauge.

The WRAP enhancements reported here provide a flexible set of options for constructing a salinity simulation model which may be applied in various ways in different river basins depending on data availability, characteristics of salinity issues being addressed, and study objectives. In this study, the SIM simulation includes the entire Brazos River Basin. However, the SALT salinity tracking computations extend from the Seymour gauge on the Brazos River and Cameron gauge on the Little River to the outlet of the Brazos River at the Gulf of Mexico.

The SALT salinity input file includes one control point on the Little River and five control points on the Brazos River. Salinity inflows for each month of the 816-month January 1940 through December 2007 period-of-analysis are provided as follows.

Cameron gauge on Little River – constant concentration of 256 mg/L for regulated flows.
Seymour gauge on Brazos River – load series for regulated flows.
Graford gauge on Brazos River – concentration series for incremental inflows.
Whitney gauge on Brazos River – concentration series for incremental inflows.
Richmond gauge on Brazos River – concentration series for incremental inflows.
Outlet of Brazos River at Gulf of Mexico – constant 339 mg/L for incremental inflows.

The Cameron and Seymour gauge control points are upstream boundaries for the salinity simulation. The 1964–1986 observed mean of 256 mg/L at the Cameron gauge was judged to adequately represent the concentration of flows from the low-salinity Little River subbasin. Salinity loads at the Cameron gauge control point are determined within SALT by assigning a constant concentration of 256 mg/L to the regulated flows computed by SIM. Large salt loads enter the Brazos River above the Seymour gauge, but inflow volumes are relatively small and water supply diversions are negligible. Salinity loads at the Seymour gauge control point vary greatly between months and are read by SALT from the salinity input file.

The salinity input file contains a 1940–2007 sequence of monthly TDS concentrations assigned to the Graford gauge that are automatically repeated for all control points located upstream of the Graford gauge but downstream of the Seymour gauge. These are TDS concentrations of inflows that enter this portion of the river system. Likewise, incremental inflow concentrations at the Whitney and Richmond gauges are repeated at upstream control points. Local inflows from the small watershed below the Richmond gauge are assigned a constant concentration of 339 mg/L based on the 1964–1986 mean concentration.

TDS loads at the Seymour gauge and incremental inflow concentrations at the Graford, Whitney, and Richmond gauges for the 816-month 1940–2007 simulation period were developed in two steps. Firstly, flows, loads, and concentrations for 1964–1986 were compiled based on the USGS database and the load budget studies. Secondly, a linear interpolation algorithm was applied using 1964–1986 flows and loads combined with 1940–2007 naturalized flows from the WAM dataset to synthesize loads and concentrations for January 1940 through September 1963 and October 1986 through December 2007. The linear interpolation routine was based on sorting the tables of 1964–1986 flows and loads by increasing flow. Loads were then generated by numerically entering flow in the table to interpolate load. Linear and nonlinear regression techniques were also investigated. However, the linear interpolation algorithm was adopted because, unlike regression methods, the interpolation algorithm preserves the variability of concentrations.

The six control points included in the salinity file are a subset of both the over 3000 control points in the full Brazos WAM and the 48 in the condensed BRAC datasets. The SIM simulation is not altered in any way when combined with SALT salinity tracking. The same salinity input file is combined with simulation results from either the Brazos WAM or BRAC simulations. The repetitive assignment of incremental inflow concentrations within SALT occurs at many more control points when applying the Brazos WAM than with the BRAC model. WRAP-SALT results were found to be both reasonable and consistent when combining the salinity input file with SIM simulation results from either the Brazos WAM or BRAC datasets.

6. Brazos River Basin simulation study

Applications may require the full TCEQ WAM System datasets with all their complexities or may benefit from simpler condensed datasets. The WAM System authorized and current use datasets are adopted here to investigate impacts on salinity concentrations resulting from potential increases in water use. The BRAC datasets designed to support BRA operational planning studies are applied to explore the impacts on salt concentrations of proposed salt control impoundments and alternative multiple-reservoir system operating strategies.

