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Runoff Inflow Volumes to the Highland Lakes in Central Texas: Temporal Trends in Volumes and Relations between Volumes and Selected Climatic Indices

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Abstract: Inflow to the Highland Lakes has substantially decreased from 1942–2013, likely due to increased evapotranspiration from the proliferation of 19 major upstream reservoirs and about 69,500 minor reservoirs and water bodies. Increased evapotranspiration from land surfaces and stream channels also probably represent major causes for inflow reduction. Eight climatic indices were evaluated with respect to correlations with inflow volumes to the lakes. A combination of the indices for the Atlantic Multidecadal Oscillation and Oceanic Niño Index (Niño 3.4 region) was found to be, up to three months in advance, a fair indicator for the wettest three-month inflow periods, and a good indicator, up to nine months in advance, of the driest three-month inflow periods. The single best index indicator of dry periods is the Pacific Decadal Oscillation—a good indicator of the driest three-month periods up to a year in advance.
Keywords: Highland Lakes, inflow, climatic indices

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Terms used in paper

Acronym/Initialism	Descriptive Name
AMO	Atlantic Multidecadal Oscillation
BEST index	Bivariate EnSo Time series
CRMWD	Colorado River Municipal Water District
ENSO	El Niño/Southern Oscillation
ft^3/s	cubic feet per second
LCRA	Lower Colorado River Authority
MEI	Multivariate ENSO Index
NAO	North Atlantic Oscillation
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NOAA	National Oceanographic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
ONI	Oceanic Niño Index
PDO	Pacific Decadal Oscillation
PNA	Pacific/North American teleconnection pattern
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
TWDB	Texas Water Development Board
TCEQ	Texas Commission on Environmental Quality
UCRA	Upper Colorado River Authority
USGS	U.S. Geological Survey

INTRODUCTION

The Highland Lakes, located on the Colorado River in Central Texas, are managed by the Lower Colorado River Authority (LCRA) and are represented by Lake Buchanan, Lake Travis, and four small pass-through reservoirs (Inks Lake, Lake Lyndon B. Johnson, Lake Marble Falls). Lake Austin, which is immediately downstream from Lake Travis, is excluded from all analyses in this report. The lakes provide drinking water to more than a million people and water to industries, businesses, agriculture, and the environment throughout the lower Colorado River Basin. However, during the period 2011–2014, inflow volumes to the lakes were minimal, resulting in their combined storage volume to be almost the lowest since the reservoirs filled in 1942. A graph presenting total storage in the Highland Lakes since 1940 is presented in Figure 1.

As of March 1, 2015, Lakes Travis and Buchanan had a combined storage of about 700,000 acre-feet, which is only 35% of their full capacity of about 2 million acre-feet. Storm runoff later in the year and in 2016 more than doubled the storage volume. However, future drought could cause the storage volume to drop below 600,000 acre-feet, or 30% of capacity. If the storage drops to that level, the LCRA Board of Directors might issue a drought worse than the Drought of Record declaration. Following a state-approved plan, LCRA might then require cities, industries, and other firm customers to reduce their water use by 20% and cut off all Highland Lakes water to interruptible customers (LCRA 2015).

Inflow volumes to the Highland Lakes have substantially reduced over time. Additionally, the effect of El Niño conditions does not provide certainty of increased inflow volumes to the Highland Lakes. The purposes of this report are to document temporal trends in inflow volumes to the Highland Lakes, identify possible causes for any trends, and analyze the relations, especially for the wettest and driest periods, between inflow volumes to the Highland Lakes and selected climatic (oceanic and atmospheric) indices.

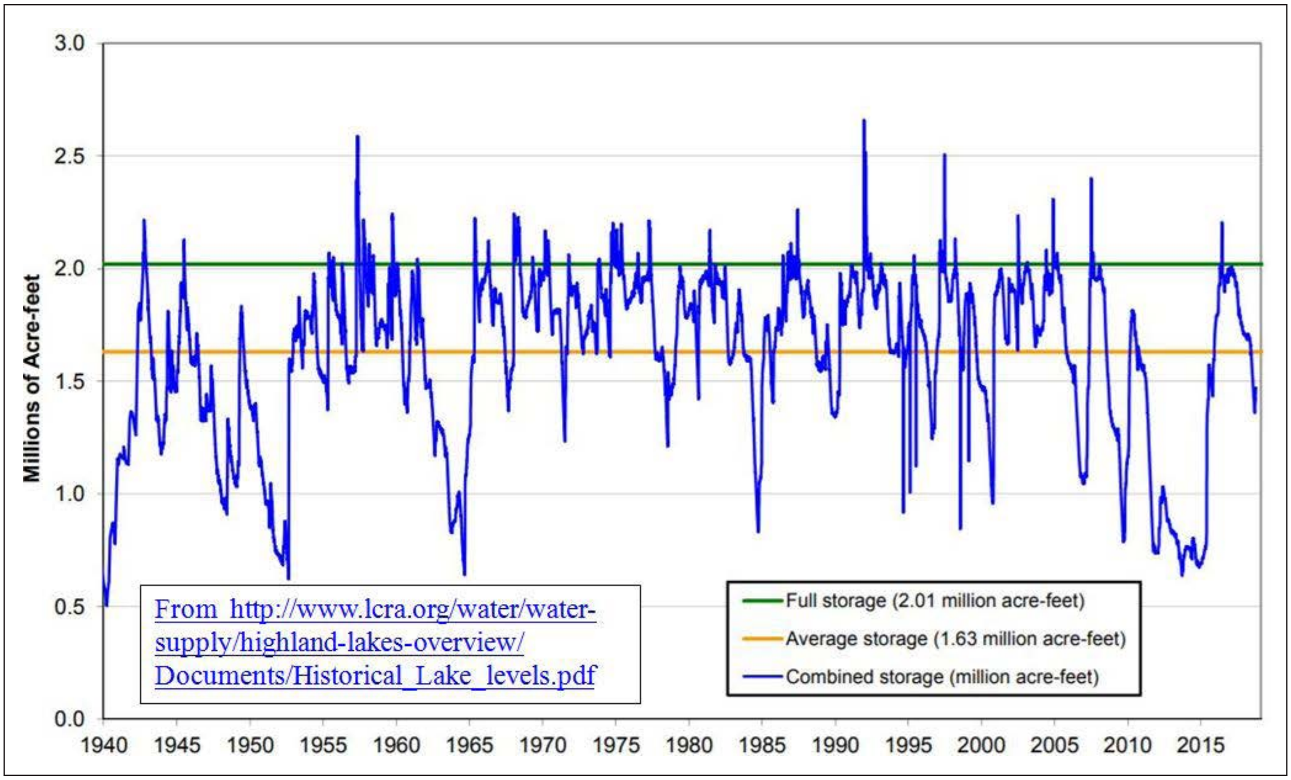

Figure 1. Total combined storage in Lakes Buchanan and Travis.

INFLOW VOLUMES TO THE HIGHLAND LAKES

The LCRA uses streamflow data from four U.S. Geological Survey (USGS) streamflow stations to calculate total stream inflow into the Highland Lakes (Figure 2, station numbers 4–7). The stations gage streamflow volumes on the four largest streams that provide direct inflow to the lakes—the Colorado River, the Llano River, Sandy Creek, and the Pedernales River. The gaged flow values are multiplied by factors equal to or exceeding 1.0 to estimate the runoff from the ungaged parts of their basins and from the ungaged basins that provide inflow to the Highland Lakes. The inflow runoff factors are presented in the section "Upstream Flow Conditions and Gauged Inflows" (LCRA 2018).

The total contributing drainage area for the four streamflow stations represents 92% of the total drainage area for the Highland Lakes; thus, inflow is estimated for only 8% of the Highland Lakes Basin. The estimated inflow values represent only a small part of the total inflow; therefore, the author considers the potential error for the total inflow values to be minimal for this analysis.

Inflow to Lake Buchanan is based solely on the Colorado River streamflow-gaging station near San Saba (Figure 2, Station 4). The contributing drainage area for the station represents about 97% of the Lake Buchanan Basin; thus, the gaged flow volumes are increased by 3% to account for total inflow to Lake Buchanan. Direct inflow to Lake Travis and the three reservoirs between Lake Buchanan and Lake Travis are based on gaged streamflow from the Llano River, Sandy Creek, and the Pedernales River (Figure 2). The drainage area for the three stations represents about 79% of the basin for Lake Travis and the associated three reservoirs.

Based on the calculations described above, monthly, seasonal (three-month period), and annual inflow volumes to the Highland Lakes were calculated for the period January 1942 through December 2013 (Figure 3) and used for analyses in this report. The LCRA presents an interactive map of the Highland Lakes Basin at http://hydromet.lcra.org/full.aspx, and the USGS has an interactive map presenting the locations and historic and current flow data for the streamflow stations at http://maps.waterdata.usgs.gov/mapper/index.html?state=tx.

The 1942–2013 mean inflow to the Highland Lakes is 1,673 cubic feet per second (ft^3/s), equivalent to 1.212 million acre-feet per year. Monthly inflow volumes to the lakes were analyzed to assess the distribution of such values. The 864 monthly values were sorted by magnitude to assess inflow volumes during the wettest and driest periods. Based on the analysis, relatively rare large regional floods produce most of the inflow to the lakes. For example, the wettest half of all months (the

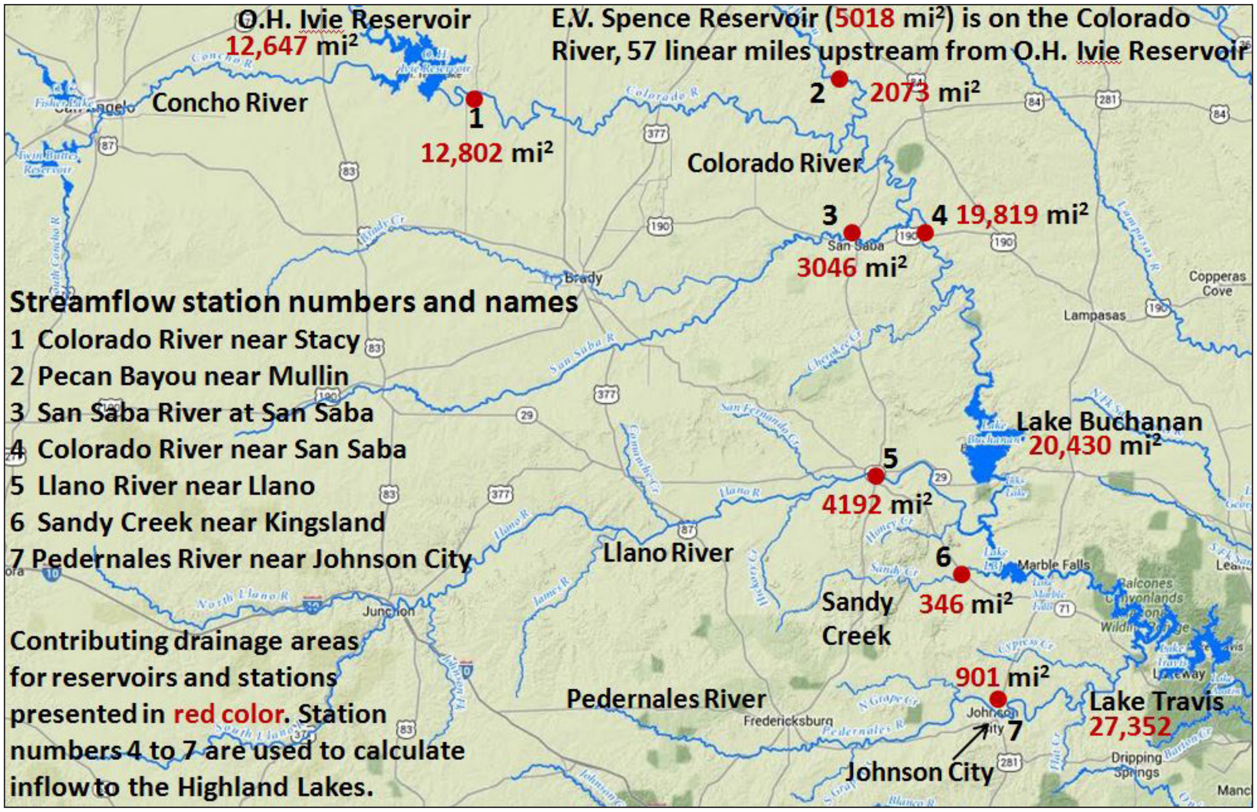

Figure 2. Locations of streams, reservoirs, and streamflow-gaging stations.

432 months with the greatest inflow volumes) produced 89% of the 1942–2013 total inflow volume to the lakes. Also, the wettest 10% of the months (87 months) produced 49% of the total inflow to the lakes. Additionally, the wettest 1% of the months (nine months) produced 13% of the total inflow volume.

Likewise, the driest months produce inflow volumes substantially lower than the mean inflow. For example, the driest half of the months (the 432 months with the lowest inflow volumes) produced only 11% of the total inflow volume to the lakes. Additionally, the 10% of the months with the lowest inflow volumes produced only 0.7% (less than 1%) of the total inflow volume.

