Impacts of Climate Variability on Water Management in Texas

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Abstract

Water resources management in Texas, like elsewhere, involves allocating extremely variable stream flow among numerous water users within a framework of extensive reservoir storage facilities and other constructed infrastructure and complex institutional mechanisms. Climate change associated with long-term global warming adds to the variability and uncertainties already inherent in managing water resources. Effective water management requires detailed assessments of future water availability and supply reliability. The Texas Water Availability Modeling (WAM) System has greatly contributed to water management in the state. The generalized software and the assessment concepts incorporated in the Texas WAM System are also applicable to other regions of the world.

Introduction

Precipitation, evaporation, stream flow, and other hydrologic processes in Texas as well as throughout the world are naturally highly variable with daily, seasonal, and multiple-year fluctuations reflecting the extremes of floods and droughts as well as less severe variations. Water availability must be viewed in terms of frequency and reliability metrics. Population growth, urbanization, agricultural and industrial development, and accompanying water resources development projects such as dams and reservoirs, diversions to supply agricultural, municipal, and industrial water needs, and return flows from surface and groundwater sources greatly impact river flows and reservoir storage. Changes in water availability and water use associated with global warming are also a major concern in the hydrologic science and water management communities. Long-term changes in hydrologic phenomena are difficult to quantify due to the great natural variability that hides long-term trends.

Effective water management requires detailed assessments of water availability and supply reliability, which depend upon natural hydrology, constructed infrastructure, and institutional water allocation and management systems. The Texas water management community created, routinely applies, and continues to expand a Water Availability Modeling (WAM) System which consists of the Water Rights Analysis Package (WRAP) developed at Texas A&M University and WRAP input datasets for all of the river basins of the state. The WRAP/WAM system significantly contributes to water management throughout Texas. WRAP is a set of computer programs for modeling and analysis of river/reservoir system management that is generalized for application anywhere in the world.

The modeling system and the water allocation and planning endeavors supported by the modeling system are based on considering historical river basin hydrology in combination with current and projected future conditions of water resources development and use. Statistical characteristics of historical hydrology are used as a representation of future hydrology. However, future hydrology may be significantly impacted by climate change. Precipitation, evaporation, and stream flow are characterized by extreme natural variability regardless of potential long-term climate change due to global warming.

Water Management in Texas

Texas is a large state 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. Texas has an area of 685,000 km^2. Climate, geography, and water management vary dramatically 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 Figure 1. Mean annual precipitation varies from 20 cm at El Paso on the Rio Grande to 140 cm in the lower Sabine River Basin. The population increased from 20,850,000 in 2000 to 25,388,000 in 2010 and is projected to increase to 29,650,000 by 2020 and 46,324,000 by 2060 (Texas Water Development Board, 2012).

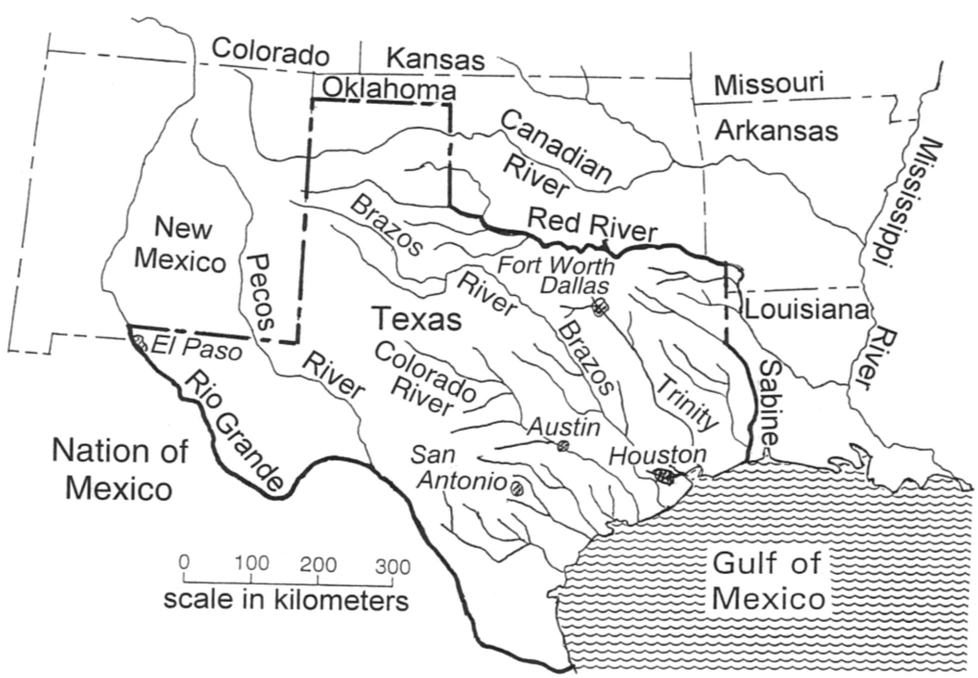

Figure 1. Map of Texas with Major Rivers, Largest Cities, and Neighboring States

Water resources development and management in Texas are governed largely by the need to be prepared for extended droughts. The hydrologically most severe drought on record began gradually in 1950 and ended in 1957 with one of the largest floods on record. Droughts in the 1910's and 1930's were also extended multiple-year dry periods over large areas of Texas and neighboring states. More recent droughts including the 1995-1996 drought that motivated water legislation noted in the next paragraph were 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. The remainder of Texas and neighboring states were also extremely dry during 2011. Severe drought conditions are continuing during 2012 and 2013 in regions of Texas and other regions of the United States.

