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Reservoir evaporation in Texas, USA

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SUMMARY

The role of reservoir surface evaporation in river/reservoir water budgets and water management is explored using a modeling system that combines historical natural hydrology with current conditions of water resources development and management. The long-term mean evaporation from the 3415 reservoirs in the Texas water rights permit system is estimated to be 7.53 billion m^3/year, which is equivalent to 61% of total agricultural or 126% of total municipal water use in the state during the year 2010. Evaporation varies with the hydrologic conditions governing reservoir surface areas and evaporation rates. Annual statewide total evaporation volumes associated with exceedance probabilities of 75%, 50%, and 25% are 7.07, 7.47, and 7.95 billion m^3/year, respectively. Impacts of evaporation are greatest during extended severe droughts that govern water supply capabilities.

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1. Introduction

Reservoir storage is essential for developing dependable water supplies and is a major component of the river system water budget. The storage contents of reservoirs fluctuate greatly over time with variations in water use and hydrologic conditions that range from severe multiple-year droughts to floods. Water surface evaporation typically represents a major component of the reservoir water budget. The impacts of reservoir evaporation on water management vary greatly with location with differences in climate, reservoir characteristics, and water management and use practices. An enhanced understanding of the relative magnitude of evaporation in reservoir/river system volume budgets is relevant to various aspects of water resources development, allocation, management, and use.

The research presented in this paper consists of simulating evaporation from the 3415 reservoirs in the Texas Water Availability Modeling (WAM) System and investigating the significance of reservoir evaporation in river system water budgets and water management. Climate, geography, and water management vary dramatically across Texas with reservoirs being managed under diverse conditions representative of many other regions of the world. The water management community of Texas invested much effort over many years to implement a statewide WAM System, maintained by the Texas Commission on Environmental Quality (TCEQ), to support administration of the water rights permit system, regional and statewide planning, and other water management endeavors. The modeling system made possible the research on reservoir evaporation presented in this paper.

Essentially all of the storage capacity in Texas is contained in man-made rather than natural lakes. Most of the dam and reservoir projects were constructed between 1945 and 1990, with the majority being completed after 1960. Thus, much of the present storage capacity did not exist during the 1950–1957 most hydrologically severe drought on record. The estimates of evaporation volumes presented here along with reservoir storage contents and stream flow and water use quantities are computed within the monthly computational time step TCEQ WAM System based on combining several decades of highly variable historical hydrology dating back to 1940 with present conditions of water resources development, management, and use. Simulation model hydrology includes naturalized stream flows developed based on adjusting observed flows to remove the effects of water development and a dataset maintained by the Texas Water Development Board (TWDB) of monthly evaporation rates extending from January 1940 to near the present derived from compiling and adjusting pan evaporation observations.

2. Other studies reported in the literature

Linsley et al. (1982) and Abtew and Melesse (2013) describe evaporation processes and measurement techniques. The use of evaporation pan measurements along with pan coefficients in the

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compilation of the TWDB statewide database of lake surface evaporation rates is consistent with conventional practices commonly adopted in hydrology and water management.

Lowe et al. (2009) assess the uncertainties associated with applying evaporation pan measurements to estimate evaporation volumes from water supply reservoirs. An uncertainty analysis strategy is applied to three reservoirs with the results indicating that 95% probability intervals are as large as ±40% of the best estimate. Spatial extrapolation of pan evaporation data and determining lake/pan coefficients are concluded to be by far the greatest contributors to the overall uncertainty. The greatest reductions in uncertainty can be achieved by installing evaporation pans near a reservoir rather than using measurements from pans located some distance away. Seasonally varying coefficients are more accurate than annual coefficients.

Reed et al. (1997) developed statewide atmospheric, soil–water, and surface water balances for Texas. Their surface water balance of precipitation, hydrologic losses, and runoff is based on 1961–1990 means that include reservoir evaporation from about 200 of the largest reservoirs in Texas estimated by applying the TWDB evaporation rates to the total reservoir water surface area in defined watersheds assuming the reservoirs are full to conservation storage capacity. Since the TCEQ WAM System is designed for detailed assessments of water supply reliabilities and stream flow and storage frequency metrics, reservoir evaporation is computed for each individual reservoir for each month of the simulation based on simulated water surface areas and historical observed evaporation rates from the TWDB database (Wurbs 2005).

Hydrologists and water managers have long recognized that reservoir evaporation represents significantly large quantities of water. Linsley et al. (1982) notes that the mean annual evaporation from Lake Mead on the Colorado River, the largest reservoir in the USA, is about 10% of reservoir inflow in a normal year. Martinez-Alvarez et al. (2008) estimate that the evaporation from numerous agricultural irrigation reservoirs in a river basin in a semiarid region of Spain is a quantity equivalent to about 8.3% of the irrigation use in the basin and equal to 27% of the domestic water use of the two million inhabitants of the region. Martinez-Granados et al. (2011) evaluate the significant economic impacts of evaporation from the numerous small irrigation reservoirs and other much larger reservoirs in this same river basin in Spain.

Measures have been implemented or proposed for reducing evaporation from reservoirs, including monomolecular films, floating devices, suspended shading covers, and wind retarding devices (Sinha et al., 2006; Martinez-Alvarez et al., 2006; Assouline et al., 2011). Pioneering work in demonstrating the potential effectiveness of monomolecular films in suppressing evaporation from reservoir water surfaces was performed during the 1950s in Australia and the USA (Magin and Randall, 1960). Barnes (1993, 2008) provides thorough literature reviews of the technology and issues associated with the use of monolayer films in reducing reservoir evaporation. Craig et al. (2005) conclude that annual evaporative losses in regions of Australia are up to 40% of reservoir storage capacity and that spreading monolayer films over water surfaces could significantly reduce these losses. Prime et al. (2012) investigate recent advances in monolayer technology that could contribute to water management in Australia. Sinha et al. (2006) highlight the importance of reservoir evaporation in India and investigate case studies of technologies that have been applied to retard reservoir evaporation in India and elsewhere.