A best-fit linear trend for the annual inflow volumes to the Highland Lakes indicates a 19% reduction in total inflow. Inflow volumes for each lake and the causes for changes in volumes are discussed below.

Inflow to Lake Buchanan

Annual inflow volumes to Lake Buchanan are presented in Figures 3 and 4. The mean inflow to Lake Buchanan is 772 ft^3/s, or 559,000 acre-feet per year, which represents 46% of total inflow to the Highland Lakes for the period 1942–2013. Prior to the completion of E.V. Spence Reservoir in 1969, inflow to Lake Buchanan represented 59% of total inflow to the Highland Lakes (Figure 3). However, since the completion of E.V. Spence Reservoir (Figure 5), inflow to Lake Buchanan represents only 39% of total inflow to the Highland Lakes and only 29% of such for 2006–2013.

Additionally, inflow to Lake Buchanan has decreased substantially over the 72-year period shown (Figure 5). A best-fit linear trend documents inflow to have decreased from about 792,000 acre-feet per year to about 323,000 acre-feet per year during the period—a 59% decrease. The portion of the Lake Buchanan Basin controlled by upstream major reservoirs has increased from 22% in 1942 to 72% since 1990 (Figure 4). The basin for O.H. Ivie Reservoir represents 62% of the Lake Buchanan Basin (Figure 2)—13 of the major reservoirs are upstream from O.H. Ivie Reservoir. An additional 10% of the Buchanan Basin is controlled by Brady Creek Reservoir and Lake Brownwood (Figure 5) on tributaries that enter the Colorado River downstream from O.H. Ivie Reservoir. Three of the smaller major reservoirs are in the drainage basin for Lake Brownwood. Information regarding these reservoirs and a map of their locations can be found on the Texas Water Development Board (TWDB) website (TWDB n.d. a).

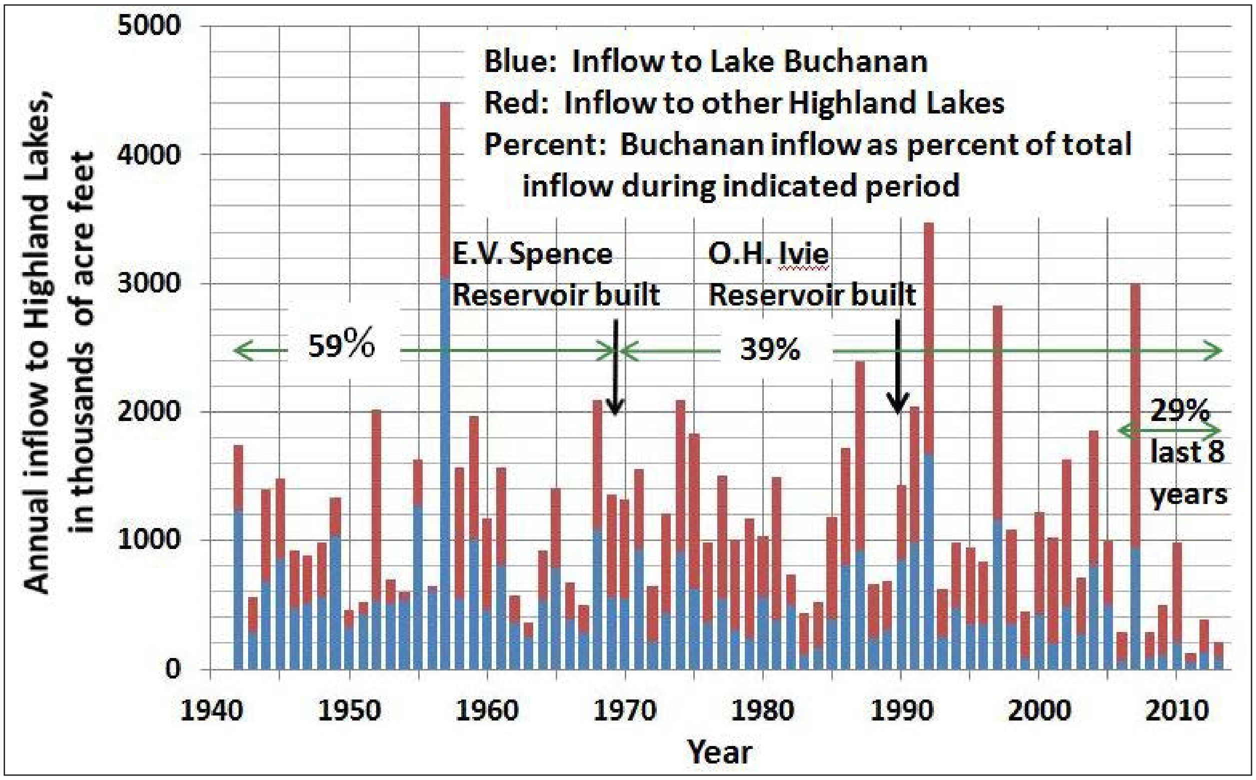

Figure 3. Annual runoff volumes to the Highland Lakes, 1942–2013.

Inflow reduction

The two largest reservoirs upstream from Lake Buchanan are E.V. Spence Reservoir and O.H. Ivie Reservoir. O.H. Ivie Reservoir was completed by the Colorado River Municipal Water District (CRMWD) in 1990 (Figure 2) and was filled to its capacity (554,000 acre-feet) by large floods in 1992. Wetter than normal years in 1996 and 1997 kept the reservoir nearly full; however, since 1998 its contents have been mostly declining.

The streamflow-gaging station on the Colorado River near Stacy, Texas is immediately downstream from O.H. Ivie Reservoir (Figure 2), and thus represents outflow from the reservoir. From 1968 to the completion of O.H. Ivie Reservoir in 1990, the streamflow volume at the gaging station (outflow from O.H. Ivie Reservoir) represented 32% of the inflow volume to Lake Buchanan (Figure 4). However, from 1990 through 2013, flow at the gaging station represented only 8% of inflow to Lake Buchanan. Additionally, since 1999, flow at the Stacy station represented only 2% of inflow to Lake Buchanan. Therefore, during the past many years, the Colorado River drainage basin downstream from O.H. Ivie Reservoir has produced the vast majority of the inflow to Lake Buchanan. However, small-discharge environmental releases are required from O.H. Ivie Reservoir (Hauck and Pandey 2015). For example, as represented by the Colorado River near Stacy gage, the monthly mean releases from O.H. Ivie Reservoir have averaged less than 1 ft^3/s, or 59 acre-feet per month, only twice since completion of the reservoir.

Based on this analysis, it is likely that releases from O.H. Ivie Reservoir will not represent substantial inflow contributions to Lake Buchanan until O.H. Ivie Reservoir and possibly the other upstream reservoirs are full or nearly full. However, as of July 29, 2016, O.H. Ivie Reservoir was only 23% full and E.V. Spence Reservoir was only about 10% full (CRMWD n.d. b). These two reservoirs are at low conditions; thus, substantial releases from O.H. Ivie Reservoir likely will not occur until that area receives substantial runoff from several large regional storms.

Additionally, outflow from Brady Creek Reservoir has decreased substantially from 1940 to 2013 (Figure 5). For example, from 1940 to 1986, the mean outflow from Brady was 17.0 ft^3/s, or 12,300 acre-feet per year, which represents about 2% of the mean inflow to Lake Buchanan. However, from 2001 to 2013 the mean outflow was 1.20 ft^3/s—an outflow reduction of 93%. Outflow data do not exist for Lake Brownwood on Pecan Bayou, but data for a downstream streamflow gage near the mouth of the creek document the mean flow to be 175 ft^3/s from 1968 to 1999 but only 129 ft^3/s from 2000 to 2013—a 26% reduction.

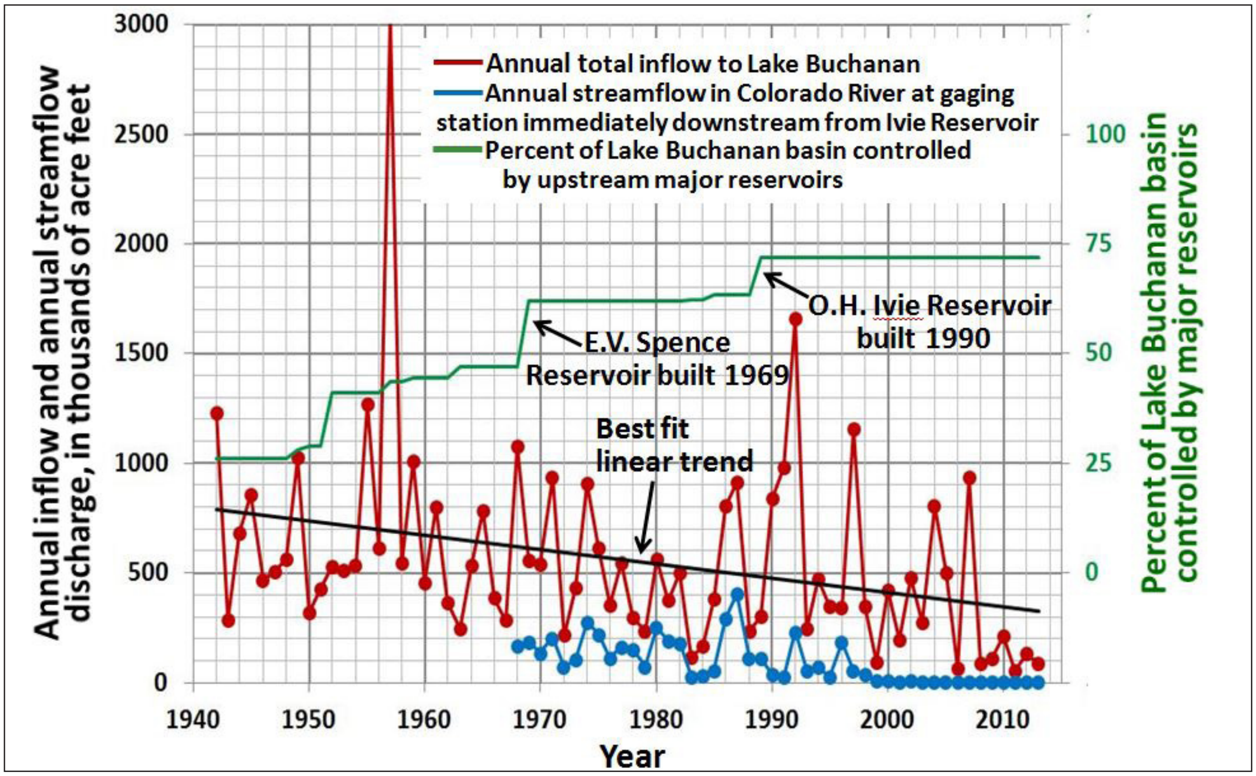

Figure 4. Temporal trends in inflow volumes to Lake Buchanan, 1942–2013.

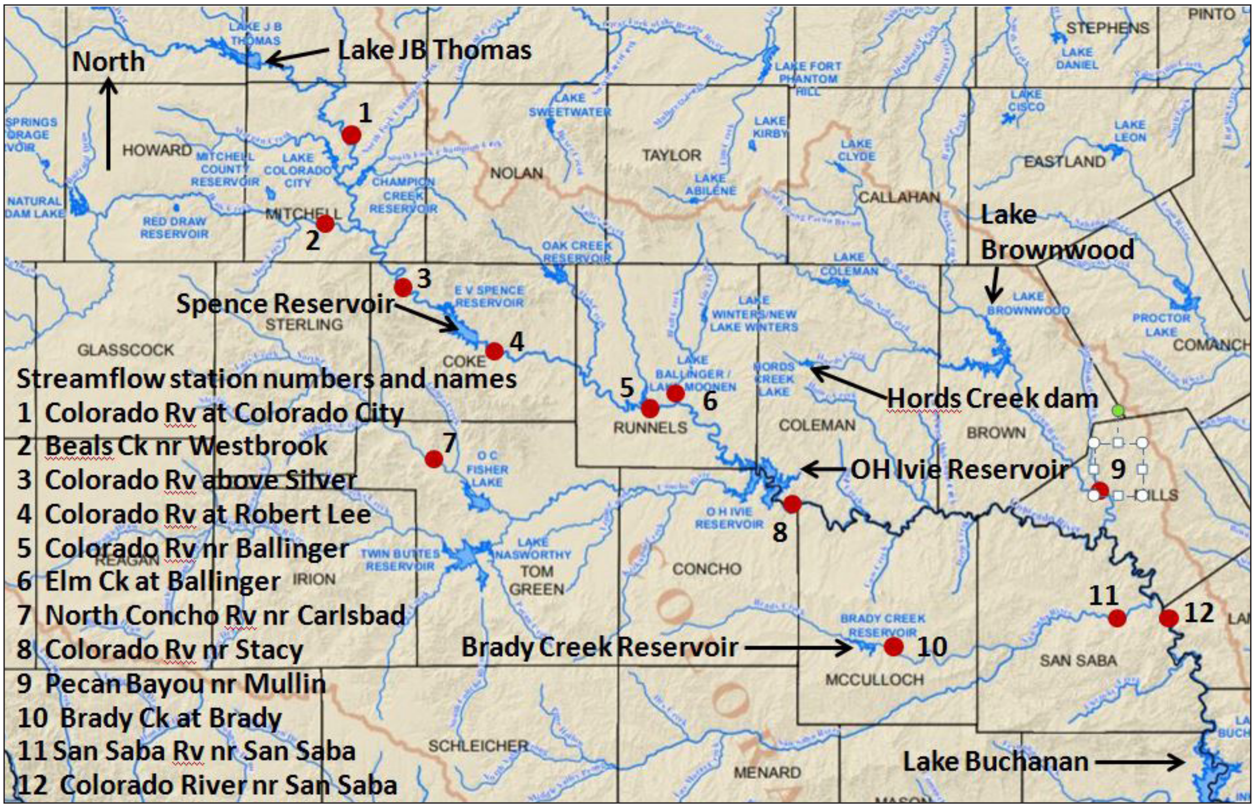

Figure 5. Locations of streamflow gages and other sites used for analyses.