The Texas Legislature in 1997 enacted major water management legislation that created a regional and statewide planning process and authorized development of the WAM System to support both the planning process and administration of the water rights permit system. The planning process is based on subdividing the state into 16 regions with water plans for each region being prepared and merged into a statewide plan in a five-year planning cycle. The Texas Water Development Board (TWDB) is the lead agency, and committees representing local water interests have been established to prepare plans for each of the 16 regions. Consulting firms and the TWDB provide technical support. The regional and statewide plans were initially completed in 2002 and updated in 2007 and 2012. Work is currently underway on the 2017 regional and state water plans.

The TWDB in partnership with 16 regional planning groups outline future needs and challenges in the 2012 State Water Plan, which is presented in a multiple volume report entitled *Water for Texas 2012* is available at the TWDB website. Although the population of Texas is expected to increase by 82 percent between 2010 and 2060, water demands are projected to increase by only 22 percent due largely to more efficient agricultural irrigation systems. Municipal and industrial water use is expected to increase dramatically while agricultural use declines. Available water supplies with existing infrastructure and current institutional arrangements will decrease by about 10 percent during 2010-2050 due to reservoir sedimentation and depletion of groundwater aquifers. Depleting aquifers have resulted in surface water use growing from less than 30 percent of total water use in 1970 to greater than 50 percent in 2010. The regional planning groups have identified 562 water management projects with an estimated cost of about $53 billion. The TWDB predicts that without implementation of needed measures, annual economic losses of about $11.9 billion/year would result if 2011 drought conditions approach the 1950-1957 drought of record and as much as $116 billion annually with projected 2060 population growth.

Texas Water Availability Modeling (WAM) System

The Texas Commission on Environmental Quality (TCEQ), TWDB, Texas Parks and Wildlife Department, university researchers, and consulting firms implemented the WAM System during 1997-2003 pursuant to the 1997 legislation (Wurbs, 2005). The Texas WAM System maintained by the TCEQ consists of WRAP (Wurbs, 2006), hydrology and water rights input files for each of the river basins of the state, and other supporting databases. The generalized WRAP modeling system has continued to be expanded at Texas A&M University under the sponsorship of the TCEQ and other agencies. The TCEQ continues to update the datasets as new and revised water right permits are approved and new modeling features are added. Recent efforts have focused on expanding capabilities for modeling environmental flow requirements that are being established through a legislatively mandated process (Wurbs and Hoffpauir, 2013).

The TCEQ requires that water right permit applicants or their consultants apply the WAM System to determine the reliabilities at which the water needs addressed in the permit application can be supplied and to assess the impacts on the reliabilities of all other water rights in the river basin. TCEQ staff applies the modeling system to evaluate the permit applications. The WAM System is applied by the TWDB and regional planning groups in planning studies. River authorities and other water management agencies use the modeling system in operational planning studies and other types of applications.

Texas is divided into 15 major river basins and eight coastal basin lying along the Gulf of Mexico between the lower reaches of the major river basins. In some cases, the WAM models combine coastal basins with adjoining major river basins. The WAM system includes WRAP datasets for each of the river basins delineated in Figure 2. Information describing each of the river basins and corresponding WAM models is tabulated Table 1.

Figure 2. WAM System River Basin Delineations

The datasets model water rights representing about 6,000 water right permits and other water allocation mechanisms. The datasets model the 3,435 reservoirs for which a water right permit has been issued and other constructed facilities. Over 90 percent of the total storage capacity of the 3,435 reservoirs is contained in the 210 reservoirs that have conservation capacities exceeding 6,170,000 m^3. Several of the river systems shown in Figures 1 and 2 are shared with neighboring states. The Rio Grande is shared with Mexico. For the interstate and international river basins, hydrology and water management in neighboring states and Mexico are considered to the extent necessary to assess water availability in Texas. The models reflect two international treaties and five interstate compacts as well as the two Texas water rights systems administered by the TCEQ. The water rights system allocating the Texas share of the waters of the lower Rio Grande is significantly different from the water rights system for the remainder of Texas.

The Texas WAM System includes WRAP water rights input datasets for two main scenarios called authorized use and current use. The authorized use scenario datasets model the water right permits as written. The current use scenario datasets reflect actual current conditions of water resources development, allocation, and use. Water right permits often reflect commitments for future growth, and water users currently use less water than their permits allow. The TCEQ uses the authorized use scenario datasets in evaluating regular permit applications and the current use datasets for term permits. Regular permits are for perpetuity. Term permit are valid only for a specified period of time, typically ranging from one to several years. The TWDB has developed datasets based on projected future water use scenarios (years 2020, 2030, 2040, 2050, 2060) for use in planning studies.

The hydrology datasets include sequences of monthly naturalized stream flows covering hydrologic periods-of-analysis of at least 50 years at a total of about 500 primary control points, most of which are sites of gauging stations, and watershed parameters for synthesizing natural flows at over 12,000 other control points based on the flows at the primary control points. Net water surface evaporation less precipitation rates are provided for the reservoirs. The datasets also include channel loss factors used to model seepage and evaporation losses in river reaches.