Ayala (2013) performed simulations with the Texas WAM System to explore the effects of potential reductions in evaporation. Timing was found to be important. Evaporation suppression is particularly important during severe reservoir draw-downs. Evaporation suppression has little impact on supply reliabilities during periods when reservoir contents lower a little and then refill to capacity and spill, either with or without evaporation suppression.

3. River/reservoir systems and water management in Texas

Texas is a large state, with an area of 685,000 km^2, located in the south-central United States that is representative of both the drier western and wetter eastern regions of the country from the perspectives of climate and water management. Climate, hydrology, geography, and water management practices vary greatly across the state from the arid western desert to humid eastern forests, from sparsely populated rural regions in the western and eastern extremes of the state to the metropolitan areas of Dallas and Fort Worth, Austin, San Antonio, and Houston shown in Fig. 1. Mean annual precipitation varies from 20 cm at El Paso on the Rio Grande to 140 cm in the lower Sabine River Basin. Mean annual lake surface evaporation ranges from 125 cm in the Sabine River Basin to 200 cm along reaches of the Rio Grande.

The population of Texas increased from 20.9 million people in 2000 to 25.4 million in 2010 and is projected to increase to 46.3 million by 2060 (TWDB, 2012). Total withdrawals from surface and groundwater sources of 22.2 billion m^3/year in 2010 were divided among water use sectors as follows: agricultural irrigation (56.0%), municipal (26.9%), manufacturing (9.6%), steam-electric consumptive use (4.1%), livestock (1.8%), and mining (1.6%). Depleting aquifers have resulted in surface water use growing from less than 30% of total water use in 1970 to greater than 50% in 2010. Population growth and declining groundwater reserves are resulting in continually intensifying demands on surface water resources.

Eleven of the 15 major river basins of Texas discharge directly into the Gulf of Mexico, and the other four are tributaries of the Mississippi River as shown in Fig. 1. Coastal basins located between the lower reaches of the major river basins are drained by smaller streams flowing into the Gulf of Mexico.

The 3415 reservoirs in the water rights permit system include essentially all impoundments with storage capacities greater than 246,800 m^3 (200 acre-feet) used for water supply, hydropower, and/or recreation and many smaller impoundments. The 196 major reservoirs with conservation storage capacities exceeding 6.17×10^6 m^3 (5000 acre-feet) contain over 90% of the total storage capacity of the 3415 reservoirs. Conservation storage capacities of 115 reservoirs range between 6.17×10^6 m^3 and 6.17×10^7 m^3, and capacities of 81 reservoirs exceed 6.17×10^7 m^3. Toledo Bend Reservoir on the Sabine River is the largest conservation storage reservoir in Texas with a capacity of 5.52×10^9 m^3 and surface area

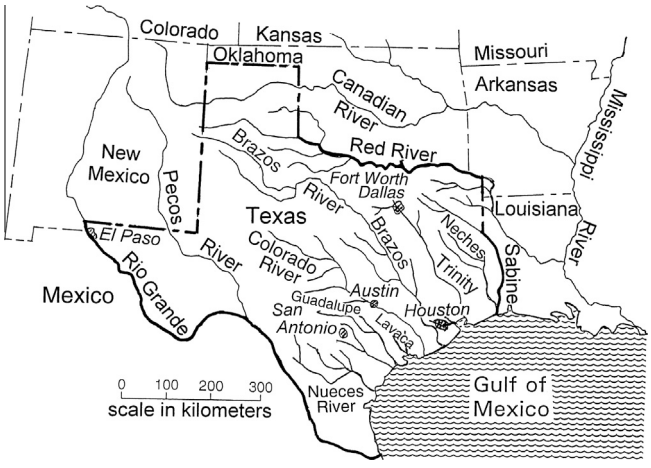

Fig. 1. Map of Texas with major rivers, largest cities, and neighboring states.

of 735 km^3. In terms of total storage capacity, Lake Texoma on the Red River and International Amistad on the Rio Grande are the largest reservoirs in Texas, and Toledo Bend is the third largest. Unlike Toledo Bend, Lakes Texoma and Amistad contain large flood control pools, which are empty except during floods, on top of their conservation pools.

Most of the 196 major reservoirs provide municipal and/or agricultural water supply. Hydroelectric energy is generated at 23 of the major reservoirs. A number of reservoirs provide cooling water for thermal electric power plants, and in some cases are maintained at constant storage levels by conveyance of water from other reservoirs or pumping from groundwater. Thirty-two multiple-purpose federal reservoirs include flood control pools with storage capacities totaling 2.2×10^{10} m^3. Reservoir recreation is popular throughout the state. Environmental flows are also an important consideration in reservoir operations.

Construction and operation of reservoirs in Texas are governed by the need to be prepared for extended droughts. The hydrologically most severe drought on record began gradually in 1950 and ended in May 1957 with one of the largest floods on record. Droughts in the 1910s and 1930s were also extended multiple-year dry periods over large areas of Texas and neighboring states. A 1995–1996 drought was much more economically costly than the earlier droughts due to the population and economic growth that had occurred. In terms of annual precipitation, for more than half of the land area of Texas, 2011 was the driest year since the beginning of official observed precipitation records in 1895. Drought conditions are continuing during 2012–2013.

4. Texas Water Availability Modeling (WAM) system

The WAM System consists of the generalized Water Rights Analysis Package (WRAP) modeling system developed at Texas A&M University, which may be applied anywhere in the world, and WRAP input datasets for all of the river basins of Texas (Wurbs, 2005, 2006, 2013a,b,c). The WAM System was initially implemented during 1997–2002 by the TCEQ and its partner agencies and contractors consisting of university researchers and ten consulting engineering firms. WRAP modeling capabilities continue to be expanded at Texas A&M University under the sponsorship of the TCEQ. The TCEQ updates the WAM datasets to incorporate new and revised water right permits and new and refined WRAP modeling features.