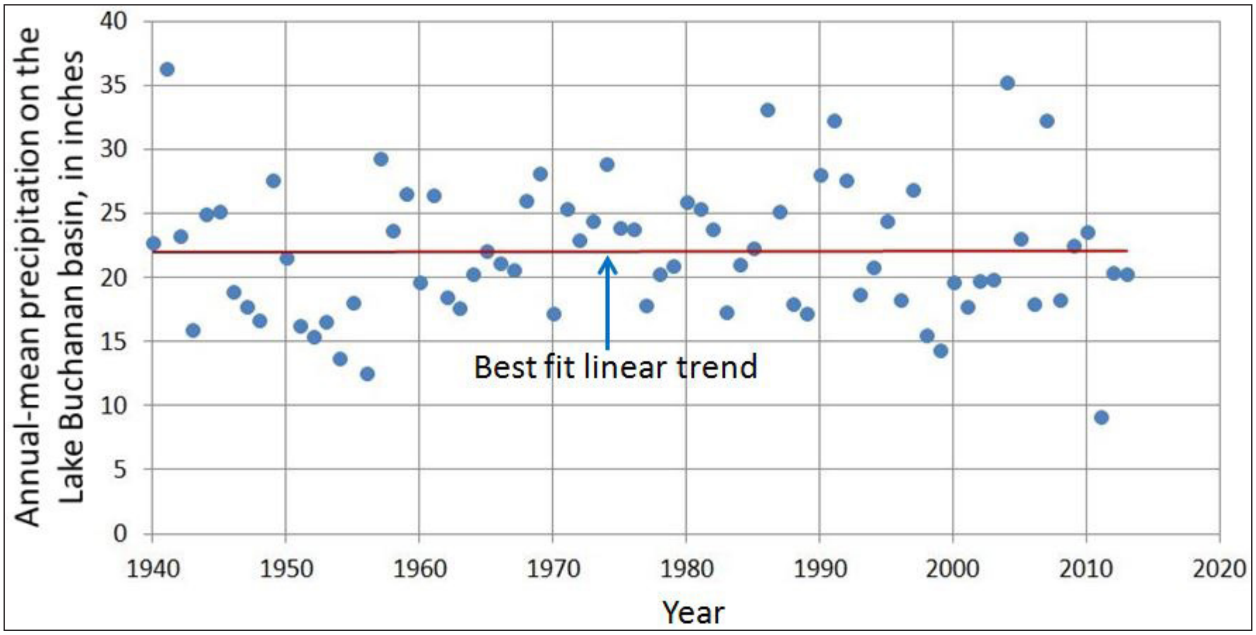

Figure 6. Annual precipitation on the Lake Buchanan Basin, 1940–2013.

Causes for inflow reduction

The purpose of this section is to identify and attempt to quantify for the Lake Buchanan drainage basin, the meteorologic and hydrologic factors that have contributed to the reduction of inflow to Lake Buchanan. Therefore, the changes in data values or significance for the factors and their impact on the reduction of inflow to Lake Buchanan from 1942 to 2013 are emphasized. The basin is believed to be free of major volumes of import or export of water and free of major deliveries of groundwater to the surface or of surface water to groundwater; thus, the factors identified below are believed to represent major water consumption within the basin. Data values for most of the factors associated with inflow reduction are estimated and have large potential error; however, the author believes the data values to be indicative of the relative magnitude of impact on the reduction of inflow values.

Precipitation and withdrawals

Temporal trends in precipitation were investigated as a potential factor affecting reduced inflow to Lake Buchanan. A graph presenting annual precipitation from 1940 through 2013 for the Lake Buchanan Basin is presented in Figure 6. The annual precipitation data are from the TWDB (TWDB n.d. c) and represent values of annual mean precipitation for the one-degree quadrangle numbers 506, 507, 606, 607, 608, and 609—the areas for those quadrangles approximate the drainage area for Lake Buchanan. A severe drought occurred in 2011, but annual precipitation values for most of the years from 2000 to 2013 have exceeded about 20 inches per year—a value within 2 inches of the long-term mean value of 22.12 inches per year (Figure 6). Additionally, the best-fit trend line indicates no meaningful temporal trend in annual precipitation for the Buchanan Basin.

However, infrequent large storms produce most of the runoff in the area. For example, for the Beals Creek, North Concho River, Elm Creek, and San Saba River streamflow-gaging stations (Figure 5), 1% of their largest daily-mean streamflow values from 1940 to 2013 contain 52%, 80%, 57%, and 31%, respectively, of the total flow volumes for the period. Therefore, daily precipitation data were analyzed for every National Weather Service rain gage in the Buchanan Basin with data from 1940 to 2013. The annual number of daily values with precipitation depths exceeding 2 inches was identified for each of the seven gages found. Based on this analysis, for each of the gages, the frequency of large storms since 2000 is comparable to the frequency of such storms prior to 2000. Therefore, changes in large-storm precipitation are not likely a major cause for reduction in inflow to Lake Buchanan.

Increases in surface water withdrawals from 1940 to 2013 were investigated as a potential source for inflow reduction to Lake Buchanan. The population for the 13 counties totally within the basin was 178,000 in 1940 and 244,000 in 2013—a 37% increase (Texas Almanac n.d.). However, other than for irrigation data beginning in 1958, surface water withdrawal data for the Buchanan Basin could not be found prior to 1974. Total reported surface water use was 112,900 acre-feet in 1974 and only 51,700 acre-feet in 2016 (TWDB n.d. b). Irrigation represented 58% of the 1974 water use but declined to only

36% of the 2016 use. Therefore, total water use, a large part of which includes irrigation, cannot be estimated based on water-use values for 1940 without substantial potential error in the value.

However, based on population data and per-capita use, it is estimated that 2016 water use was 37% greater than 1940 water use. Therefore, 1940 water use is estimated to be 37,700 acre-feet per year. All withdrawn water is assumed to be directly consumed. The permitted total withdrawal from the major reservoirs is 358,500 acre-feet per year—a value about six times greater than was reported withdrawn in 2016 and 64% of the mean-annual inflow to Lake Buchanan. Therefore, if future withdrawal values approach those for permitted values, additional reduction of inflow to Lake Buchanan would probably occur.

Temporal increases in unpermitted surface water withdrawals also are probably a major source of reduction in inflow to Lake Buchanan (2018 personal communications from David Bass, LCRA; unreferenced). However, data or information for this factor could not be found.

Reported total groundwater withdrawal for the 13 counties totally within the Buchanan Basin was 82,500 acre-feet in 1980 and 138,000 acre-feet in 2013. The pumpage increase of 55,500 acre-feet per year is substantial, but the impact on surface water availability is unknown. However, streamflow gain-loss studies conducted on the Colorado River, Beals Creek, Concho River, Elm Creek and San Saba River document large streamflow discharge gains in some channel reaches and large losses in other reaches. The gains and losses mostly represent interchange of water between stream channels and underlying aquifers. For example, a gain-loss study for the Colorado River from J.B. Thomas Reservoir to O.H. Ivie Reservoir in January 1987 documents the reach to be losing water in some parts and gaining in others, but the entire reach lost 23.6 ft^3/s (17,100 acre-feet per year) during high base-flow conditions (Slade et al. 2002). Increased groundwater pumpage probably reduces base-flow discharges in the major streams, but the majority of inflow to Lake Buchanan is flood runoff, which the author believes has had only a minimal impact from groundwater withdrawals.

Evaporation

Temporal changes in air temperature, wind speed, solar radiation, and relative humidity associated with climate change could cause an increase in evaporation rates, which would contribute to reductions of inflow to Lake Buchanan. Annual gross lake evaporation values from 1954 to 2013 for the Lake Buchanan Basin are presented in Figure 7. The data are from the TWDB (TWDB n.d. c) and represent the annual mean gross lake evaporation for one-degree quadrangle numbers 506, 507, 606, 607, 608, and 609—the areas for those quadrangles approximate the drainage area for Lake Buchanan. A best-fit linear trend for the data documents an increase of about 1.4 inches during the 60-year period. The trend was calculated to be an increase of 1.68 inches (3% increase) after adjustment for the longer period of 1942–2013. Based on the mean value for the 1940 and 2013 mean surface areas for all reservoirs in the basin, this increase represents an increase of 8,060 acre-feet per year or 1% of the mean inflow to Lake Buchanan (Table 1). To verify the finding above, a search was made for National Weather Service weather stations with long-term evaporation data within the Buchanan Basin. Two such stations were found: Hords Creek Dam in Coleman County and San Angelo Mathis Field in Tom Green County (Figure 5). Analysis of the evaporation data for the two stations substantiate a small temporal increase in evaporation comparable to that indicated above.

Additionally, total lake evaporation in the Lake Buchanan Basin has increased due to the proliferation of reservoirs in the basin (Table 1). Three databases for reservoirs in the area were used to assess evaporation and storage characteristics. In the basin area, the National Inventory of Dams (NID) identifies all 19 major reservoirs and 558 minor reservoirs, including all Natural Resources Conservation Service (NRCS) reservoirs (Table 1). This database (National Inventory of Dams n.d.) was used to determine the surface area and storage characteristics for the major reservoirs and NRCS reservoirs in Table 1. The database includes physical characteristics for each identified reservoir posing a failure risk or meeting specific criteria for minimum storage volume or minimum dam height. The Texas Commission on Environmental Quality (TCEQ) dam safety database represents dams that are routinely inspected by the agency. It includes 531 minor reservoirs in the area. This database was used to verify the reservoir characteristics from the NID database.

The National Hydrography Dataset (NHD) for water bodies in the Upper Colorado River Basin was created in about 2005 by the USGS using land use and aerial photo information. Water bodies in this database were used to develop the characteristics for "other minor reservoirs" in Table 1. The database identifies the location and exposed surface water area for all water bodies greater than about 0.25 acres in size but contains no other data or information about the water bodies. The coverage identifies 69,211 water bodies, excluding major and NRCS reservoirs; however, the majority of the water bodies are small (Kennedy Resource Company 2017). For example, surface areas are not available for 19% of the reservoirs—likely those with less than 0.25 acres of surface area. Also, an additional 70% of the water bodies have a surface area less than 1 acre. Many if not most of the water bodies probably are not reservoirs but herein are collectively referenced as "other minor reservoirs." Although data are not readily available, some of these reservoirs are within

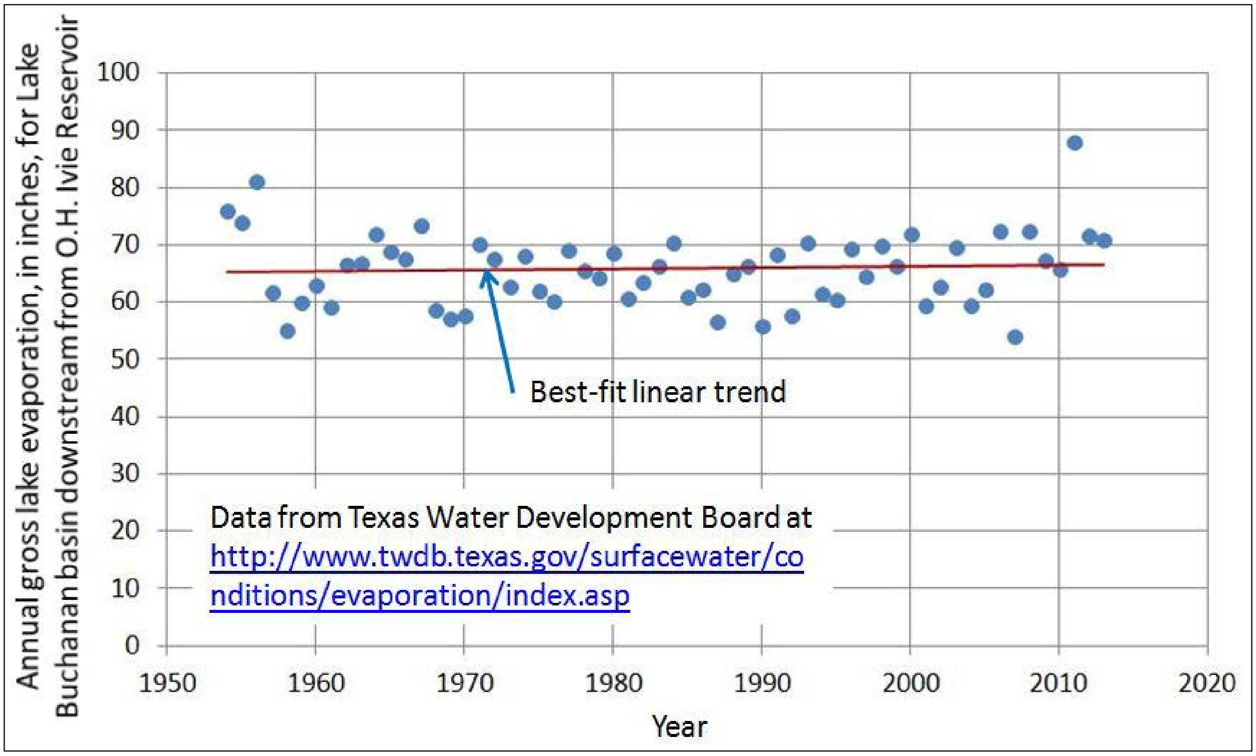

Figure 7. Annual mean gross lake evaporation for the Lake Buchanan Basin.

the non-contributing drainage area for the Colorado River, but the number of such reservoirs and their water-surface area are deemed to be minimal.