Table 1. Texas WAM System River Basins

1 Map ID Fig 2	2 River Basin or Coastal Basin	3 Area in Texas ($10^3 km^2$)	4 Area Outside ($10^3 km^2$)	5 Mean Precip (cm/yr)	6 Mean Evap (cm/yr)	7 Reser-voirs	8 Storage Capacity ($10^6 m^3$)	9 Mean Storage (% cap)	10 Natural Flow ($10^6 m^3/yr$)	11 Regulated Flow ($10^6 m^3/yr$)
1	Canadian	32.9	90.7	51	165	47	1,191	55.9	279	138
2	Red	63.4	61.0	94	144	245	4,947	82.7	3,841	2,639
3	Sulphur	9.2	0.5	124	124	57	934	81.1	3,197	2,733
4	Cypress	7.3	0.3	121	121	91	1,085	76.7	2,157	1,723
5	Rio Grande	125.0	347.0	48	171	74	5,964	59.5	5,312	1,178
6	Colorado	108.0	5.1	80	147	511	6,405	58.1	4,317	1,334
7	Brazos	115.0	6.7	84	144	678	5,736	75.8	8,971	6,707
8	Trinity	46.5	0	107	136	700	9,058	69.9	8,339	4,284
9	Neches	25.9	0	124	119	180	4,817	86.8	7,692	5,683
10	Sabine	19.2	6.0	129	123	212	7,901	89.0	8,618	5,916
11	Nueces	43.9	0	76	141	121	1,281	26.4	797	266
12	GSA	26.5	0	82	140	238	994	72.6	2,617	2,095
13	Lavaca	6.0	0	102	127	22	290	88.3	1,156	983
14	San Jacinto	14.5	0	120	122	114	781	83.4	2,801	2,403
15	Nueces-RG	27.0	0	67	148	64	138	31.3	1,006	973
16	SA-Nueces	6.9	0	78	148	9	1.8	76.3	697	696
17	Colorado-Lav	2.4	0	96	137	8	8.9	75.1	489	455
18	Trinity-SJ	0.7	0	104	123	13	6.0	60.7	223	208
19	Neches-Trin	2.0	0	121	115	31	71.6	36.9	1,422	1,242
20	Lavaca-Guad	2.6	0	86	142	0	0	-	194	192

Column 1 of Table 1 refers to the Figure 2 map.

Watershed areas lying within and outside of Texas are shown in columns 3 and 4. The mean annual precipitation during 1940-2012 is tabulated in column 5. Mean annual reservoir water surface evaporation during 1940-2012 is shown in column 6. The number of reservoirs in each basin and total conservation storage capacity of the reservoirs are listed in columns 7 and 8. Column 9 shows the mean storage contents as a percentage of storage capacity. Mean naturalized and regulated flows from the WAM System are shown in the last two columns of Table 1. Naturalized flows represent natural conditions without human water resources development and use. The regulated flows are computed based on the premise that all water users use the full amount of water to which they are entitled under the water rights permit system.

Major reaches of rivers, particularly in dry west Texas and populous urban areas elsewhere in the state, are over-appropriated. Reliabilities for supplying permitted water use are unacceptably low, and the TCEQ will not issue permits for additional use. Marketing or transferring of existing water rights among users is encouraged. For other river reaches, water is available for further appropriation. The TCEQ continues to issue or modify many water right permits each year. The WAM System is used to determine reliabilities associated with water use proposed by the permit applicants and the impacts on reliabilities of the proposed use on the reliabilities associated with all of the other water users in the river basin.

Water Rights Analysis Package (WRAP) Modeling System

The WRAP modeling is generalized for application to river/reservoir systems located anywhere in the world, with input datasets being developed for the particular river basins of concern. For simulation studies in Texas, readily available WAM System data files are altered as appropriate to reflect proposed water management plans of interest, which could involve changes in water use or reservoir system operating practices, construction of new facilities, or other water management strategies. The WRAP software and reference and users manuals (Wurbs, 2009, 2011, 2012a, 2012b, 2012c; Wurbs and Hoffpauir, 2012) are available at: https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm, which links to the TCEQ WAM website that provides information including WRAP datasets for all of the river basins of Texas.

WRAP simulates water resources development, management, regulation, and use under priority-based water allocation systems. The modeling system facilitates assessments of hydrologic and institutional capabilities for satisfying requirements for water supply, hydroelectric energy generation, environmental instream flows, and reservoir storage. In WRAP terminology, water use requirements, water control infrastructure, and reservoir/river system operating strategies are called water rights. Basin-wide impacts of water resources development projects and management practices are modeled.

WRAP modeling capabilities documented by Wurbs (2011b, 2012a, 2012b) have been routinely applied with the Texas WAM System based on using a hydrologic period-of-analysis of about 50 to 80 years and a monthly computational time step to perform water availability analyses for municipal, industrial, and agricultural water supply, environmental flow, hydroelectric power, and reservoir storage needs. Water supply reliability metrics and stream flow and reservoir storage frequency relationships in various optional formats are developed from simulation results.

Work underway for several years resulted in the addition of daily modeling capabilities to the August 2012 version of WRAP (Wurbs and Hoffpauir, 2012), motivated primarily by needs for improved modeling of environment flow requirements and their impacts on water supply capabilities. WRAP simulates environmental flow regimes that include subsistence flows, base flows, and high pulse flow events of specified frequencies. The daily modeling system also simulates reservoir operations for flood control. The daily time step modeling capabilities include flow forecasting and routing, disaggregation of monthly naturalized stream flows to daily quantities, and daily variations in water demands that may reflect storage capabilities.