The WRAP/WAM System is designed for assessing river/reservoir system reliabilities in meeting water supply, hydroelectric energy, environmental flow, and reservoir storage needs. The modeling system supports administration of the water rights permit system, regional and statewide planning, and other endeavors. The TCEQ requires that applications for new or amended water right permits include WAM assessments of reliabilities for supplying the water demands proposed in the application and the impacts on all other water right permit holders in the river basin. The WAM System is also routinely applied in a statewide water planning process in which regional groups update 16 regional plans which are incorporated by the TWDB in the statewide Texas Water Plan in a five-year planning cycle (TWDB, 2012).

4.1. River/reservoir system simulation

WRAP has been routinely applied with the Texas WAM System using a hydrologic period-of-analysis of 50 or more years and a monthly computational time step. A conventional WRAP application with WAM System datasets involves assessing capabilities for meeting specified water management and use requirements during an assumed repetition of historical hydrology. The modeling process includes the following tasks.

1. Sequences of monthly naturalized flows input to the simulation model were developed by adjusting observed flows at gauging stations to remove the effects of reservoirs, diversions, return flows, and, in some river basins, changes in land use and groundwater use.
2. Naturalized flows are distributed from gauged to pertinent ungauged locations within the simulation model.
3. The river/reservoir water allocation/management/use system is simulated for each month considering each water right in a specified priority sequence.
4. Simulation results are organized and water supply reliability indices, flow and storage frequency relationships, and other summary statistics are computed.

Task 1 was completed during 1997–2002 for all of the river basins of Texas, though the hydrologic periods-of-analysis are currently being updated. Tasks 2 and 3 occur each time the simulation model is executed. Post-simulation programs are used for task 4, with time series plots, water supply reliability metrics, stream flow and reservoir storage frequency relationships, and summary tables being developed in various optional formats.

Alternative scenarios of water resources development, allocation, management, and use can be simulated with the WRAP/WAM system. The simulations reported in this paper are based on the premise that water resources are managed with existing reservoirs and associated facilities in accordance with current water right permits. Water users are assumed to use the full quantities authorized by their permits subject to water availability. River basin hydrology is represented by input datasets of hydrologic period-of-analysis sequences of naturalized stream flows and net reservoir surface evaporation less precipitation depths. The spatial configuration of all relevant components of a river system is defined by control points.

4.2. Reservoir water surface evaporation and precipitation

Evaporation volumes are computed for each reservoir for each month of the simulation by multiplying the computed mean reservoir water surface area during the month by an evaporation depth from the input dataset. Storage volumes and associated surface areas typically fluctuate greatly over time for most reservoirs. Evaporation rates vary significantly between years as well as varying greatly seasonally.

The reservoir evaporation computations in the simulation model were modified for purposes of the research presented here. The WRAP input datasets in the WAM System for each of the river basins include a file containing net evaporation less precipitation depths for each month of the hydrologic period-of-analysis for each reservoir. Net evaporation-precipitation volumes computed in the simulation reflect evaporation from the reservoir water surface less precipitation falling on the water surface. However, evaporation and precipitation volumes are computed and recorded separately in the version of the model modified for this investigation. Likewise, separate evaporation and precipitation rate datasets are incorporated in the input.

Precipitation gages and evaporation pans have been maintained at numerous sites throughout Texas by the National Weather Service and other federal, state, and local agencies since the early 1900s. The TWDB has compiled available precipitation and pan evaporation data and developed monthly rates for the entire state by one-degree quadrangles that extend back to January 1940 and are updated each year to add data for the preceding year. These datasets and descriptions of methods used in their compilation

Table 1
Texas WAM System River Basins.

Map ID Fig. 2	Major river basin or coastal basin	Hydrologic simulation period	Watershed area		Mean precip.	Mean evap.	Number of reservoirs	Storage capacity
			Texas (km^2)	Outside (km^2)	(cm/year)	(cm/year)		(10^6m^3)
1	Canadian River Basin	1948–1998	32,900	90,700	51.4	164.5	47	1191
2	Red River Basin	1948–1998	63,400	61,000	94.0	143.8	245	4947
3	Sulfur River Basin	1940–1996	9220	9220	123.7	123.5	57	934
4	Cypress Bayou Basin	1948–1998	7280	259	121.2	120.9	91	1085
5	Rio Grande Basin	1940–2000	125,000	347,000	47.7	170.5	74	5964
6	Colorado River Basin	1940–1998	108,000	5100	80.2	146.6	511	6405
7	Brazos River Basin	1940–1997	115,000	6660	84.3	144.0	678	5736
8	Trinity River Basin	1940–1996	46,500	0	107.4	136.2	700	9058
9	Neches River Basin	1940–1996	25,900	0	123.5	118.9	180	4817
10	Sabine River Basin	1940–1998	19,200	6040	129.1	122.6	212	7901
11	Nueces River Basin	1940–1996	43,900	0	75.8	140.8	121	1281
12	Guadalupe & San Antonio	1940–1989	26,500	0	82.3	140.2	238	994
13	Lavaca River Basin	1940–1996	5980	0	102.1	127.3	22	290
14	San Jacinto River Basin	1940–1996	14,500	0	119.6	121.5	114	781
15	Nueces-Rio Grande Coastal	1948–1998	27,000	0	66.7	148.1	64	138
16	San Antonio-Nueces Coastal	1948–1998	6860	0	78.3	148.3	9	1.8
17	Colorado-Lavaca Coastal	1940–1996	2440	0	96.0	137.2	8	8.9
18	Trinity-San Jacinto Coastal	1940–1996	648	0	103.7	122.7	13	6.0
19	Neches-Trinity Coastal	1940–1996	1990	0	121.4	115.4	31	71.6
20	Lavaca-Guadalupe Coastal	1940–1996	2590	0	99.1	132.2	0	0
	Total		684,808	525,979	103.8	135.1	3415	51,610

are publically accessible at the TWDB website. The TWDB computer database system includes a Thiessen polygon network for averaging monthly evaporation pan observations, algorithms for assigning mean depths to the one-degree quadrangles, and sets of 12 monthly pan coefficients for each quadrangle for converting pan measurements to reservoir surface evaporation depths. The TWDB compiles data for 168 one-degree quadrangles covering an area extending 12 degrees longitude and 14 degrees latitude that encompasses Texas along with adjacent surrounding area. Many of the reservoirs in the WAM datasets are located totally within a single quadrangle, and other reservoirs extend across the boundaries of two to four quads, with evaporation depths being weighted in proportion to area in each quad. The TWDB datasets were used by the TCEQ and its contractors during 1997–2002 to compile the original WAM System datasets, continue to be used in updating the WAM datasets, and were used in the research presented here.