For 13 of the largest 19 major reservoirs, water elevations have been gaged since they began filling; thus, long-term mean pool areas and mean storage volumes were calculated based on the entire period of record (Table 1), from data maintained by the USGS (USGS n.d.) and the TWDB (TWDB n.d. a). The gaged reservoir data represent 96% of total conservation storage for the major reservoirs and 77% of total conservation storage for all reservoirs. Therefore, the evaporation and storage characteristics for all reservoirs and especially the major reservoirs presented in Table 1 probably contain minimal potential error. For the other major reservoirs and minor reservoirs, the average surface areas and average storage contents are estimated in Table 1.

The long-term mean storage contents for the major reservoirs without gaging data and the NRCS reservoirs are estimated to be about one-third of conservation storage (2018 personal communications from John Newman, unreferenced). Most of the reservoirs have a flat bed with sloping sides; thus, the long-term mean surface areas for these reservoirs are estimated to be one-half of the conservation pool area. Therefore, the evaporation loss for NRCS reservoirs and major reservoirs without water-elevation data are based on one-half of the value for the conservation pool area. However, the surface areas for minor reservoirs other than NRCS reservoirs are based on the NHD coverages collected in about 2005. The assumption is made that these surface-area values represent long-term mean conditions, even though, based on streamflow throughout the Colorado River Basin, 2005 was drier than long-term mean conditions. The conservation and flood storage for the 8,311 other minor reservoirs exceeding 1 acre of surface area were estimated based on mathematical relations between surface areas and storage characteristics for reservoirs in the other two reservoir databases. Additionally, the number of the other minor reservoirs existing in 1940 and their surface area and storage characteristics are based on reservoir completion dates and data from the same other two databases.

In 2013, the mean evaporation volume for all reservoirs, the major reservoirs, and the minor reservoirs represented 79%, 25%, and 54%, respectively, of the mean-annual inflow to Lake Buchanan (Table 1). The evaporation volume for reservoirs in 1940 was substantially less than that in 2013; thus, temporal increase in lake evaporation is a major cause for decreased inflow to Lake Buchanan.

Evaporation from stream channels is estimated based on data from discharge measurements made at nine streamflow gaging stations on the Colorado River and one station each on Beals Creek, the Concho River, Elm Creek, Pecan Bayou and the San Saba River (Figure 5). Based on the long-term median discharge value for each station and channel data for each dis-

Table 1. Hydrologic characteristics of reservoirs in the Lake Buchanan Basin.

Lake Buchanan began filling in 1940	Reservoir and water body types							
	All		Major[1]		NRCS[2]		Other minor[3]	
	1940	2013	1940	2013	1940	2013	1940	2013
Number of reservoirs or water bodies	17,302	69,545	2	19	0	315	17,300	69,211
Total drainage area (square miles)[4]	7,630	41,240	5,380	30,700	0	1,540	2,250	9,000
Surface area (acres)	--	--	--	--	--	--	--	--
Conservation pool	12,000	248,000	8,680	82,400	0	7,200	39,500	158,000
Long-term mean[5]	26,900	120,000	7,080	37,600	0	3,600	19,800	79,000
Net evaporation, mean annual (inches)[6]	43.88	43.88	43.88	43.88	0	43.88	43.88	43.88
Volume (thousands of acre-feet)[7]	98.3	439	25.9	137	0	13.2	72.4	289
Volume as percent of Buchanan inflow[8]	18%	79%	5%	25%	0%	2%	13%	52%
Storage, volume (thousands of acre-feet)	--	--	--	--	--	--	--	--
Conservation	253	2,500	138	2,000	0	41.8	115	459
Long-term mean[9]	152	815	114	648	0	13.9	38.3	153
Mean as percent of Buchanan inflow[8]	27%	146%	20%	116%	0	2%	7%	27%
Conservation minus long-term mean[10]	101	1,680	24	1,350	0	27.9	76.7	306
As percent of Buchanan inflow[11]	18%	301%	4%	242%	0%	5%	14%	55%
Flood	1,270	8,360	1,040	6,600	0	839	230	918

[1] Reservoirs with at least 5,000 acre-feet of conservation storage

[2] Floodwater retarding structures built by the Soil Conservation Service, now named the National Resources Conservation Service

[3] Data from aerial images as explained in text. All 1940 data for these reservoirs estimated. Conservation pool areas and storage capacities estimated only for the 8,311 reservoirs with pool areas exceeding one acre.

[4] Much of total drainage area duplicated—some reservoir basins are within the basins of other reservoirs

[5] Based on long-term gaged data for most major reservoirs and one-half of conservation pool area for other major reservoirs and NRCS reservoirs. Based on aerial photo images for other minor reservoirs

[6] For Lake Buchanan Basin—equals long-term mean annual gross lake evaporation (66.00 inches) minus long-term mean annual precipitation (22.12 inches)

[7] Product of long-term mean pool area and long-term mean annual net evaporation (43.88 inches)

[8] Based on 1942–2013 mean annual inflow to Lake Buchanan—559,000 acre-feet per year

[9] Based on long-term gaged data for most major reservoirs and one-third of conservation storage for other reservoirs

[10] Represents average conservation storage void, in thousands of acre-feet, that must be filled by runoff before full conservation storage, and typically outflow from reservoir, is attained

[11] Average conservation storage deficit expressed as percent of 1942–2013 mean annual inflow to Lake Buchanan

charge measurement, the stream width was determined for the median discharge at each gaging site (USGS n.d.). Also, based on the stream-mile distance between gages, the total area for the major stream surfaces during median flow conditions was calculated. Evaporation from minor streams is not included in this analysis, but most have small widths and intermittent flow; thus, evaporation from these streams is deemed to be minimal. The mean annual net evaporation rate of 43.88 inches (Table 1) was assumed to occur over the 6,030 acres of stream-surface area, which produces 22,000 acre-feet per year as the mean annual net evaporation from major streams—a value representing 4% of the mean annual inflow to Lake Buchanan. This analysis represents the period 1942–2013. Median stream widths, and thus the evaporation in 2013, might be slightly less than the long-term average due to temporal reduction of streamflow. However, the slight increase in evaporation rate mentioned above might offset that reduction. Therefore, it is likely that changes in stream evaporation are minimal and not a major factor of inflow reduction for Lake Buchanan.

Evaporation from wetted soil also is a major source of water loss in the basin. However, due to lack of long-term soil moisture and other data, a value for soil evaporation cannot be estimated without substantial potential error. However, it is unlikely that soil evaporation has substantially increased from 1942 to 2013; thus, this factor is not considered to be a major cause for reduction in inflow to Lake Buchanan.

Transpiration and reservoir losses to groundwater

Transpiration due to phreatophytes within reservoirs was evaluated for the major reservoirs in the Buchanan Basin. A study of transpiration from brush above the normal water level and within the O.H. Ivie Reservoir conservation pool area found that brush removal would provide a water yield averaging about 25,000 gallons per acre per year (Hauck and Pandey 2015). The assumption was made for each of the major reservoirs within the Buchanan Basin that the land area between the mean surface area and that inundated by the flood storage pool is covered with the same type and density of brush as that within O.H. Ivie Reservoir. This total area is about 92,300 acres, which, based on the yield identified above, is only 7,080 acre-feet per year—a value representing only 1.3% of the mean annual inflow to Lake Buchanan.

However, transpiration and other losses from NRCS floodwater retarding structures (Table 2) are substantial. Consumptive losses for the reservoirs, which include evaporation, transpiration, and seepage to groundwater, have been extensively studied by the USGS via calculations and analyses of inflow-outflow water budgets. Landowners are prohibited from withdrawing water from most NRCS reservoirs; thus, water-use for the reservoirs is considered to be minimal (2018 personal communications from John Newman, NRCS; unreferenced). Six NRCS reservoirs in each of two studied stream basins within the Lake Buchanan Basin were gaged for many years to measure monthly inflow and outflow volumes for the reservoirs. The volume of water by which inflow exceeds outflow represents the consumption value. Water budgets were computed for reservoirs in the Deep Creek Basin in McCulloch County and Mukewater Creek Basin in Coleman County (Figure 5). Based on data for Deep Creek, the mean consumptive loss for the reservoirs represents 30% of inflow and losses for transpiration, and groundwater seepage exceeded net evaporation by 113% (Gilbert and Sauer 1970). Losses for transpiration and groundwater seepage for the Mukewater reservoirs exceeded net evaporation by 91%; thus, the mean value for the two basins is 102%. Net evaporation losses for the NRCS and other minor reservoirs were calculated independently of these studies and reported in Table 1; thus, losses for transpiration and groundwater seepage were assumed to be 102% of net evaporation values.

However, the soils beneath the Deep Creek and Mukewater Creek reservoirs contain greater clay content than the majority of other NRCS structures in the Buchanan Basin; thus, consumption for the other NRCS reservoirs likely is greater due to increased seepage to groundwater (2018 personal communications from John Newman, NRCS; unreferenced). Therefore, the loss identified above is a minimal value. The same consumptive loss for transpiration and groundwater seepage is assumed to apply to the other minor reservoirs. Therefore, total water losses from all minor reservoirs for transpiration and seepage to groundwater was calculated to be 308,000 acre-feet per year in 2013—a value equal to 55% of the mean annual inflow to Lake Buchanan (Table 2).

The evaporation value for the minor reservoirs is about double that for the major reservoirs, but transpiration for the minor reservoirs exceeds that for the major reservoirs by many orders of magnitude (Table 2). For a comparison of transpiration losses, all the major reservoirs and all the 8,311 other minor reservoirs with surface areas exceeding 1 acre were used. Assuming a circular shape for all reservoirs, the total circumference for the conservation pool would be 175 miles for the major reservoirs and 5,885 miles for the other minor reservoirs. Additionally, assuming that phreatophytes exist around each reservoir conservation pool for a distance of 0.05 miles (about 260 feet), then there would be a phreatophyte zone of 5,700 acres around the major reservoirs and 147,000 acres around the minor reservoirs. Though the reservoirs are not perfectly circular, this exercise demonstrates the extent by which the area of phreatophyte coverage around the minor reservoirs exceeds that around the major reservoirs.

Information or data regarding losses to groundwater from major reservoirs could not be found for the area. The results for inflow-outflow water budgets performed for a dry period for Lake J.B. Thomas and Brady Creek Reservoir accounted for essentially all reservoir losses without the inclusion of reservoir losses to groundwater. Therefore, such losses likely are minimal.

However, transpiration losses are considerable in the stream channels upstream from O.H. Ivie Reservoir (Slade and Buszka 1994). Prior to 1950, salt cedar was confined to a few areas in small thickets; however, from 1950 to 1969, areal coverage increased at least 500% (Larner et. al 1974). As of 1969, salt cedar of various densities covered 1,450 acres in the Colorado River flood plain. As of 1982, salt cedar covered about 10,000 acres in the Colorado River flood plain and about 2,500 acres in the Beals Creek flood plain in the study area (Slade and Buszka 1994).

The lengths of the reaches of the Colorado River, Beals Creek, Elm Creek, and the Concho River upstream from O.H. Ivie Reservoir are 239 miles, 13 miles, 10 miles, and 33 miles, respectively. The flood plain along the Colorado River covers

Table 2. Summary of water losses in the Lake Buchanan Basin, 1942–2013.