Water management is combined with natural hydrology. WRAP simulates capabilities of river and reservoir systems in meeting water management/use targets for given sequences of naturalized stream flows and reservoir net evaporation less precipitation rates. Historical natural hydrology is used to capture the hydrologic characteristics of a river basin. The water management and use scenario might be actual current water use, projected future conditions, the premise that all permit holders use their full authorized amounts, or some other scenario of interest. Control points define the spatial configuration of all relevant components of a river system. Naturalized stream flows for primary control points are read by the simulation model from an input file. Naturalized flows are distributed from primary control points to all other control points within the simulation based on alternative computational options and watershed parameters.

WRAP is commonly used in planning studies and water right permitting to determine long-term supply reliabilities and flow and storage frequencies. WRAP can also be applied to perform short-term reliability and frequency analyses conditioned upon preceding reservoir storage contents.

A conventional WRAP application with WAM System datasets assesses 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 selected gauging stations to remove the effects of human activity.
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 has been completed for all of the river basins in Texas, though methods for updating the hydrologic periods-of-analysis are currently being investigated. Tasks 2 and 3 occur each time the simulation model is executed. A post-simulation WRAP program is used for task 4.

Period reliabilities for water supply or hydroelectric energy demands are expressed in terms of the percentage of months during the simulation during which either 100% or certain percentages of the demand are supplied. Volume reliability is the total volume of water supplied, as constrained by water availability, expressed as a percentage of the demand target. Stream flow and reservoir storage are quantified in terms of the percentage of months during the simulation during which specified volumes are equaled or exceeded. Supply reliabilities and storage and flow frequency metrics are governed by hydrologic variability.

Hydrologic Variability

Water resources management in Texas, as is typically the case in many other regions of the world, focuses largely on dealing with spatial and temporal variability. Long-term mean stream flow volumes exceed water demands, but much of the flow occurs during floods. Large volumes of reservoir storage capacity are required to store excess high flows for use later during dry periods of inadequate flow.

Although the following discussion focuses on hydrologic variability, water demands as well as supplies are highly variable. Water use varies greatly seasonally. Municipal and industrial water use is higher during hot dry summer months. Irrigation use occurs during a certain season of the year. Water supply contracts between river authorities and farmers may vary the amounts supplied each year based on the contents of reservoirs prior to the beginning of the irrigation season. Irrigation use is curtailed during years of low reservoir storage content. Municipal and industrial water users may also be curtailed during droughts with activation of demand management strategies.

Hydrologic variability is illustrated by the plots of 1940-2012 monthly and annual precipitation depths, reservoir surface evaporation depths, and naturalized stream flow volumes presented as Figures 3, 4, 5, 6, 7, and 8. The great temporal variability of these data from the lower Brazos River Basin in south-central Texas is characteristic of hydrology throughout Texas. Naturalized flow and reservoir net evaporation less precipitation rates represent river basin hydrology in the WAM System. Precipitation is the source of stream flow. These quantities are extremely variable and their prediction is highly uncertain.