4.3. TCEQ WAM system models

Activities of numerous water management entities operating 3415 reservoirs and other facilities in accordance with two variations of a water right permit system with 6000 active permits, US-Mexico treaties, five interstate compacts, and other institutional arrangements are simulated by the Texas WAM System WRAP datasets listed in Table 1. The river basins covered by each dataset are delineated in Fig. 2. Watershed areas lying within and outside of the borders of Texas are tabulated in Table 1. The WAM System is designed to simulate water availability in Texas and includes only reservoirs located partially or totally within Texas. For the international Rio Grande and the interstate rivers, stream flow is allocated in the model in accordance with a US-Mexico treaty and interstate compacts.

The coastal basin lying between the Lavaca and Guadalupe River Basins, with identifier 20 in Fig. 2 and Table 1, contains run-of-river diversions but is the only basin that contains no reservoirs. The number of reservoirs and the totals of their conservation storage capacities are shown in Table 1. Flood control storage capacities are not shown.

The WRAP/WAM simulations for each river basin combine historical natural hydrology covering the hydrologic period-of-analysis shown in Table 1 with the premise that water resources are managed using existing reservoirs, appurtenant facilities, and practices, with the full amounts of water authorized by the water right permits being used subject to water availability. The monthly computational time step simulation results include reservoir storage volumes and associated surface areas, reservoir evaporation rates and volumes, stream flows and associated channel losses, water supply diversions and return flows, and multiple-purpose reservoir releases. These quantities fluctuate greatly over the hydrologic period-of-analysis.

The climate varies dramatically from the semiarid desert of West Texas to the wet forests of East Texas. Isohyets of mean annual precipitation extend north/south increasing fairly uniformly from 20 cm at the City of El Paso which is the western extremity of Texas to 140 cm along the Sabine River which is the eastern border of the state. The reservoir surface precipitation and evaporation depth averages in Table 1 are weighted in proportion to the simulated water surface areas of all reservoirs in the river basin or state.

Fig. 2. Rivers basins modeled by the Texas WAM system.

Table 2
Mean and coefficient of variation of monthly quantities from simulation model.

Map ID	River or coastal basin	Mean of monthly quantities				Coefficient of variation in percent			
Fig. 2		Storage volume (10^6 m^3)	Surface area (km^2)	Evap. depth (cm)	Evap. volume (10^6 m^3)	Storage volume (Standard deviation as % of mean)	Surface area	Evap. depth	Evap. volume
1	Canadian	666	55	13.86	7.53	31.2	26.7	7.06	53.4
2	Red	4092	529	12.27	63.4	9.42	12.0	7.14	47.0
3	Sulfur	758	219	10.25	22.5	15.0	11.0	4.18	46.9
4	Cypress	831	194	9.87	19.5	17.7	17.8	5.92	44.5
5	Rio Grande	3550	393	11.85	55.8	51.8	42.4	8.96	57.7
6	Colorado	3724	312	12.99	38.2	33.5	33.7	6.65	57.7
7	Brazos	4347	700	12.58	84.0	17.1	16.9	5.88	45.7
8	Trinity	6333	1077	11.43	122.4	25.1	20.6	4.43	46.5
9	Neches	4182	673	9.45	66.7	14.7	12.3	5.49	42.1
10	Sabine	7029	1008	9.32	103.0	13.0	11.5	7.23	43.6
11	Nueces	338	82	12.06	9.63	104.0	80.0	5.13	94.7
12	Guadalupe-SA	722	80	12.06	9.32	28.5	22.7	5.25	47.5
13	Lavaca	256	57	10.13	6.10	15.2	23.1	4.76	41.6
14	San Jacinto	652	140	9.81	14.2	22.8	16.4	4.49	41.0
15	Nueces-RG	43.3	15.7	11.96	1.95	45.0	36.2	4.48	45.2
16	SA-Nueces	1.4	1.6	11.50	0.181	21.2	19.7	4.50	45.1
17	Colorado-Lav	6.7	2.7	9.80	0.273	21.4	22.4	4.56	34.8
18	Trinity-San Jac	3.6	1.5	8.99	0.146	36.9	31.4	5.54	48.4
19	Neches-Trinity	26.4	28.5	8.31	2.53	18.4	41.4	4.70	51.5

Table 3
Annual reservoir evaporation by river basin and the entire state.

Fig. 2	River or coastal basin	Evaporation volume in million m^3/year				Mean evaporation as percentage of			
ID		Mean	75%	50%	25%	Capacity	Content	Nat. flow	Reg. flow
1	Canadian	90	76.3	85.3	95.4	7.6	13.6	32.4	65.5
2	Red	761	653	715	810	15.4	18.6	19.8	28.8
3	Sulfur	270	257	273	283	28.9	35.7	8.4	9.9
4	Cypress	234	223	234	249	21.6	28.2	10.9	13.6
5	Rio Grande	670	559	639	781	11.2	18.9	12.6	56.9
6	Colorado	458	360	410	502	7.2	12.3	10.6	34.3
7	Brazos	1009	925	984	1041	17.6	23.2	11.2	15.0
8	Trinity	1469	1366	1482	1623	16.2	23.2	17.6	34.3
9	Neches	801	753	805	836	16.6	19.1	10.4	14.1
10	Sabine	1236	1108	1211	1333	15.6	17.6	14.3	20.9
11	Nueces	116	36.1	101	176	9.0	34.2	14.5	43.4
12	Guadalupe-SA	112	41.3	116	124	11.3	15.5	4.3	5.3
13	Lavaca	73	67.9	73.0	81.8	25.3	28.6	6.3	7.4
14	San Jacinto	170	159	174	184	21.8	26.1	6.1	7.1
15	Nueces-RG	23.4	20.1	22.1	24.9	17.0	54.2	2.3	2.4
16	SA-Nueces	2.2	2.0	2.2	2.4	120.2	157.2	0.3	0.3
17	Colorado-Lav	3.3	3.0	3.3	3.6	36.8	49.0	0.7	0.7
18	Trinity-San Jac	1.8	1.4	1.8	2.1	29.4	48.4	0.8	0.8
19	Neches-Trinity	30.3	26.2	29.2	32.8	42.4	114.9	2.1	2.4
	Entire State	7530	7070	7470	7950	14.6	20.0	11.8	18.0