Lake Buchanan began filling in 1942 All values in acre-feet per year	Year		Increase in data value 1942–2013	Data value increase as percent of	
	1942	2013		annual-mean inflow to Lake Buchanan	1942–2013 reduction in inflow to Lake Buchanan
All reservoirs	--	--	--	--	--
Net evaporation	98,300	439,000	341,000	61%	73%
Transpiration and other[1]	73,900	315,000	241,000	43%	51%
Major reservoirs	--	--	--	--	--
Net evaporation	25,900	137,000	111,000	20%	24%
Transpiration	111	7,080	6,970	1%	1%
Minor reservoirs	--	--	--	--	--
Net evaporation, total	72,400	302,000	230,000	41%	49%
TRNS reservoirs	0	13,200	13,200	2%	3%
Other reservoirs	72,400	289,000	217,000	39%	46%
Other losses, total[2]	73,800	308,000	234,000	42%	50%
TRNS reservoirs	0	13,500	13,500	2%	3%
Other reservoirs	73,800	295,000	221,000	40%	47%
Surface water withdrawals[3]	37,700	51,700	14,000	2%	3%
Channel transpiration[4]	18,900	189,000	170,000	30%	36%
Channel evaporation[4]	22,000	22,000	0	0%	0%

The vast majority of basin losses are from reservoirs. Basin losses exceed the reduction of inflow to Lake Buchanan because much of the water loss from the reservoirs would otherwise be lost downstream as evapotranspiration in the channel before arriving at Lake Buchanan.

Although values could not be found, increased evapotranspiration outside stream channels due to increased phreatophytes is probably a major cause for reduced inflow to Lake Buchanan.

See Table 1 for additional information and data for reservoirs.

[1] Represents transpiration losses for major reservoirs and losses for transpiration and seepage to groundwater for minor reservoirs

[2] Represents transpiration and seepage to groundwater

[3] As reported based on permits. Unpermitted withdrawals considered to be substantial.

[4] Represents major stream channels as described in this report

34,200 acres, and an additional 11,000 acres is included for the flood plain around E.V. Spence Reservoir. Flood plains for Beals Creek, Elm Creek, and the Concho River cover about 3,200 acres, 1,200 acres, and 12,000 acres, respectively. As of 1992, excluding E.V. Spence Reservoir, 50,600 acres of flood plain along the four streams were covered by salt cedar and mesquite. The transpiration rate from phreatophytes across the flood plain of the four major streams is estimated to be 29.6 inches per year on the basis of the coverage data for salt cedar and mesquite and the Blaney-Criddle formula (Rantz 1968). This transpiration loss calculates to be 125,000 acre-feet per year (Slade and Buszka 1994)—a value representing 130% of the mean annual inflow to O.H. Ivie Reservoir (CRMWD n.d. a) and 22% of the mean annual inflow to Lake Buchanan. After 1994, the CRMWD initiated control measures for phreatophytes in major stream channels, which likely have mitigated spread of the phreatophytes; thus, it is likely that the current phreatophyte coverage for the stream channels listed above is comparable to that in the 1990 decade (2018 personal communications from John Newman, NRCS; unreferenced).

Based on the estimated increase in brush described above in the years 1950–1969, 1969–1982, and 1982–1992, phreatophyte coverage is estimated to have been more than 1000% greater in 1992 than in 1950. However, some brush likely

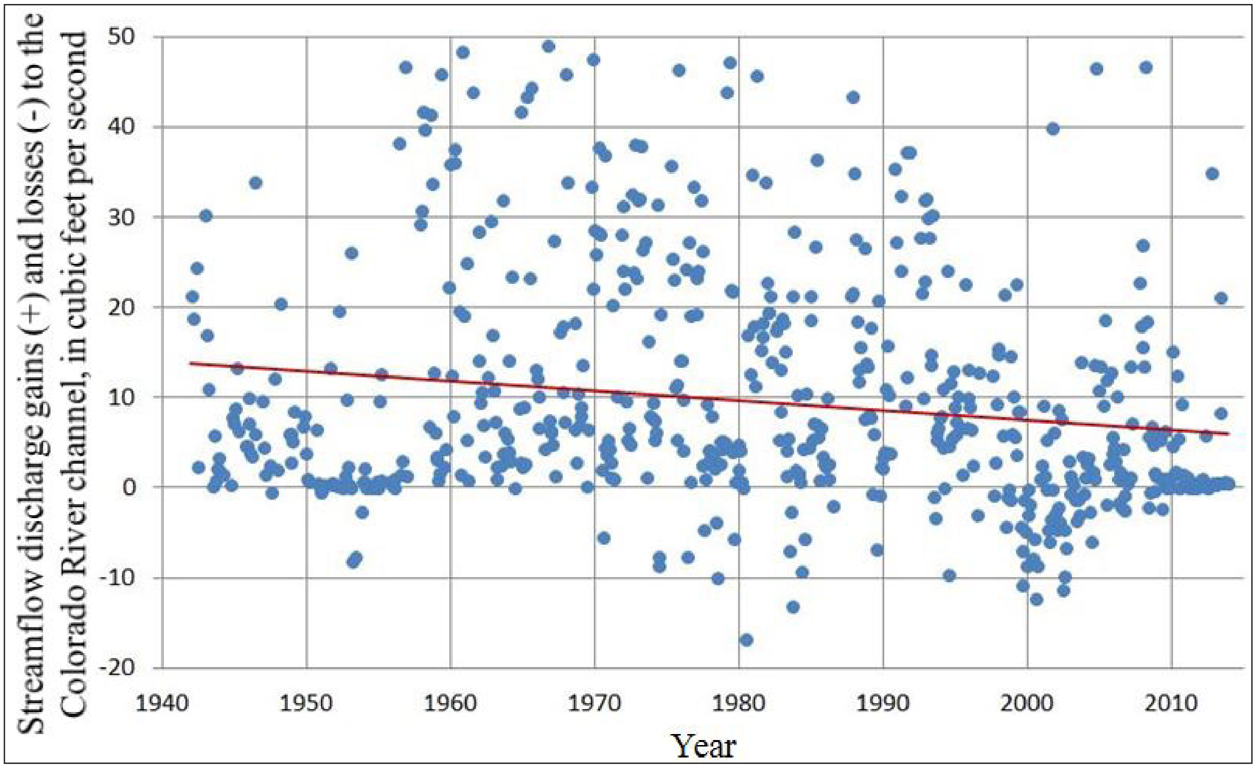

Figure 8. Channel gains and losses for the Colorado River between E.V. Spence Reservoir and O.H. Ivie Reservoir.

existed in the floodplains in 1940; thus, channel transpiration at that time is estimated to be about 10% of that in 1992 and 2013. Phreatophyte density in the 201-river mile reach of the Colorado River between O.H. Ivie Reservoir and Lake Buchanan, and the 58-mile reach of Pecan Bayou from Lake Brownwood to its mouth (Figure 5) is estimated to be about one-half of that in the channel upstream from O.H. Ivie Reservoir (2018 personal communications from David Bass, LCRA; unreferenced). Additionally, the width of the floodplain for Pecan Bayou is about one-half of that of the Colorado River; thus transpiration in these reaches is estimated to be about 49,000 acre-feet per year in 2013. Additionally, phreatophyte density in the 140-mile reach of the San Saba River is estimated to be one-quarter of that in the Colorado River upstream from O.H. Ivie Reservoir (2018 personal communications from David Bass, LCRA; unreferenced); thus, transpiration for that stream is estimated to be about 15,000 acre-feet per year. This analysis does not account for transpiration from phreatophytes in tributaries to the major streams, but total transpiration from all the major streams is 189,000 acre-feet per year—a value representing 34% of the mean inflow to Lake Buchanan. Therefore, the increase in transpiration due to spread of phreatophytes in streambeds is a major cause of reduced inflow to Lake Buchanan.

In an attempt to verify temporal increases in loss of flow in the Colorado River channel, an analysis was conducted for the 47-mile Colorado River channel from a streamflow gage immediately downstream from E.V. Spence Reservoir to a gage about one-half the distance to O.H. Ivie Reservoir (Figure 5, station numbers 4 and 5). The analysis is based on low-flow discharges because during such conditions, little if any overland flow or local runoff exists. Thus, the majority of runoff is within the channel of the Colorado River. Based on comparison of monthly mean discharge values, a best-fit linear trend indicates a decrease of 8.1 ft^3/s in channel flow from 1940 to 2013 (Figure 8). This represents, from 1940 to 2013, a channel loss increase of 5,900 acre-feet per year or 125 acre-feet per year per mile of channel. For the Colorado River channel investigated by Slade and Buszka (1994), the 1992 channel loss due to phreatophytes was about 420 acre-feet per year per mile. However, the latter analysis evaluated transpiration losses for the flood plain while the channel-flow analysis identifies losses during low-flow conditions.

Brush coverage outside streambeds is increasing in the North Concho River Basin and in much of the remainder of the Concho River Basin (2018 personal communications from Chuck Brown, UCRA; unreferenced). For a paired watershed study of two small basins within the North Concho River Basin, brush was mostly eradicated in one basin and the evapotranspiration rate was compared to that for the untreated basin. The evapotranspiration rate for the treated basin was as much as 25% lower than that for the untreated basin (Saleh et al. 2009).

Within the Buchanan Basin, brush coverage has substantially increased outside stream channels from 1942 to 2013. However, data or information that would document the extent of increased transpiration due to such could not be found. The author believes the increase in transpiration due to increased brush coverage outside stream channels would be greater than that within major channels as documented above.

Conclusion and summary

An analysis is made of temporal trends in runoff from large subbasins within the Buchanan Basin to document inflow reduction without the impact from major reservoirs. Chosen for analysis were large basins with long-term gaged streamflow values (generally 1942–2013), and no or only small major reservoirs. In order to document spatial variability, a basin was chosen in each of the northern, western, eastern, and southern parts of the Buchanan Basin. Respectively, these basins are Beals Creek, the North Concho River, Elm Creek, and the San Saba River (Figure 5). Data from 1942 to 2013 exist for each of these gages except for the Beals Creek gage, which has data from 1958 to 2013.

A substantial temporal decrease in annual runoff was found for each of the four streams. The decreases indicated by the best-fit linear trend for Beals Creek, the North Concho River, Elm Creek, and the San Saba River are 50%, 98%, 38%, and 37% respectively (Figures 9-12). Based on the linear trend for 1958–2013, the percent decrease for Beals Creek was adjusted to represent that for 1942–2013. Removing the last 10 or 12 years of flow data would cause the trends to indicate almost no temporal reduction in flow for all but the North Concho River. The four basins cover 4,952 square miles, or 24% of the Lake Buchanan Basin, and the results are believed to be representative of the remainder of the basin. The major causes for the reduction in runoff for the North Concho River are increased evapotranspiration due to the spread of brush and the proliferation of minor reservoirs (2018 personal communications from Chuck Brown, UCRA; unreferenced). These factors also are probably responsible for decreased runoff for the other three basins. For example, the number of identified other minor reservoirs in the basins for Beals Creek, the North Concho River, Elm Creek, and the San Saba River are 7,557, 849, 2,852, and 6,039 respectively (Kennedy Resource Company 2017). The vast majority of the reservoirs did not exist in 1942. However, the total surface area for the reservoirs in the North Concho River Basin is only 833 acres, which represents about 0.1% of the basin area; thus, evapotranspiration from reservoirs is probably not a major cause of runoff reduction for the basin.

In addition, an analysis of runoff was conducted for the downstream-most part of the Lake Buchanan Basin not regulated by major reservoirs—the part of the basin area downstream from O.H. Ivie Reservoir, Brady Creek Reservoir, and Lake Brownwood (Figure 5). Streamflow gages exist immediately downstream from each of the three reservoirs (Figure 5, station numbers 8-10); thus, the annual mean discharge values for these gages were subtracted from those for the Colorado River near San Saba station (Figure 5, station number 12) in order to document runoff values from the intervening basin area. Based on the common period of record, 1968–2013, the mean runoff is 341 ft³/s (247,000 acre-feet per year) and a best-fit linear trend documents the discharge to have decreased from 414 ft³/s to 267 ft³/s—a 36% reduction (Figure 13). Extending this trend to the 72-year period from 1942 to 2013 produces a mean discharge of 382 ft³/s (277,000 acre-feet per year) and a flow reduction of 230 ft³/s or 46%. A major cause for runoff reduction is evaporation and transpiration losses from the proliferation of minor reservoirs in the area, most of which were built after 1942. Based on the USGS NHD coverage, 23,485 reservoirs with a total surface area of 14,615 acres exist in the area. Based on the net evaporation rate for the area, total evaporation losses in 2013 were about 53,400 acre-feet, and losses to groundwater and transpiration from the reservoirs were about 54,500 acre-feet. These losses collectively represent 44% of the mean runoff from the area and a large percentage of reduced runoff. The remaining reduction in flow is attributed to increases in phreatophytes within and outside stream channels and probably to increased unpermitted withdrawals from the reservoirs and streams due to population increases (2018 personal communications from Chuck Brown, UCRA; unreferenced).