6.1. Simulation results for the TCEQ WAM System datasets

The SIM simulations reflect over 3000 control points. TDS loads are provided at the Seymour gauge and TDS concentrations are provided for five other control points in the SALT salinity input file. These salinity concentrations are applied at 1938 and 1941 control points, respectively, in the authorized use and current use models. The 1940–1997 naturalized stream flows and salt loads entering the river system average 5590 million m^3/year and 1660 million kg/year for both the authorized and current use scenarios.

Water supply diversion targets in the authorized and current use simulations basinwide total 3040 Mm^3/year and 1880 Mm^3/year, respectively, as shown in Table 4. Thus, if all water supply diversion targets are increased to the maximum amounts legally authorized by the water right permits, the total of the diversions targets are 162% of the total current use scenario diversions. The mean diversion volumes constrained by water availability not considering salinity are 89.9% and 94.2% of the mean targets, respectively, for the authorized and current use scenarios. Mean annual total diversion amounts with TDS concentrations exceeding various concentrations ranging from 1000 mg/L to 2500 mg/L at the 1938 and 1941 control points included in the salinity simulation are also shown in Table 4.

Table 4
Summary of total water supply diversions.

Water use scenario	Authorized	Current
Diversion target (Mm^3/year)	3040	1880
Diversion (Mm^3/year)	2740	1770
Diversion shortage (Mm^3/year)	306	109
Diversion (Mm^3/year) with		
TDS Concentration ⩾ 1000 mg/L	494	242
TDS Concentration ⩾ 1500 mg/L	290	115
TDS Concentration ⩾ 2000 mg/L	95	37
TDS Concentration ⩾ 2500 mg/L	31	12

Table 5
Frequency statistics for TDS concentrations for TCEQ WAM datasets.

Model control point at stream gauge or lake	Weighted mean	Exceedance frequency for TDS concentrations				
		90%	75%	50%	25%	10%
Concentration (mg/L) for current use scenario						
Seymour gauge	3200	2000	3490	5750	8630	11080
South Bend gauge	1890	1320	2090	3550	5100	6130
Lake Possum Kingdom	1680	1090	1440	1720	1960	2240
Lake Granbury	1260	502	849	1190	1500	2140
Lake Whitney	951	592	719	913	1140	1480
Hempstead Gauge	375	137	208	376	599	917
Richmond Gauge	360	143	213	355	547	861
Concentration (mg/L) for Authorized Use Scenario						
Seymour gauge	3320	2150	3640	6040	8710	11,100
South Bend gauge	1890	1110	1840	3180	5540	9000
Lake Possum Kingdom	1670	1170	1430	1700	1970	2210
Lake Granbury	1400	345	740	1160	1540	2520
Lake Whitney	844	425	775	748	930	1270
Hempstead Gauge	349	140	206	341	557	847
Richmond Gauge	336	145	208	322	520	780

The authorized use scenario has significantly greater water supply diversion volumes and lower reservoir evaporation volumes than the current use scenario. Concentration frequency statistics from the simulation results are compared in Table 5. The weighted mean salinity concentrations of the Brazos River at and below Lake Whitney are lower for the authorized use than for the current use scenario due to the greater diversion of water from the high-salinity upper Brazos River.

Surface water use in Texas is increasing with population growth and declining groundwater reserves (Texas Water Development Board, 2007). The Texas Water Development Board is presently developing future-year scenario versions of the TCEQ WAM System datasets for use in regional planning studies. The new WRAP salinity simulation capabilities will allow assessments of the impacts of future increases in water use and associated water management plans on salinity concentrations.

6.2. Simulation results for the BRAC2008 dataset

TDS concentrations at the Hempstead gauge for the base BRAC2008 simulation are plotted as Fig. 7. Concentrations are extremely variable through the 1940–2007 simulation and increase significantly during the 1950–1957 most hydrologically severe drought-of-record.

The BRAC2008 dataset with the reservoirs and year 2008 diversions summarized in Tables 1 and 2 is designed for analyzing issues of concern in operating the BRA reservoir system. Two water management strategies addressed in the following discussion are multiple-reservoir system operations and construction of salt control impoundments.