5. Statewide WAM simulation results

The mean and coefficient of variation of the summation of the end-of-month storage volume in all the reservoirs, summation of end-of-month surface area, area-weighted mean evaporation depth each month, and corresponding total evaporation volume are tabulated in Table 2. The coefficient of variation is the ratio of the standard deviation to the mean, expressed as a percentage. Evaporation volumes for each reservoir are computed in the simulation based on multiplying surface areas by evaporation depths. Reservoir surface area varies greatly seasonally and between years with variations in water supply withdrawals and releases, evaporation, and stream inflows. The greatest contributor to variability is stream flow which varies from severe multiple-year droughts to major floods.

Both monthly evaporation rates and water surface areas reflect modeling uncertainties. As noted earlier, Lowe et al. (2009) analyze the uncertainties associated with applying pan evaporation measurements and pan coefficients to estimate reservoir evaporation rates. Although the WAM system simulates storage volumes, surface areas, and other variables for each month of the hydrologic period-of-analysis, the modeling system is designed to estimate frequency metrics rather than predict quantities for a specific point in time. Stream flow, with its effect on reservoir surface area exposed to evaporation, probably represents the greatest uncertainty as well as variability. The model incorporates a full range of stream flows and evaporation rates over a long hydrologic period-of-analysis.

The mean evaporation volume for each river basin in million m^3/year is shown in Table 3 along with the evaporation volume as a percentage of reservoir storage capacity and mean storage contents and mean naturalized and regulated stream flows at the basin outlet at either the Gulf of Mexico or state border. Naturalized stream flows represent natural conditions without human water resources development and use. Simulated regulated stream flows represent the present conditions of water development/use being modeled. The simulated evaporation volume from the 3415 reservoirs is 7.53 billion m^3/year, which equals 14.6% of the storage

Table 4
Storage frequency metrics with and without including evaporation in the simulation.

		Mean storage	Percentage of time storage contents is equaled or exceeded							
			100%	95%	90%	80%	70%	50%	30%	10%
Reservoir storage contents as a percentage of capacity with and without evaporation										
1	Canadian	55.9	38.7	41.1	41.6	41.9	42.9	48.6	58.6	88.8
		84.4	54.7	60.7	63.8	69.9	74.6	88.7	95.5	99.5
2	Red	82.7	58.2	68.7	70.5	76.6	80.0	84.1	87.1	92.0
		97.1	85.2	90.9	92.8	95.0	96.1	97.6	98.4	99.2
3	Sulfur	81.1	37.1	59.8	65.8	71.8	76.2	83.0	87.1	98.0
		87.5	65.2	75.3	78.2	82.2	83.9	85.5	91.9	99.8
4	Cypress	76.7	27.9	41.5	51.2	62.9	69.9	80.2	88.9	96.2
		87.5	54.3	65.5	71.5	78.4	83.0	90.4	95.8	99.0
5	Rio Grande	59.5	5.9	19.6	28.7	34.8	41.4	44.7	55.5	74.2
		69.9	30.3	38.0	39.7	43.1	45.2	52.1	63.1	81.3
6	Colorado	58.1	28.1	37.0	42.5	47.8	52.0	58.2	63.8	72.6
		79.6	52.1	67.7	71.3	75.0	77.8	81.3	85.2	90.8
7	Brazos	75.8	33.5	49.1	58.3	67.3	71.8	77.8	83.1	90.1
		92.6	76.3	82.8	85.4	88.5	90.4	92.6	94.3	96.3
8	Trinity	69.9	7.3	35.4	46.1	57.0	65.4	74.1	80.6	88.3
		81.8	43.5	64.6	68.4	74.8	78.0	82.8	86.4	91.5
9	Neches	86.8	45.3	60.1	67.7	75.2	82.8	90.5	96.5	99.4
		96.4	80.5	88.6	90.2	93.1	95.2	98.2	99.4	100.0
10	Sabine	89.0	48.1	64.5	72.3	80.9	85.7	92.6	97.4	99.9
		97.3	81.5	90.1	91.8	94.5	96.4	99.0	99.9	100.0
11	Nueces	26.4	0.3	0.4	0.5	0.8	1.4	18.0	37.8	69.2
		39.4	2.8	3.0	3.0	4.6	15.2	35.9	58.9	82.8
12	Guadalupe-SA	72.6	3.1	18.4	32.8	52.9	65.1	80.9	91.3	96.9
		82.0	29.5	53.0	58.9	68.3	75.8	84.5	94.0	99.1
13	Lavaca	88.3	25.6	63.5	71.7	79.3	84.4	92.1	99.8	100.0
		93.2	45.2	78.1	53.2	88.2	91.1	96.0	99.9	100.0
14	San Jacinto	83.4	10.1	45.7	54.2	70.0	79.5	90.4	96.9	99.0
		97.5	75.1	90.0	92.5	95.0	96.7	98.7	99.0	99.0
15	Nueces-RG	31.3	17.2	20.2	21.5	23.9	25.4	29.2	32.7	39.3
		91.1	83.8	85.8	86.3	87.3	88.4	90.8	92.6	95.1
16	SA-Nueces	76.4	27.5	47.1	51.8	63.2	68.1	79.1	89.2	95.2
		91.5	82.4	82.4	82.4	82.4	84.2	92.4	95.8	95.8
17	Colorado-Lav	75.1	26.9	46.1	52.1	60.4	65.9	78.1	85.7	94.8
		82.1	50.5	61.9	66.1	70.8	76.6	84.2	88.7	97.9
18	Trinity-San Jac	60.7	5.2	13.7	22.0	40.4	52.6	72.7	78.4	78.5
		67.0	6.7	18.8	28.9	52.7	68.3	78.2	78.7	80.6
19	Neches-Trinity	36.9	35.2	47.3	52.1	57.3	60.0	64.6	72.2	85.5
		42.0	43.4	55.1	59.9	63.6	66.6	76.9	86.7	89.7

capacity, 20.0% of storage contents, 11.7% of naturalized flow, or 18.0% of regulated flow.