When Lake Buchanan began filling in 1942, its basin, which covers 20,430 square miles, contained two major reservoirs that controlled 22% of the basin. Eight percent of the basin was controlled by Lake Brownwood. The other major reservoir, Lake Nasworthy, controlled 14% of the Lake Buchanan Basin but because of its minimal conservation storage volume of only 9,600 acre-feet, it was basically a "flow-through" reservoir. Additionally, in 1942, about half of the minor reservoirs within the NID database were in the basins for Lakes Nasworthy or Brownwood; thus, the vast majority of 92% of the Lake Buchanan Basin was unregulated by reservoirs. In 1942, evaporation from all reservoirs represented only 18% of the value for mean annual inflow to Lake Buchanan (Table 2). Reservoir transpiration and seepage to groundwater collectively represented about 13% of the mean inflow value. Also, surface water withdrawals and transpiration from major channels represented 7% and 3%, respectively, of the mean inflow value. Evaporation losses from streams were about 4% of the inflow value. However, most of the consumption values for 1942 are estimated and subject to substantial potential error. Major sources for losses also include evapotranspiration outside stream channels and unreported surface water withdrawals. However,

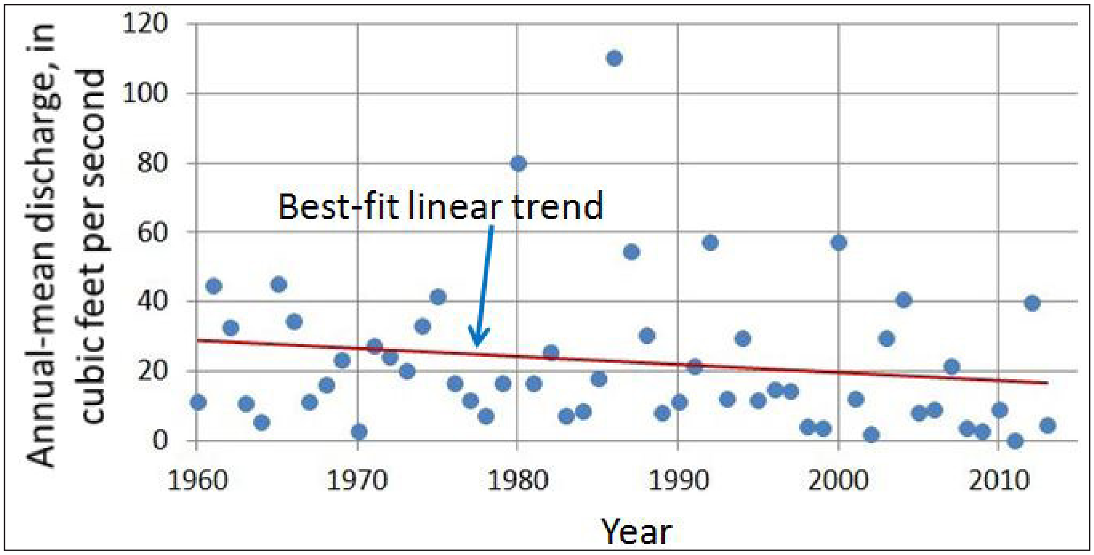

Figure 9. Annual mean discharges for Beals Creek near Westbrook, Texas.

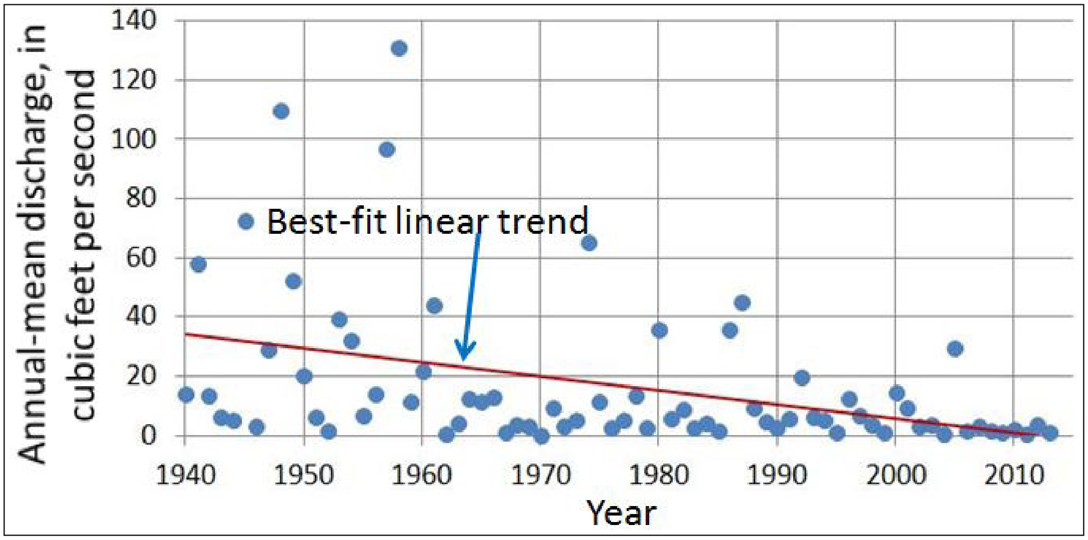

Figure 10. Annual mean discharges for the North Concho River near Carlsbad, Texas.

data values for neither could be estimated without substantial potential error. Additional information and data for basin losses are summarized in Table 2.

Finally, the average storage volume for the existing reservoirs in 1942 was less than conservation storage by only about 101,000 acre-feet—a value that represented only 18% of the mean-annual inflow to Lake Buchanan (Table 1). Therefore, only a minimal volume of runoff within the Lake Buchanan Basin was attenuated by deficits in conservation storage within reservoirs.

However, by 2013, the Buchanan Basin contained 19 major reservoirs, which control 72% (14,700 square miles) of the basin. About half of the controlled basin is within the basins of two or more major reservoirs. Also, more than 69,000 minor reservoirs were within the basin. The total drainage area for all reservoirs is 41,240 square miles; thus, on average, runoff is attenuated by 2.0 reservoirs en route to Lake Buchanan. Evaporation losses from the reservoirs represented 79% of the value for mean inflow to Lake Buchanan and was 7.5 times greater than water use in the basin. Reservoir transpiration and seepage to groundwater collectively were 56% of the mean inflow value. Additionally, surface water withdrawals and transpiration from major channels represented 9% and 34%, respectively, of the value for mean inflow to Lake Buchanan. Evaporation losses from streams was about 4% of the inflow value.

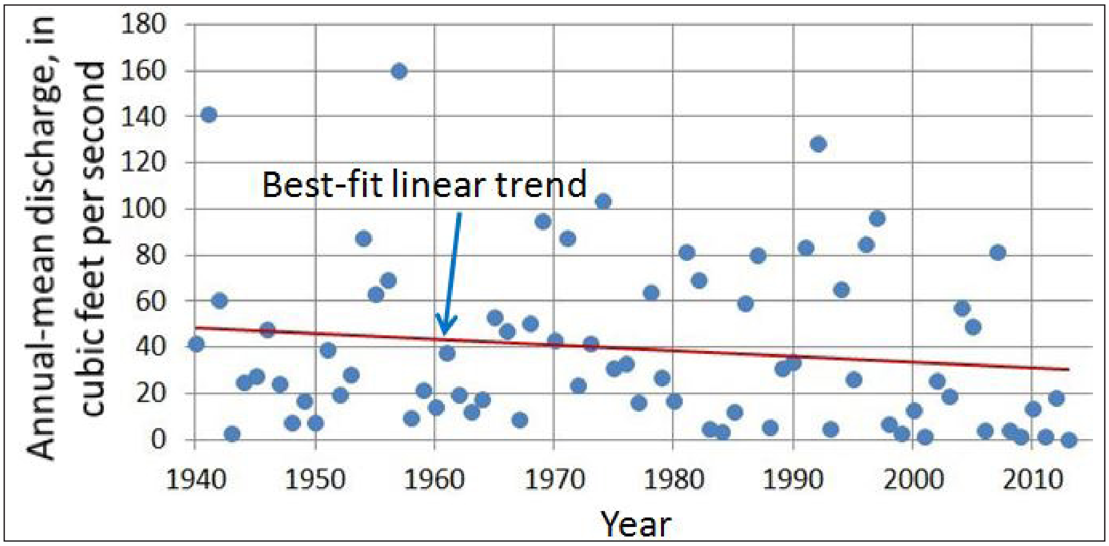

Figure 11. Annual mean discharges for Elm Creek at Ballinger, Texas.

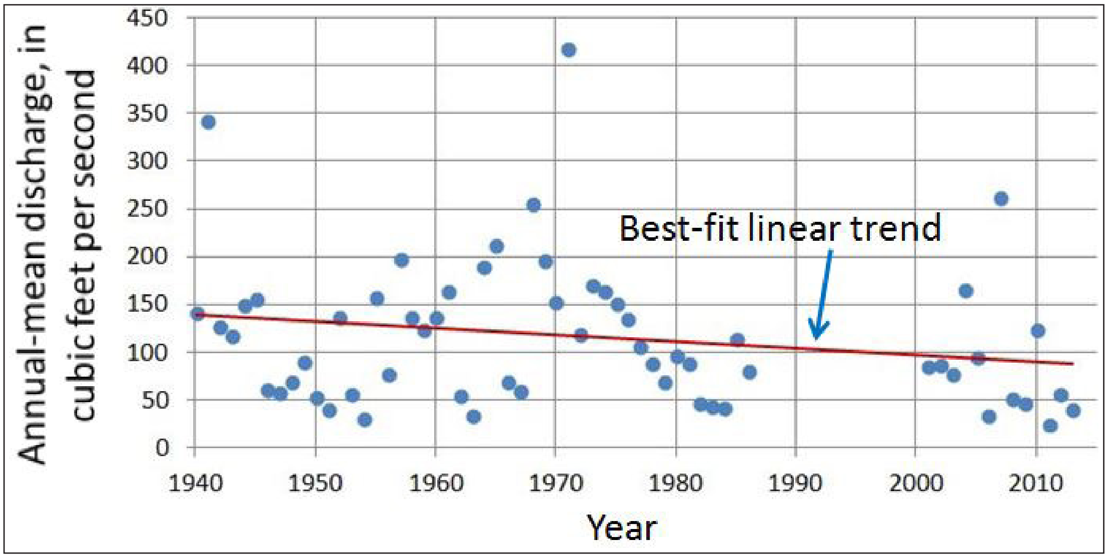

Figure 12. Annual mean discharges for the San Saba River at San Saba, Texas.

Some of the consumption data are estimated and subject to large potential error. However, the 2013 consumption values are considered to have much less potential error than the 1942 values. Major sources for losses also include evapotranspiration outside stream channels and unreported surface water withdrawals. However, data values for neither could be estimated without substantial potential error. Additional information and data for basin losses are summarized in Table 2. Finally, the average storage volume for the existing reservoirs was less than conservation storage by about 1,680,000 acre-feet—a value that represented 301% of the mean annual inflow to Lake Buchanan (Table 1); thus, the deficit in reservoir conservation storage is three times the value for the mean annual inflow to Lake Buchanan.

Also, an additional 8.4 million acre-feet of flood storage exists for the major reservoirs; however, the vast majority of this storage is attenuated but released downstream. Total flood storage for the NRCS reservoirs (Table 1) is much larger than the conservation storage for these reservoirs. However, the purpose of these structures is to attenuate flood peaks—their dams contain discharge pipes, which drain flood storage after storms. Thus, such storage has minimal if any impact on downstream runoff volumes. Additionally, only rare large storms produce sufficient runoff to produce flood storage in most of the struc-

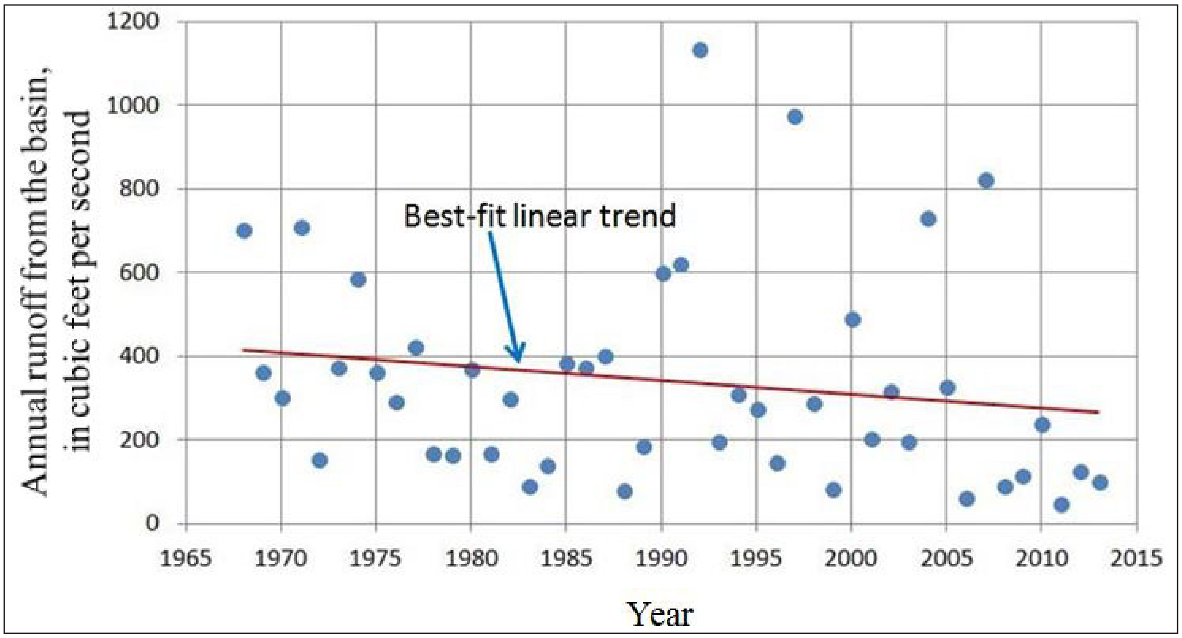

Figure 13. Runoff from the basin upstream from Lake Buchanan and downstream from O.H. Ivie, Brady Creek, and Brownwood reservoirs.

tures (2018 personal communications from John Newman, NRCS; unreferenced).