Water supply diversions at the Hempstead and Richmond gauge control points represent 13.4% of the total diversions tabulated in Table 2. These diversions from the lower Brazos River are supplied by unregulated flows supplemented by releases from BRA

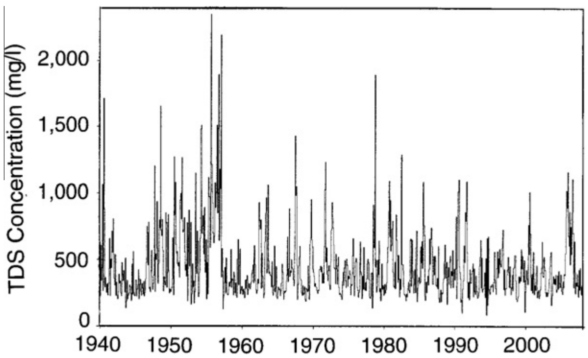

Fig. 7. Simulated mean monthly TDS concentrations at Hempstead gauge.

reservoirs located both on the high-salinity upper Brazos River and low-salinity tributaries. Alternative simulations with releases from the three main-stem Brazos River reservoirs versus releases from the tributary reservoirs resulted in only minimal differences in concentration frequency statistics for the lower Brazos River. Reservoir releases to meet these diversions at current levels of demand are a relatively small portion of the flow in the lower Brazos River most of the time.

Salt control measures have been proposed but not yet implemented in the Brazos River Basin. Although similar projects have been implemented in neighboring river basins, their implementation in the Brazos Basin has been constrained by economic, financial, and environmental considerations. The Corps of Engineers (McCrory, 1984) developed a plan during the 1970s consisting of three salt control impoundments that has been revisited periodically and is once again being addressed in regional planning studies.

Croton, Dove, and Kiowa Peak Lakes are proposed salt control impoundments on Croton, Salt Croton, and North Croton Creeks at the sites shown in Fig. 2. The proposed salt control dams would impound runoff from their respective watersheds which have been identified as encompassing primary salt source areas. The impounded water would be lost over time due to evaporation, with the remaining brine being permanently stored. USGS flow and salt load data collected near the impoundment sites were used to express flow and load losses due to the impoundments as a percentage reduction in flows and loads at the Seymour gauge control point. WRAP-SIM/SALT simulation results are summarized in Tables 6 and 7. The impoundments significantly impact simulation results. The median (50% exceedance frequency) TDS concentration of Lake Possum Kingdom is reduced from 1680 mg/L to 1210 mg/L. The median concentration at the Hempstead gauge is reduced from 369 mg/L to 336 mg/L.

Table 6
Simulated 1940–2007 mean flows, loads, and concentrations.

USGS gauge near city of	Without salt dams			With salt dams		
	Flow (m^3/s)	Load (kg/s)	Conc. (mg/L)	Flow (m^3/s)	Load (kg/s)	Conc. (mg/L)
Cameron	49.5	12.7	256	49.5	12.7	256
Seymour	8.99	29.4	3270	8.16	17.1	2100
Graford	24.1	42.5	1760	23.7	31.0	1310
Whitney	44.6	37.8	848	44.2	29.9	678
Richmond	216.9	77.7	358	216.5	69.6	322

Table 7
Frequency statistics for TDS concentrations.

Model control point at stream gauge or lake	Weighted mean	Exceedance frequency for TDS concentrations				
		90%	75%	50%	25%	10%
Concentration (mg/L) without salt control dams						
Seymour gauge	3270	2120	3570	5930	8780	11,100
South Bend gauge	1830	1380	1890	3020	4450	6140
Lake Possum Kingdom	1620	1070	1350	1680	1900	1130
Lake Granbury	1290	631	915	1240	1540	1990
Lake Whitney	979	580	717	890	1180	1470
Hempstead Gauge	370	231	276	369	528	790
Richmond Gauge	358	224	269	354	507	763
Concentration (mg/L) with salt control dams						
Seymour gauge	2100	1350	2190	3690	5360	6850
South Bend gauge	1310	1040	1420	2040	2930	3920
Lake Possum Kingdom	1190	813	1020	1210	1380	1540
Lake Granbury	971	516	722	938	1180	1470
Lake Whitney	776	458	583	715	929	1110
Hempstead Gauge	331	224	262	336	464	639
Richmond Gauge	322	217	255	325	453	627