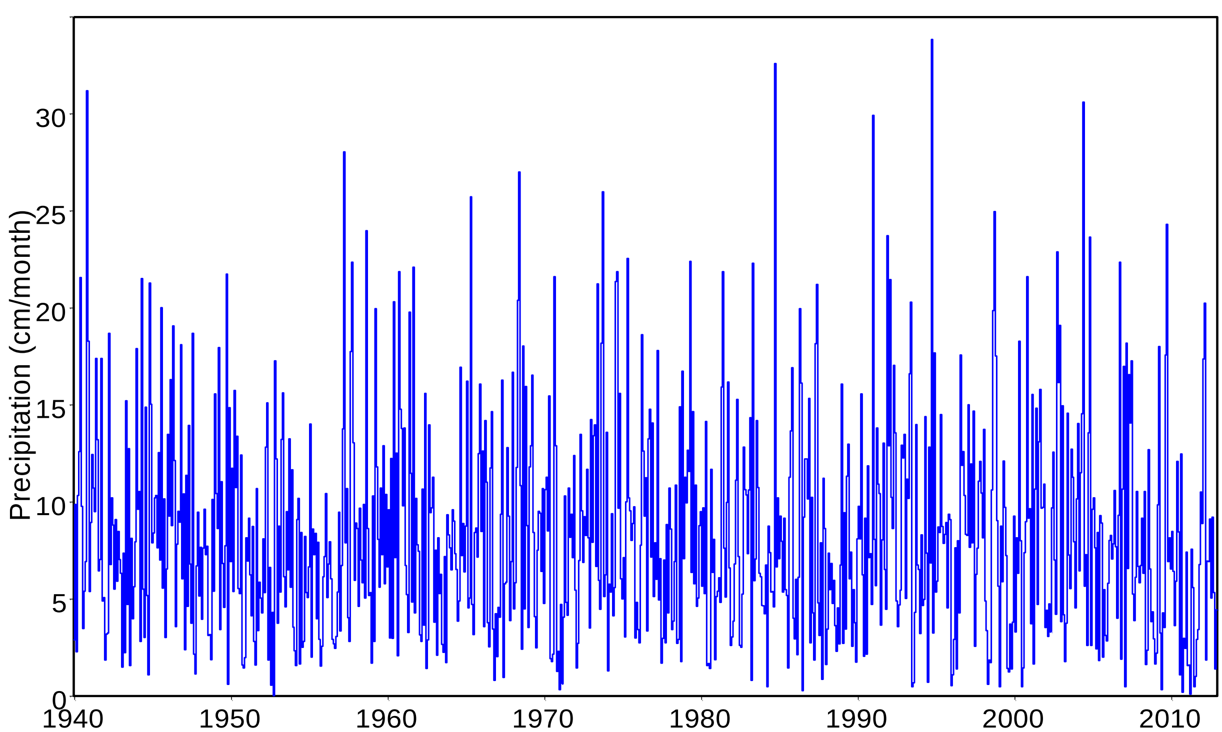

Figure 3. Monthly Precipitation in Lower Brazos River Basin

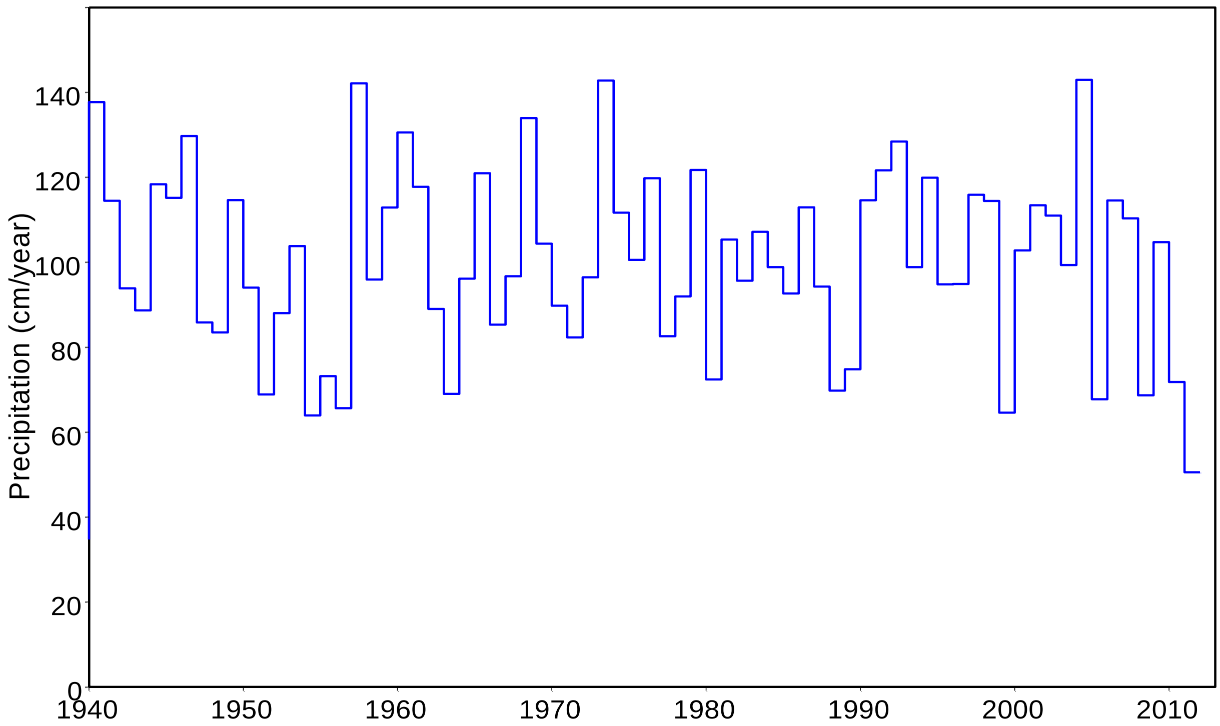

Figure 4. Annual Precipitation in Lower Brazos River Basin

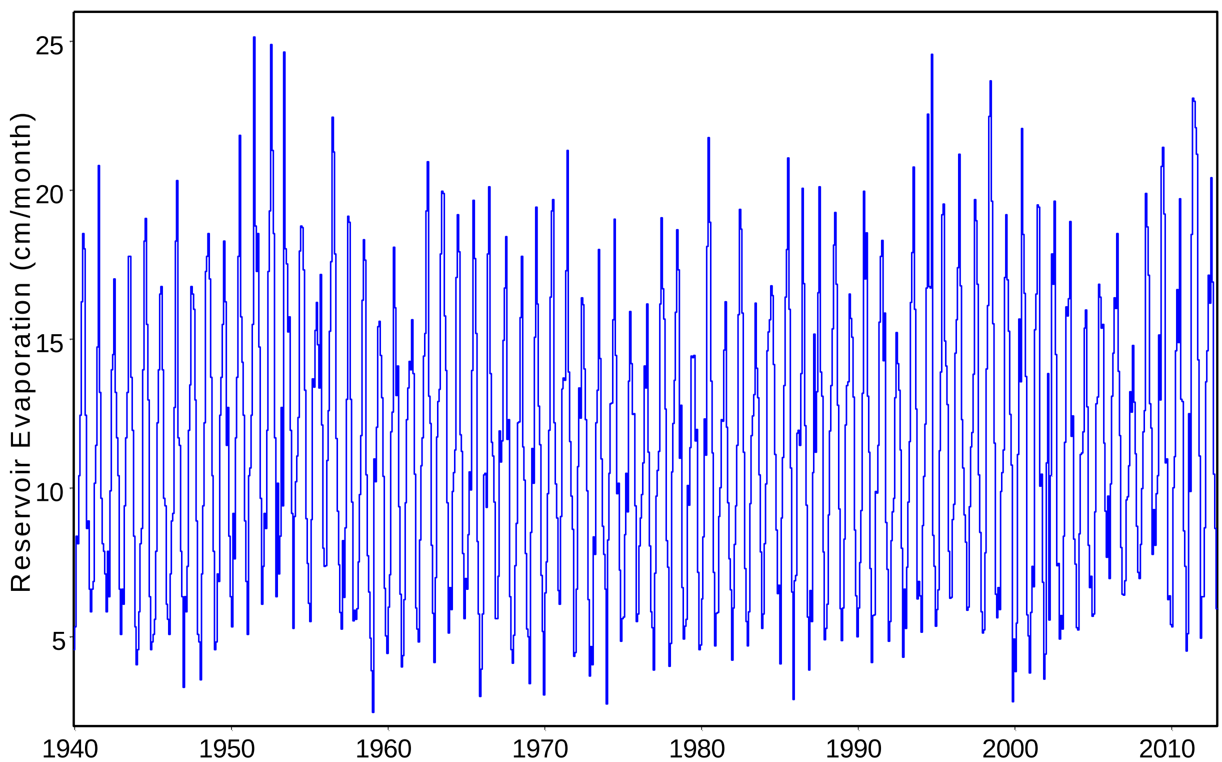

Figure 5. Monthly Reservoir Surface Evaporation Depths in Lower Brazos River Basin

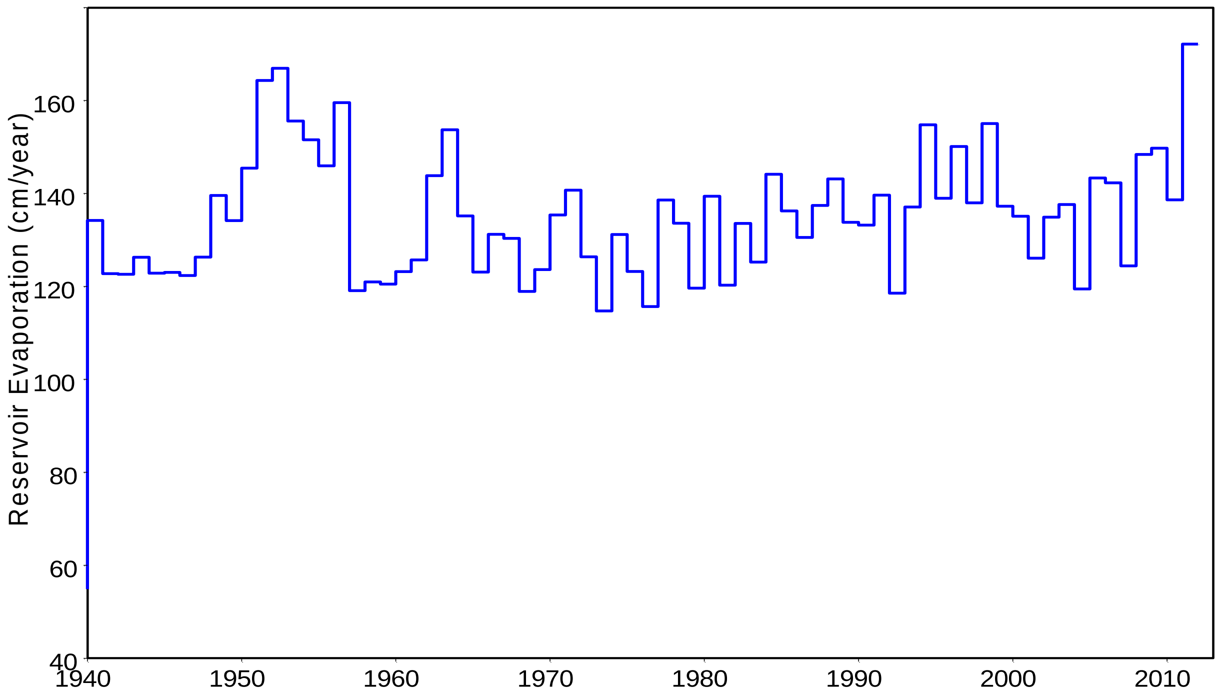

Figure 6. Annual Reservoir Surface Evaporation Depths in Lower Brazos River Basin

The TWDB maintains datasets of monthly precipitation and reservoir surface evaporation rates for each quadrangle of a grid of 75 one-degree quadrangles that cover the state of Texas. Monthly and annual precipitation and evaporation depths for a quadrangle in the lower Brazos River Basin northwest of Houston are plotted in Figures 3, 4, 5, and 6.