From 1942 to 2013, inflow to Lake Buchanan was reduced by 647 ft^3/s or 469,000 acre-feet per year. During the same period, increased lake evaporation represented 73% of the value for inflow reduction, and increased transpiration in major stream channels represented 36% (Table 2). The 1942–2013 increase in reservoir transpiration and seepage to groundwater was 51% collectively of the value for inflow reduction, and increased surface water withdrawal was 3%. Although information for such could not be found, increased transpiration outside stream channels due to spread of phreatophytes is believed to be a major cause for inflow reduction, as is increased unreported surface water withdrawals.

Finally, based on the linear trend for inflow to Lake Buchanan (Figure 4), the mean inflow value was 792,000 acre-feet per year in 1942 and 323,000 acre-feet per year in 2013—values that represent 3.3% and 1.3%, respectively, of the mean annual precipitation on the Buchanan Basin. Therefore, in 1942, almost 97% of precipitation was consumed in the basin and did not inflow to Lake Buchanan. Even during relatively natural conditions in the basin, before most reservoirs and the spread of phreatophytes, only a minimal amount of rainfall became runoff to Lake Buchanan. By 2013, almost 99% of precipitation was consumed. However, the value for the identified increase in basin consumption from 1942 to 2013 greatly exceeds the value for the decrease in inflow to Lake Buchanan (Table 2). This is because much, if not most, of any restored consumption would be consumed downstream and thus would not inflow to Lake Buchanan. For example, potential evapotranspiration from land and stream channels and potential channel losses to groundwater exceed actual values most of the time. For instance, any increased discharge in the Colorado River downstream from O.H. Ivie Reservoir would extend the width of the stream, which would cause increased evapotranspiration during the long travel time. Also, stream channel losses to groundwater in the Colorado River channel from J.B. Thomas to O.H. Ivie Reservoir increase with increased streamflow discharge (Slade et al. 2002), as do streamflow losses in the 9.7 mile reach of the Colorado River channel immediately upstream from Lake Buchanan (Braun and Grzyb 2015).

Additionally, stream travel time for runoff is extensive, which creates long durations for flow to be consumed. For example, based on stream velocity measurements by the USGS (USGS n.d.) at nine streamflow gages on the Colorado River in the Lake Buchanan Basin, the travel time for the 202-mile stream distance from O.H. Ivie Reservoir to Lake Buchanan is about 47 days during low-flow conditions and 7 days during high-flow conditions. The travel time for the 423-mile distance from Lake J.B. Thomas to Lake Buchanan is about 98 days during low-flow conditions and 19 days during high-flow conditions. Therefore, it is the author's opinion that much, if not most, "restored" water losses in the basin would not inflow Lake Buchanan, many miles downstream.

Inflow to Lake Travis and the other small reservoirs

Direct inflow to Lake Travis, excluding that released from Lake Buchanan, increased 42% from 1942 to 2013. Unlike the basin for Lake Buchanan, no major reservoirs exist in the basins that feed Lake Travis and the three small reservoirs between Lakes Buchanan and Travis (Figure 2). In order to assess temporal trends in inflow to Lake Travis and the other reservoirs, a double-mass graphical analysis was conducted for annual inflow volumes to the lakes and associated annual precipitation on the basin for the lakes. Figure 14 presents, for 1942 through 2013, the relation between cumulative values of annual precipitation and cumulative values for annual inflow volumes to Lake Travis and the other 3 reservoirs. The annual precipitation data are from the TWDB (TWDB n.d. b) and represent the mean values of the annual mean precipitation for one-degree quadrangle numbers 708 and 709. The areas for those quadrangles approximate the drainage area providing inflow to Lake Travis and the other reservoirs.

A best fit linear trend to the data is included in Figure 14. Based on the relations between the plotted values, a change in the slope of the plotted cumulative values is not evident. A change in the slope of the best fit line would have indicated a substantial change in inflow characteristics to the lakes. A decrease in the slope of the line would have indicated a substantial decrease in inflow volumes, which could have been caused by phenomena such as increased surface water withdrawals, increased groundwater withdrawals, or other loss of runoff due to, for example, land-use changes. The findings, however, are inconclusive due to the relatively weak statistical relations between values of annual precipitation and annual inflow. Therefore, it is unknown if a minor reduction in inflow volumes has occurred during the period of record for the data.

To evaluate the potential effect of water use on inflow volumes to Lake Travis and three associated reservoirs, values for annual surface water withdrawals and annual groundwater withdrawals were aggregated for each of the Llano and Pedernales River basins (Figure 2). These data are estimated by the TWDB (TWDB n.d. b) . The data are aggregated by county: Llano, Mason, and Kimble counties were used to represent the Llano River Basin, and Blanco and Gillespie counties represent the Pedernales River Basin. A detailed map presenting the rivers and county boundaries is available online (TWDB 2014). Surface water withdrawals occur directly from the streambeds, but it is likely that some of the withdrawal volumes are not directly consumed—part of such volumes are probably directly returned to the stream. Likewise, some of the groundwater withdrawals are likely not directly consumed, and part of such volumes could be directly returned to groundwater or streams. Additionally, at least some of the groundwater withdrawals, especially those remote from major streambeds, would likely cause minimal, if any, reduction in streamflow volumes. Furthermore, some groundwater may be produced from regional flow paths that would have little to no impact on local streamflow.

Based on the data, groundwater withdrawals for the Llano River Basin represent a mean value of about 14 ft^3/s over the last several years, and surface water withdrawals represent about 13.4 ft^3/s. Total withdrawals (groundwater and surface water) represent about 72% of the lowest annual mean gaged flow in the Llano River but only about 7% of the gaged long-term (1942–2013) mean flow at the gage. Therefore, based on this analysis, it is likely that withdrawals would cause substantial reduction in runoff during dry periods only. Based on data from the TCEQ, permitted total surface water withdrawals from the Llano River Basin represent about 20 ft^3/s (TCEQ n.d.). However, at least some of the permitted water use is likely not being withdrawn.

For the Pedernales River Basin, groundwater withdrawals have increased substantially over the 38-year period for which data are available. For example, in 1974, groundwater withdrawals represented 6.9 ft^3/s but have increased to 16.7 ft^3/s by 2011. However, surface water withdrawals represent only 1.7 ft^3/s over the last few years. Total withdrawals represent 260% of the lowest gaged annual mean flow in the Pedernales River but only about 9% of the gaged long-term (1942–2013) mean flow in the river. Therefore, based on this analysis, it is likely that withdrawals would cause substantial reduction in runoff during dry periods only. Based on TCEQ data, permitted total surface water withdrawals from the Pedernales River Basin represent 6.4 ft^3/s (TCEQ n.d.); however, at least some of the permitted water use is likely not being withdrawn.

The substantial reduction in inflow volumes to the Highland Lakes perhaps identifies a need for increased planning and management of water use from the lakes. Therefore, a tool that provides possible advanced notification of extreme high- and low-inflow volumes could be beneficial in such management. In an attempt to identify one such tool, the relations between extreme inflow volumes to the Highland Lakes and selected climatic indices were investigated and reported below.

TELECONNECTIONS BETWEEN TEXAS STREAMFLOW AND CLIMATIC INDICES

A major source of precipitation in Texas is from the Gulf of Mexico and subtropical Atlantic moisture carried into the state by low-level southerly and southeasterly winds. Another major source is moisture from the eastern Pacific from the southwest via tropical continental air masses (Slade and Patton 2003).

Many publications report that precipitation or runoff conditions in the Texas area are related to global atmospheric pressure cycles associated with atmospheric and oceanic variations.

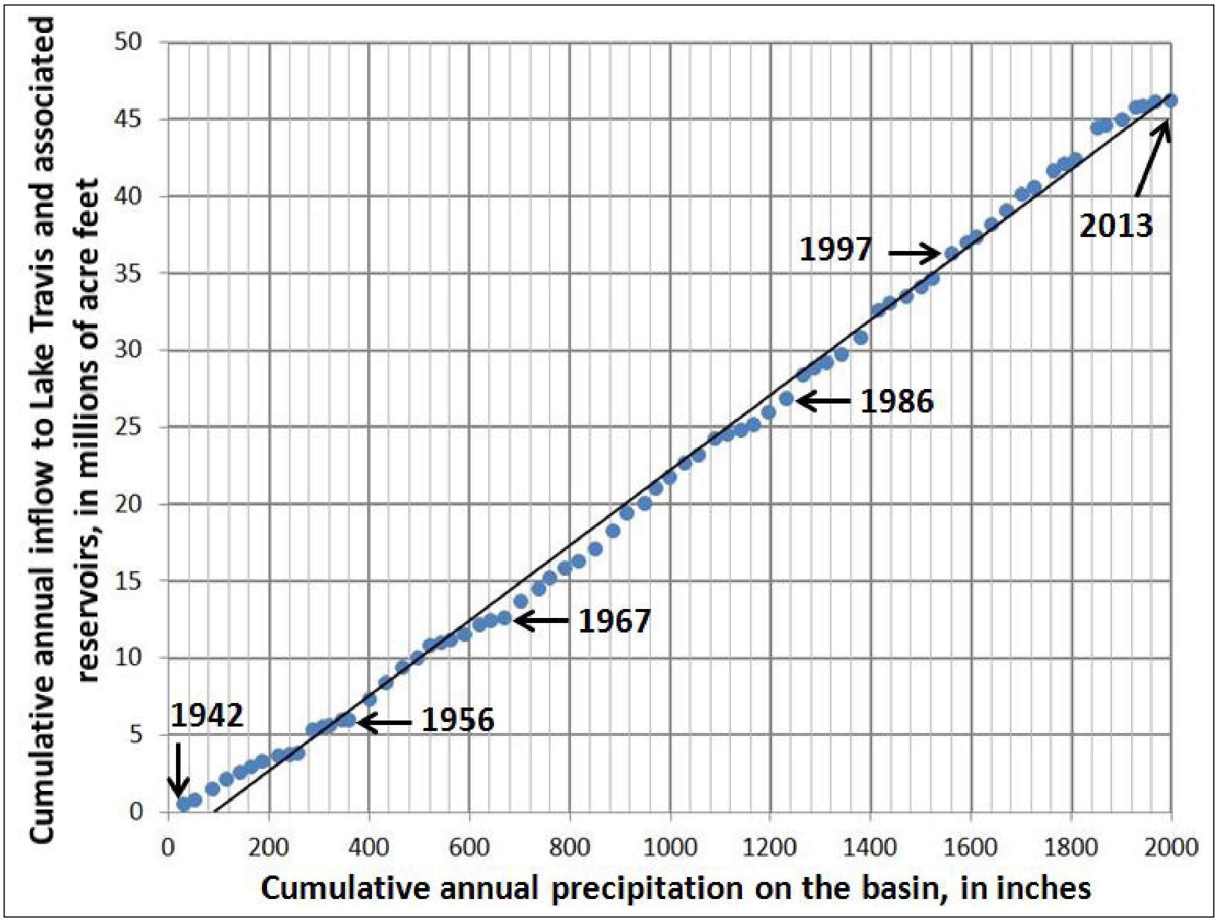

Figure 14. Relation between cumulative annual inflow to Lake Travis and associated reservoirs and cumulative annual precipitation on their basin, 1942–2013.

Such relations have been called "teleconnections," which, in general terms, are causal connections or correlations between meteorologic or other environmental phenomena that occur a long distance apart. Several of these publications (referenced below) have used limited statistical or climatic models to document such relations. The objective for many of the studies is to attempt, using individual climatic indices or combinations of climatic indices, to develop a conceptual or statistical model that could be effectively used by water managers to forecast, three to 12 months in advance, seasonal or annual hydrologic conditions (especially drought or flood conditions). However, to date (2016), none of the identified publications have developed a viable model that accurately predicts seasonal or annual hydrologic anomalies. A brief summary of studies identifying teleconnections between hydrologic forecasting for the Highland Lakes area and climatic indices is presented in the next section.