7. Conclusions

Natural salt pollution severely constrains the water supply capabilities of major river basins in the Southwestern United States involving large volumes of water. The generalized WRAP modeling system has been expanded to include tracking salinity loads and concentrations through river/reservoir systems. The WRAP salinity simulation features are designed to provide flexibility in combining water quantity simulation datasets from the Texas Water Availability Modeling System or other sources, which may be quite complex, with available salinity data which varies in extent and format between different river basins. The Brazos River Basin case study illustrates modeling capabilities and issues addressed in developing salinity input datasets and incorporating salinity in water availability studies. The generalized WRAP software and modeling methods demonstrated by the Brazos River Basin study can be applied in other river basins in Texas or elsewhere in the world.

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References

Hendrick, J., 1973. Techniques for modeling reservoir salinity, Hydrology Paper No. 62, Colorado State University, Fort Collins, CO, USA, 50 pp.
Imberger, I., 1981. The influence of stream salinity on reservoir water quality. J. Agric. Water Manage. 4, 255–273.
Inosako, K., Yuan, F., Miyamoto, S., 2006. Simple methods for estimating outflow salinity from inflow and reservoir storage. J. Agric. Water Manage. 82, 411–420.
Lee, C., 2010. Impacts of natural salt pollution on water supply capabilities of river/reservoir systems. Ph.D. dissertation, Texas A&M University, College Station, TX, USA, 334 pp.
McCrory, J.A., 1984. Natural salt pollution control, Brazos River Basin, Texas. In: French, R.H. (Ed.), Salinity in Watercourses and Reservoirs. Buttersworth Publishers, Stoneham, MA, USA, pp. 135–144.
Prairie, J.R., Rajagopalan, B., 2007. A basin wide stochastic salinity model. J. Hydrol. 344, 43–54.

Rought, B.G., 1984. The Southwestern salinity situation: the Rockies to the Mississippi River. In: French, R.H. (Ed.), Salinity in Watercourses and Reservoirs. Buttersworth Publishers, Stoneham, MA, USA, pp. 125–134.
Strause, J.L., Andrews, F.L., 1983. Water quality of Lake Whitney. Open-File Report 82-677, US Geological Survey, Reston, VA, USA, 126 pp.
Tanji, K.K., 1981. River basin hydrosalinity modeling. J. Agric. Water Manage. 4, 207–225.
Texas Water Development Board, 2007. Water for Texas 2007. GP-8-1, vol. 1. Austin, TX, USA, 44 pp.
US Army Corps of Engineers, 2009. HEC-DSSVue HEC Data Storage System Visual Utility Engine, User's Manual. Hydrologic Engineering Center, Davis, CA, USA, 322 pp.
Wurbs, R.A., 2002. Natural salt pollution control in the Southwest. J. Am. Water Works Assoc. 94 (12), 58–67.
Wurbs, R.A., 2004. Modeling river/reservoir system management, water allocation, and supply reliability. J. Hydrol. 300 (2005), 100–113.
Wurbs, R.A., 2009. Salinity simulation with WRAP. TR-317, Texas Water Resources Institute, College Station, Texas, USA, 84 pp.
Wurbs, R.A., Lee, C., 2009. Salinity budget and WRAP salinity simulation studies of the Brazos river/reservoir system, TR-352. Texas Water Resources Institute, College Station, Texas, USA, 315 pp..
Wurbs, R.A., Kim, T.J., 2011. River flows for alternative conditions of water resources development. J. Hydrol. Eng. 16 (2), 148–156.
Wurbs, R.A., 2011. Water rights analysis package (WRAP) modeling system reference and users manuals. TR-255 and TR-256, 8th ed. Texas Water Resources Institute, College Station, Texas, USA, 548 pp.
Zhang, W., Wang, Y., Peng, H., Li, Y., Tang, J., Wu, K.B., 2010. A coupled water quantity–quality model for water allocation analysis. J. Water Res. Manage. 24, 485–511.