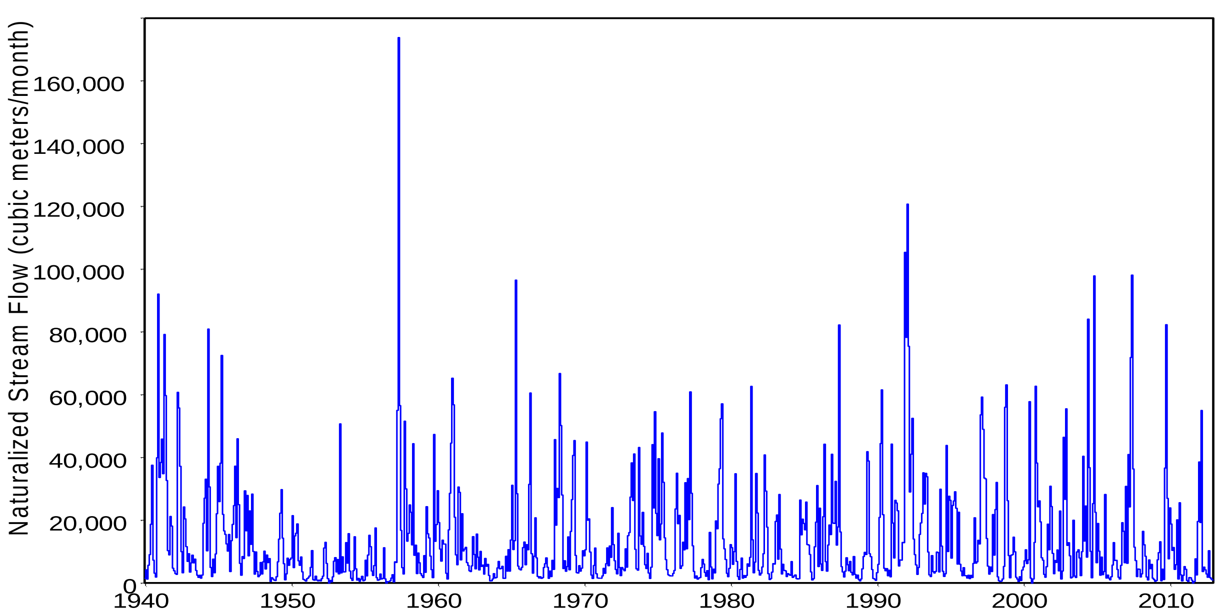

Figure 7. Monthly Naturalized Flow of Brazos River near Houston

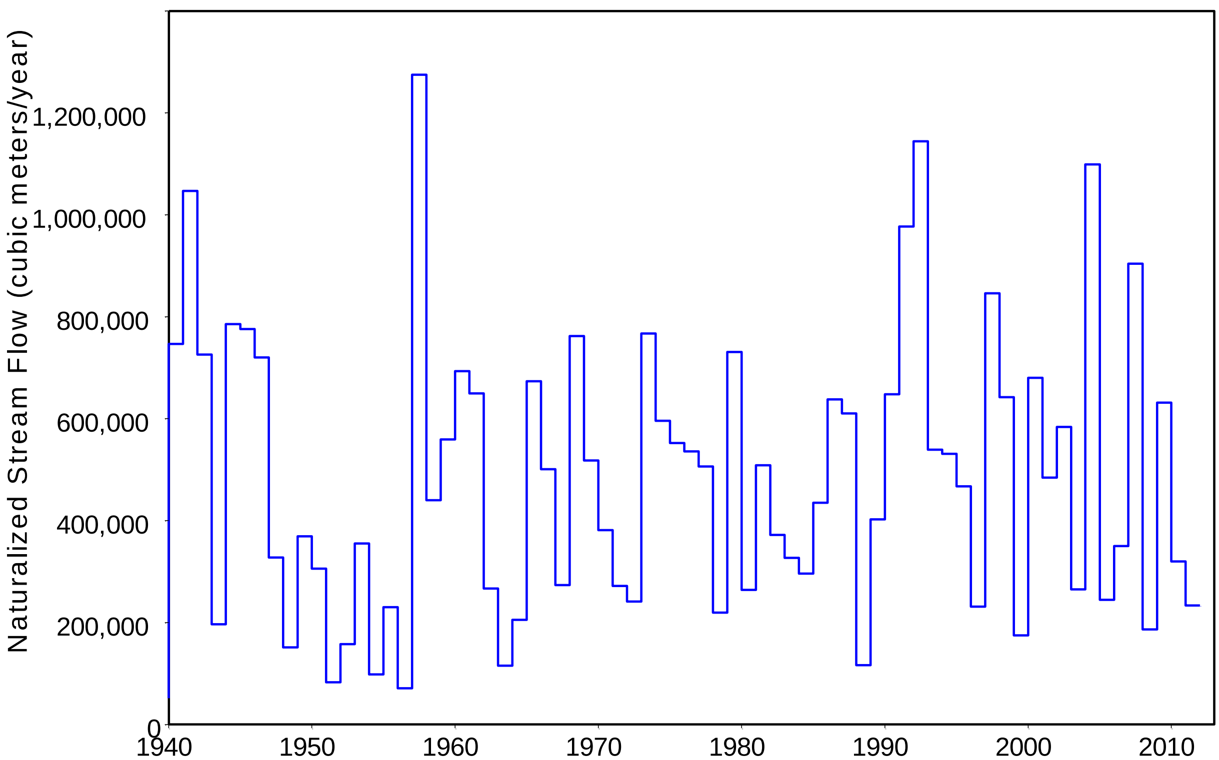

Figure 8. Annual Naturalized Flow of Brazos River near Houston

Naturalized monthly flows in units of m^3/month and annual flows in m^3/year from the WAM for the Brazos River at a gauging station located about 100 km upstream of the river outlet at the Gulf of Mexico are plotted in Figures 7 and 8. The annual flows are simply summations of monthly flows.

Long-Term Climate Change

The WAM System is based on the premise that historical natural hydrology is stationary and adequately representative of unknown future hydrology. Global warming is a significant issue in this regard, adding to modeling uncertainties. Long-term trend analyses were performed during the original development of naturalized flows for each of the river basins for the WAM System. At the time of these analyses, the naturalized flows extended from about 1940 to sometime between 1997 and 2000. Wurbs, Muttiah, and Felden (2005) report additional analyses performed for the Brazos River Basin covering a 1900-1997 historical period-of-analysis. Hidden several-year cycles have been detected and found to have significant correlation with El Nino-Southern Oscillation events. However, the naturalized flows have been found to be homogenous with no evident long-term trends. This could change in the future.