Simulated annual evaporation volumes with exceedance frequencies of 75%, 50% (median), and 25% are also shown in Table 3 for the individual river basins and the entire state. The statewide annual evaporation volume totals for the 3415 reservoirs with exceedance frequencies of 75%, 50%, and 25% are 7.07, 7.47, and 7.95 billion m^3/year, respectively.

The simulations with the 19 WAM datasets were repeated hypothetically assuming no evaporation from the 3415 reservoirs. The effects of evaporation on reservoir storage contents are illustrated by Table 4, which presents storage frequency metrics with and without including evaporation in the simulation. End-of-month storage volumes expressed as a percentage of storage capacity are tabulated in Table 4 for specified exceedance frequencies. For each river basin, the first row contains storage contents, as a percentage of capacity, based on the simulation that includes evaporation. The second line contains these quantities based on the alternative simulation with zero evaporation from the reservoirs.

For example, Table 4 indicates that the 50% exceedance frequency (median) monthly summation of end-of-month storage in the 678 reservoirs in the Brazos River Basin during the 696-month 1940–1997 hydrologic period-of-analysis is 77.8% and 92.6% of capacity with and without evaporation. The total storage contents during the month with 100% frequency (minimum) storage is 33.5% and 76.3% of capacity in the two Brazos WAM simulations.

The difference between storage contents with and without evaporation is significant for the full range of storage levels, but significantly greater during dry periods with low storage levels. During periods of high stream flow, reservoirs may be full to capacity and spilling either with or without evaporation. During extended draw-down periods, cumulative evaporation losses can greatly reduce storage contents. Water supply reliability is governed by extended drought periods characterized in Table 4 by low storage levels. However, evaporation losses during the full range of hydrologic conditions may be important for hydropower, recreation, and environmental flows. Tables 1–4 present simulation results for the aggregation of many reservoirs. The effects of evaporation may vary greatly between individual reservoirs.

Table 5
Reservoirs in the Brazos River Basin.

Capacity range (million m^3)	Number of reservoirs	Storage capacity (million m^3)
Less than 0.617	534	69
0.617–6.169	95	163
6.17–61.69	30	688
61.7–616.9	17	3181
617–894	2	1635
Total	678	5736

6. Simulation results for ten reservoirs in the Brazos River Basin

The 115,000 km^2 Brazos River Basin extends across central Texas as shown in Figs. 1 and 2. The 678 reservoirs in the Brazos

River Basin with water right permits are categorized in Table 5 by conservation storage capacities. A number of federal multiple-purpose reservoirs also contain large flood control pools on top of their conservation pools that are empty except during flood events. The Brazos River Basin is representative of Texas as well as many other regions in that there are numerous reservoirs, but most of the storage capacity is contained in a relatively few larger reservoirs.

The ten largest water supply reservoirs in the Brazos Basin are listed in Tables 6 and 7. Most of the major reservoirs in the Brazos Basin and throughout Texas are used primarily for municipal, industrial, and agricultural water supply, though Whitney, the second largest reservoir in the Brazos Basin, is used primarily for hydropower. Initial impoundment of Possum Kingdom and Belton Reservoirs occurred in 1941 and 1954, respectively. The other eight reservoir projects in Tables 6 and 7 were constructed between 1960 and 1980.

The original 1940–1997 hydrologic period-of-analysis for the Brazos WAM was adopted for the simulations of Tables 1–4 to be consistent with the other river basin models. However, updated 1940–2011 hydrology was adopted for the Brazos WAM simulations of Tables 6 and 7. Simulation input includes naturalized flows and reservoir surface evaporation and precipitation depths for the 864 months of January 1940 through December 2011.

Mean annual evaporation rates for the ten reservoirs are shown in Table 6. The evaporation rates, expressed as monthly depths in cm, for Lake Limestone plotted in Fig. 3 illustrate the great seasonal variability and significant year-to-year variability characteristic of all of Texas.

Results are presented in Tables 6 and 7 and Figs. 4–6 for two simulations, one with and the second without evaporation. The objective is to explore the effects of evaporation on reservoir storage and the other components of the water budget. The second simulation is identical to the first, except evaporation rates of zero are assigned to the ten reservoirs. Both simulations include evaporation at the 668 other reservoirs not included in the selected ten.

The water supply diversion targets from the water right permits for each of the ten reservoirs are tabulated in Table 6. Diversion targets are supplied each month of the simulation unless the conservation storage capacity is depleted. Reliabilities are shown in Table 6 for the simulations including and excluding evaporation. Reliability is defined as the percentage of the total diversion target volume that is supplied.

Table 6
Ten largest water supply reservoirs in the Brazos River Basin.

Reservoir	Stream	Storage capacity	Diversion target	With evaporation		Without evaporation		Mean precip. rate	Mean evap. rate
				Mean storage	Diversion reliability	Mean storage	Diversion reliability		
		(10^6 m^3)	(10^6 m^3/year)	(%)	(%)	(%)	(%)	(cm/year)	(cm/year)
Possum K.	Brazos River	894	284.7	92.0	100.0	96.5	100.0	75.6	160.8
Belton	Leon River	565	138.5	87.0	100.0	93.9	100.0	80.6	146.8
Hubbard	Hubbard Creek	392	69.1	32.6	85.83	94.3	100.0	70.7	164.9
Stillhouse	Lampasas River	291	83.6	82.5	99.31	93.6	100.0	80.5	146.0
Limestone	Navasota River	278	80.3	82.3	100.0	96.2	100.0	101.3	144.2
Waco	Bosque River	255	99.2	88.0	99.67	96.0	100.0	83.2	149.3
Somerville	Yequa Creek	198	59.2	82.2	99.58	97.2	100.0	99.0	133.7
Granbury	Brazos River	191	79.9	88.2	100.0	96.0	100.0	81.8	154.8
Granger	San Gabriel R.	80.8	24.5	86.2	99.84	97.2	100.0	87.7	141.1
Proctor	Leon River	73.3	24.3	78.1	99.97	94.8	100.0	74.7	158.0

Table 7
Reservoir volume budgets with (upper line) and without (lower line) evaporation for the same reservoirs listed in Table 5.

Reservoir	Inflow (10^6 m^3/year)	Precip. volume (10^6 m^3/year)	Storage change (10^6 m^3/year)	Supply diversion (10^6 m^3/year)	Spills & releases (10^6 m^3/year)	Evap. volume (10^6 m^3/year)
Possum Kingdom	800.4	56.8	4.2	284.7	457.1	119.5
	831.8	59.2	2.3	284.7	608.5	0.0
Belton	582.2	20.6	0.9	138.5	427.9	37.4
	596.8	21.7	0.2	138.5	480.2	0.0
Hubbard Creek	109.7	18.9	5.4	59.3	33.5	41.5
	109.7	42.0	0.8	69.1	83.2	0.0
Stillhouse Hollow	283.5	18.2	1.2	83.0	188.1	31.8
	283.5	20.0	0.4	83.6	220.2	0.0
Limestone	278.7	49.8	2.6	80.3	181.3	69.6
	278.7	54.9	0.6	80.3	253.9	0.0
Waco	455.0	23.7	0.7	98.9	330.4	49.3
	455.0	25.1	0.3	99.1	382.1	0.0
Somerville	272.4	40.3	1.2	59.0	200.7	54.3
	272.4	44.4	0.0	59.2	257.4	0.0
Granbury	818.7	26.2	1.1	79.9	717.5	48.8
	960.4	28.2	0.3	79.9	909.0	0.0
Granger	217.8	14.0	0.0	24.4	185.7	21.7
	217.8	15.3	0.0	24.5	208.6	0.0
Proctor	154.8	11.7	0.0	24.3	118.6	24.1
	154.8	13.5	0.0	24.3	143.5	0.0

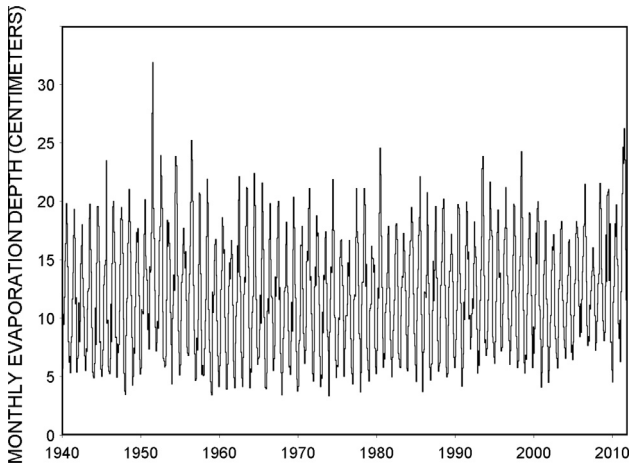

Fig. 3. Limestone Reservoir evaporation rates in cm/month during each month from 1940 through 2011.

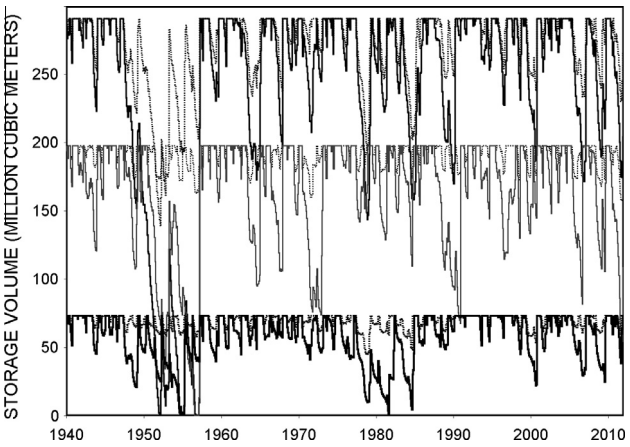

Fig. 5. Simulated storage contents of Stillhouse Hollow (291 million m^3 capacity), Somerville (198×10^6 m^3), and Proctor Reservoirs (73.3×10^6 m^3) with (solid lines) and without (dotted lines) evaporation.

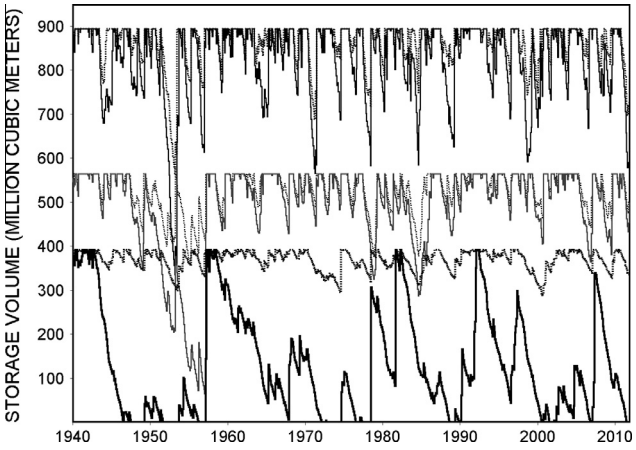

Fig. 4. Simulated storage contents of Possum Kingdom (894 million m^3 capacity), Belton (565×10^6 m^3), and Hubbard Creek (392×10^6 m^3) Reservoirs with (solid lines) and without (dotted lines) evaporation.