Wurbs, Muttiah, and Felden (2005) investigated methodologies for predicting the future impacts of global warming on hydrology and water management in Texas in a research study sponsored the National Institute for Global Environmental Change of the U.S. Department of Energy. This investigation applied a general strategy to the Brazos River Basin that had been adopted both previously and since by many researchers in modeling the effects of climate change on hydrology and water management throughout the world. The general strategy combines the results of a general circulation model (GCM) with watershed (precipitation-to-streamflow) and water management models. Wurbs, Muttiah, and Felden (2005) combined the Canadian Center for Climate Modeling and Analysis GCM with the Soil and Water Assessment Tool (SWAT) watershed model and WRAP/WAM water management model for the Brazos River Basin. WRAP/WAM naturalized flows were adjusted based on flows synthesized with SWAT for alternative climate scenarios. The impacts on water management of a projected year 2050 climate scenario based on assuming 1.0 percent increase in CO_2 concentrations were modeled.

The projected 2050 climate scenario with 1.0%/year CO_2 increases resulted generally in decreases in stream flows corresponding to decreases in precipitation and increases in evapotranspiration. However, the changes in precipitation vary spatially across the Brazos River Basin and included both increases and decreases. The investigators concluded that all aspects of the modeling were very approximate and highly uncertain, with prediction of future changes in precipitation characteristics being particularly questionable. Improving predictions of climate change and associated effects on hydrology and water management is extremely challenging. Predictive capabilities have probably not progressed to the level of meaningfully quantifying long-term future impacts on water management in Texas.

Water Supply Reliability

For most of Texas including the Brazos River Basin, the hydrologically most severe drought on record began gradually in 1950 and ended in 1957 with one of the largest floods on record. Other more recent droughts have been much more damaging economically than the 1950's drought due to the population and economic growth that has occurred since the 1950's. The 1950's drought-of-record and other droughts can be seen in the plots of Figures 3 through 8. The 7-year 1950's drought has served as a benchmark in assessing water supply capabilities. Water management in the state has been based largely on preparing for a future drought that will equal or exceed the severity of 1950's drought. The water management community realizes that a drought more hydrologically severe than the 1950's drought will occur at some time in the future, but the time is unknown. The current drought that began in 2011 could possibly eventually surpass the 1950's drought-of-record.

The WAM System provides an assortment of supply reliability and flow and storage frequency metrics. The TCEQ applies firm yield and 75%/75% reliability criteria to new water right permit applications and municipal and agricultural uses, respectively. The 75%/75% reliability criteria for agricultural irrigation means that at least 75% of the irrigation demand must be supplied at least 75% of the time for the water right permit application to be approved. Firm yield is the maximum annual diversion rate that can be supplied continuously without shortage during the hydrologic period-of-analysis based on all of the premises and approximations reflected in the model. The firm yield has volume and period reliabilities of 100%. The reliabilities for many of the 6,000 existing water right permits are much lower than the criteria applied to new permit applications. Planning studies include comparisons of projected future water needs with the firm yields of water supply sources.

Over 1,200 river authorities, water districts, cities, private companies, and individual citizens hold permits to store and divert the flows of the Brazos River and its tributaries. These permits include storage in 678 reservoirs. Several of the larger reservoirs are operated as multiple-reservoir systems. The volume reliability is 89.1 percent for the aggregate of all water rights in the basin, based on a 1940-2012 hydrologic simulation period, meaning that 89.1% of the total water demand is supplied in the simulation, constrained by water availability. Reliabilities vary greatly between individual water rights. The 89.1% reliability for the aggregated total of all water rights in the Brazos River Basin is higher than the corresponding reliabilities for most of the other river basins of the state.

The monthly naturalized flows of the lower Brazos River plotted in Figure 7 illustrate the tremendous natural variability of flows in rivers throughout Texas. The natural unregulated flows are sometimes zero or essentially zero. Thus, without reservoir storage, the river provides a firm yield of zero. Reservoir storage is essential for developing firm yield. The firm yield is controlled by a critical drought, which for the Brazos River and most of Texas, is the drought of the 1950's. The quantities of water available for commitment to water users can be increased significantly by accepting a smaller reliability, or greater risk of being unable to supply the commitments. Water supply contracts may be based on curtailing diversions whenever reservoir storage levels fall below trigger storage levels.

Evaporation from reservoir water surfaces and precipitation falling on the water surfaces are significant. The hydrologic period-of-analysis mean annual reservoir evaporation from the 3,435 reservoirs in the Texas WAM System is a computed volume equivalent to about 60 percent of the actual agricultural water use or 125 percent of the actual municipal water use from all surface and groundwater sources in Texas during the year 2010. Thus, reservoir storage is essential for developing reliable water supplies but results in large evaporation losses. Reservoir surface evaporation losses are partially mitigated by precipitation falling on the water surface. The great variation in precipitation and evaporation rates between the various river basins of the state is shown in columns 3 and 4 of Table 1.

Conclusions

River basin hydrology is extremely variable, subject to extremes of floods and droughts along with continuous seasonal, year-to-year, and multiple year cycles and random fluctuations. Variability and uncertainty are necessarily inherent in water management. Global warming certainly adds to the uncertainties and perhaps adds to variability. Water managers with relatively large reservoir storage capacity, senior water rights, and effective water conservation strategies are better able to deal with variability and uncertainty. Effective water management requires capabilities for assessing water availability and supply reliability. The WRAP/WAM System significantly contributes to water management in Texas.

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