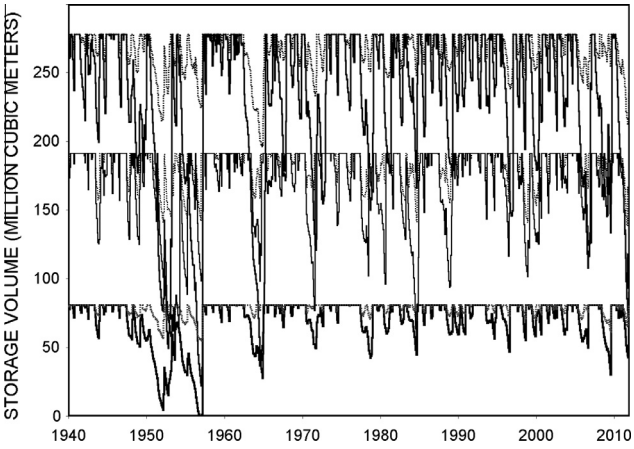

Fig. 6. Simulated storage contents of Limestone (278 million m^3 capacity), Granbury (191×10^6 m^3), and Granger Reservoirs (80.8×10^6 m^3) with (solid lines) and without (dotted lines) evaporation.

Volume budgets for each of the ten reservoirs are presented in Table 7 for the two alternative simulations with and without evaporation. The first line of quantities for each reservoir is from the simulation that includes evaporation. The second line is from the simulation that hypothetically includes no evaporation at the ten lakes. The summation of stream inflows, precipitation falling on the lake, and storage change equals the summation of outflows in the last three columns consisting of water supply diversions, spills from full reservoirs or releases for downstream senior water rights, and losses to evaporation. Initial storage contents at the beginning of the simulation are set equal to capacity in all reservoirs. The storage change in Table 7 is the difference in storage volume between the beginning of January 1940 and end of December 2011 divided by 72 years.

End-of-month storage volumes are plotted in Figs. 4–6 for the simulations with and without evaporation. Storage for the simulation with evaporation is plotted as a solid line. Storage is plotted as a dotted line for the alternative simulation that has evaporation rates for the ten reservoirs set at zero. The differences in simulated storage contents are very significant.

Reservoir draw-downs reflect the cumulative differences between total inflows and outflows since the reservoir was last full. Evaporation from a full and spilling reservoir reduces spills. During time spans of continuous storage decrease since the conservation capacity was last full, the differences in storage between the alternative simulations with and without evaporation reflect the cumulative volume of evaporation loss occurring since the last time the conservation capacity was full. In other time periods, the differences in storage between the alternative simulations with and without evaporation reflect combinations of inflows, releases, and withdrawals in addition to evaporation losses.

Evaporation lowers storage levels particularly severely during extended drought periods. Water supply development and management in Texas is based on reliability estimates that are governed by the most hydrologically severe drought on record, which for most of the state began gradually during 1950 and ended with an extreme flood in May 1957. The 1950s drought is clearly evident in Figs. 4–6. Other major droughts are evident but less severe in terms of simulated storage depletions.

Evaporation significantly affects storage contents of all of the reservoirs, but some much more than others. The effects of evaporation on lowering storage levels are most severe for Hubbard Creek Reservoir, which is located in the upper Brazos Basin in semiarid west Texas where evaporation rates are high. Stream inflows from the creek are small relative to the storage capacity of the reservoir. Storage capacity is filled during floods or other high

flow periods but the storage volume and associated surface area subject to evaporation are large compared to normal inflows. The effects of evaporation are dramatic. Hubbard Creek Reservoir is representative of a number of other reservoirs located in the drier western half of Texas.

7. Summary and conclusions

The Texas WAM System provides a unique opportunity to investigate the relative magnitude of reservoir evaporation for a diverse range of hydrologic conditions and water management practices. The WAM simulations combine historical natural hydrology reflecting highly variable hydrology with the premise that water is managed with existing reservoirs and other facilities, with the full amounts of water authorized by the water right permits being used subject to water availability.

Based on the premises reflected in the WAM System, the long-term mean of reservoir evaporation statewide is estimated to be 7.53 billion m^3/year, varying greatly between years with fluctuations in storage levels and evaporation rates. Comparison with other quantities provides perspective on the relative magnitude of the 7.53 billion m^3/year mean annual evaporation. This aggregated total annual evaporation volume from 3415 reservoirs is equivalent to:

- 14.6% of the simulated mean conservation storage capacity or 20.0% of the mean storage contents of the 3415 reservoirs.
- 18.0% of the simulated mean stream flow that leaves the state either as inflow to the Gulf of Mexico or, for the Mississippi River tributaries, flow at the state border or 11.7% of the naturalized flow leaving the state under natural conditions with no human water development and use.
- 61% of agricultural or 126% of municipal water use supplied from all surface and groundwater sources in Texas during the year 2010.

The estimated long-term statewide mean evaporation rate of 7.53 billion m^3/year, as well as other evaporation quantities presented in this paper, are simulated quantities computed based on operating the reservoirs in accordance with currently existing water right permits, other allocation mechanisms, and operating practices through a hypothetical repetition of historical hydrology which is considered to be representative of a full range of hydrologic conditions. These estimates are necessarily approximate, reflecting significant uncertainties. However, the quantities represent best estimates considered to have about equal likelihoods of being either high or low.

Reservoir evaporation is a significant component of reservoir/river system water budgets in Texas and significantly affects water supply capabilities. Evaporation in the 3200 smaller reservoirs included in the water rights permit system is important to the owners of the individual reservoirs, but most of the reservoir evaporation in the state occurs at the largest 200 reservoirs. The effects of evaporation on reducing reservoir storage levels are significant for a full range of hydrologic conditions but greatest during extended drought periods.

Reservoir evaporation is a fundamental process affecting a variety of water management strategies. Population growth and depleting groundwater supplies are resulting in intensifying demands on limited surface water resources in Texas. Evaporation reduction measures have been investigated in the past and are currently being revisited with renewed interest motivated by pressing water supply needs. The losses of large volumes of water to evaporation should encourage incorporation of evaporation suppression technologies in future water research, planning, and management.

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