Reports relating streamflow in the Highland Lakes area to climatic indices

The analyses done by Redmond and Koch (1991) were limited to the western United States and excluded Texas. However, they found that for southeastern New Mexico, October–March precipitation increases (decreases) were strongly correlated with negative (positive) Southern Oscillation Index (SOI) values averaged for the preceding June through November period. Since southeastern New Mexico is adjacent to the headwaters of the Colorado River in Texas, these findings might also apply to the Highland Lakes area. For southeastern New Mexico, the authors also reported strong correlations between increased (decreased) October–March Pacific North American (PNA) pattern and increased (decreased) precipitation depths during the same period.

Watkins and O'Connell (2006) concluded that SOI and the indices North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) could not effectively be used with a nine- to 12-month lead time to predict seasonal or annual inflows to the Highland Lakes. However, they stated "there is potential for skillful season forecasts (with 3–6 months lead time) based on a combination of the indices," but did not provide such forecasts.

Kurtzman and Scanlon (2007) reported that for the Colorado River Basin area, October–March precipitation increased (decreased) in response to El Niño (La Niña) conditions based on the preceding June–September SOI. They also found that precipitation's decreases (increases) correlated with increased positive (negative) SOI.

Mishra et al. (2011) performed correlation analysis between seasonal streamflow extremes and climatic indices based on PDO and SOI evaluations for El Niño for many major Texas streams. They reported that the seasonal Oceanic Niño Index (ONI) sea surface temperature for the 3.4 region showed stronger connection with winter streamflow extremes (95^{th}-and-greater percentile) for the upper part of the Colorado River Basin.

Slade and Chow (2011) reported that, with the exception of summer months (July–September), increased (decreased) precipitation in the Texas Hill Country was generally associated with El Niño (La Niña) conditions based on the ONI. They also reported, however, that for streamflow gaged at the USGS stations Pedernales River near Johnson City and Llano River at Llano, El Niño-period flow exceeded La Niña-period flow for each season except fall. During fall, La Niña flow generally exceeds El Niño flow at both stations. Hurricanes produce much of the fall rainfall, and many studies have found that La Niña periods yield more hurricanes and more intense hurricanes in the Atlantic Ocean (Slade and Chow 2011).

At least three other studies—Piechota and Dracup (1996), Rajagopalan et al. (2000), Tootle and Piechota (2006)—found no spatially coherent teleconnections between streamflow in Central Texas and climatic indices.

Wei and Watkins (2011) evaluated many potential predictors for forecasting inflows to the Highland Lakes during various seasons, including large-scale climatic indices related to the El Niño-Southern Oscillation (ENSO), PDO, NAO, and others. Results indicate that hydrologic persistence (autocorrelation of inflows) is a useful predictor of seasonal inflows to the Highland Lakes during winter and spring. In addition, the authors state that winter inflow forecasts may be improved by including either a derived Sea Surface Temperature (SST) index or the PDO index, and spring reservoir inflow forecasts may be improved by including a derived SST index and PNA. However, the authors do not present the tools for such analyses.

In a report on precipitation and water availability in the Rio Grande Basin in Texas, Khedun et al. (2012) stated that "positive PDO enhances the effect of El Niño and dampens the negative effect of La Niña, but when it is in its neutral or transition phase, La Niña tends to dominate climatic conditions and reduce water availability."

Measures of atmospheric and oceanic variations

The above reports indicate five indices (SOI, PNA, NAO, PDO, and ONI) that can be associated with runoff conditions in the study area. Although not found in the above reports, an index for the Atlantic Multidecadal Oscillation (AMO) is added below because a preliminary investigation indicated it to be related to high- and low-flow conditions in the study area. Additionally, the National Oceanographic and Atmospheric Administration (NOAA) has produced two separate indices (Bivariate EnSo Time series [BEST index] and Multivariate ENSO Index [MEI], presented below) that incorporate multiple indices, including sea surface temperature and air pressure components.

Therefore, a total of eight indices can be considered measures of atmospheric and oceanic variations for the study area. The first six indices below represent sea surface temperatures or air pressures for the Pacific Ocean, and the last two indices represent sea surface temperatures and air pressure differences for the Atlantic Ocean. A definition and description of the eight indices are presented in the Supplemental Information section, along with a reference for values of the indices. Some of the monthly indices are smoothed—typically on the basis of values for consecutive months—and some are standardized on the basis of recent climate patterns.

RELATIONS BETWEEN INFLOW VOLUMES IN THE HIGHLAND LAKES AND CLIMATIC INDICES

To assess the statistical relations between inflow volumes to the Highland Lakes and each of the eight indices described above, a database was created that includes the 1942–2013 monthly values for total inflow and each of the associated indices. The inflow values are based on streamflow discharges as described earlier in the report. Additionally, the monthly inflow and index values were aggregated by seasons so that seasonal analyses also could be performed. The seasonal values are represented by winter (January–March), spring (April–June), summer (July–September), and fall (October–December). Each seasonal inflow and index is calculated as the mean of the three monthly-mean values for each season. In addition to allowing exploration of the relations between seasonal indices and corresponding inflow, the three-month seasonal database

Table 3. Statistical summaries for selected climatic indices.

Index	Monthly indices			Seasonal (three-month) indices		
	Lag 1 autocorrelation coefficient	Mean	Standard deviation	Lag 1 autocorrelation coefficient	Mean	Standard deviation
AMO	0.93	0.01	0.21	0.86	0.01	0.20
ONI	0.05	-0.03	0.79	0.80	-0.03	0.77
PDO	0.81	-0.15	1.07	0.73	-0.15	0.99
SOI	0.08	0.19	10.20	0.69	0.19	8.76

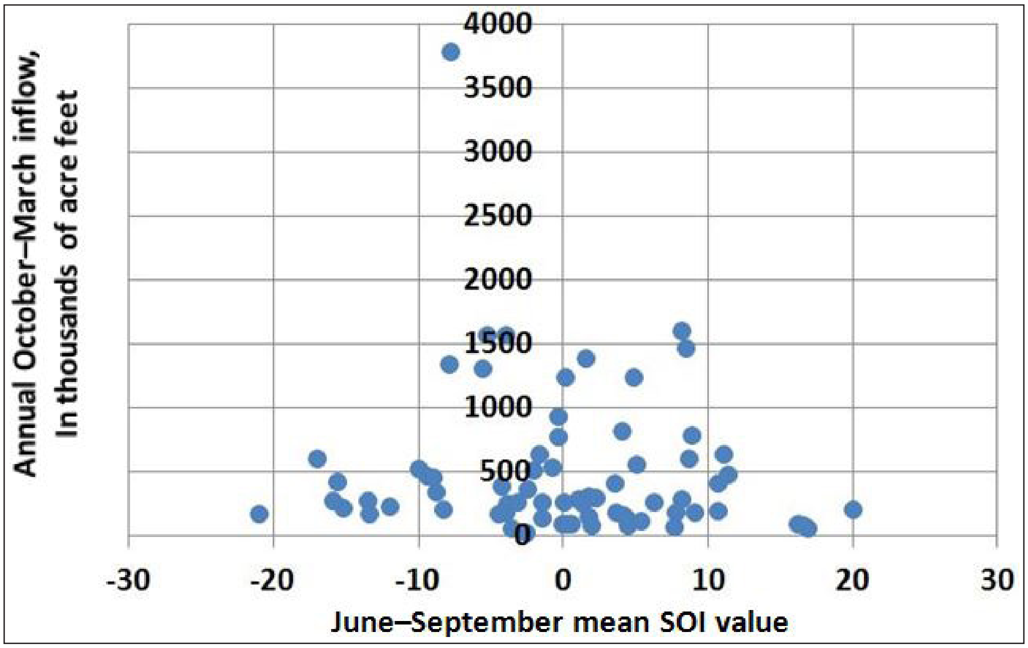

Figure 15. Relation between annual June–September mean Southern Oscillation Index and following October–March inflow volumes to the Highland Lakes, 1942–2013.

allows a longer period in which to explore the relations between indices and inflow, regardless of the season. For example, the effect from a given climatic index might be better realized as rainfall and runoff during a three-month period than during a one-month period.

The watersheds that provide inflow to the lakes are relatively large; thus, substantial runoff volumes can occur for many days after the end of each storm. For large storms near the end of a month or season, some of the flow volume could carry over and become part of the volume for the following month or season. However, the lag 1 autocorrelation coefficient for monthly mean inflow volumes is only 0.28; thus, carryover is not considered to be substantial for most months. The lag 1 autocorrelation coefficient for seasonal inflow volumes is only 0.21. Statistical summaries for selected climatic indices are presented in Table 3.

The lag 1 autocorrelation coefficients vary substantially among the climatic indices. However, as noted previously, some of the coefficients represent smoothed or standardized values—such indices would be expected to have lag 1 autocorrelation coefficients larger than those not smoothed or standardized.

The relations between values for each of the eight climatic indices and corresponding values for Highland Lakes inflow were evaluated, but only those with the best correlations are reported in the following sections.

Relations between inflow volumes for extended periods and Southern Oscillation Index

Redmond and Koch (1991) and Kurtzman and Scanlon (2007) reported that decreased (increased) SOI values from June–November or June–September, respectively, were relat-

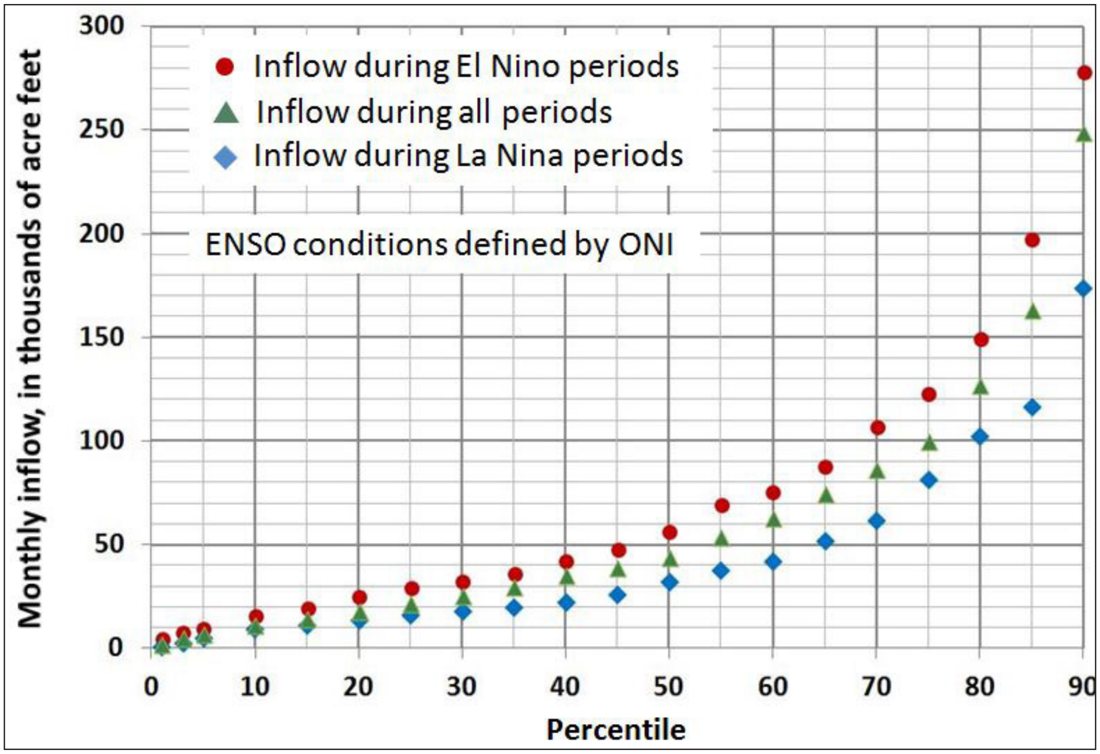

Figure 16. Percentiles for monthly total inflow volumes to the Highland Lakes for various ENSO conditions, 1950–2013.

ed to the following October–March precipitation increases (decreases). Figure 15 presents the relation between June–September mean SOI values and the following October–March (six-month period) total inflow volumes to the Highland Lakes for 1942–2013. The correlation coefficient between the two datasets is -0.10. The long-term (71-year) mean for October–March inflow associated with negative SOI values is 603,000 acre-feet, and the mean for October–March inflow associated with positive SOI values is 429,000 acre-feet. Therefore, negative SOI periods (indicative of El Niño conditions) have produced 41% more inflow than have periods with positive SOI values (indicative of La Niña conditions). For the 22 periods with the largest inflow volumes (those exceeding 500,000 acre-feet), 12 of the SOI values are negative, and 10 of the SOI values are positive. The mean period inflow for the 12 negative SOI values is 1.18 million acre-feet, and the mean period inflow for the 10 positive SOI values is 1.040 million acre-feet—a difference of only 13%. Therefore, the data suggest that negative SOI values are predictive of large inflow volumes but less predictive of the largest inflow volumes.

Additionally, this analysis indicates that positive SOI values imply dry conditions. For example, 12 of the 16 months with the lowest (25^{th} percentile) inflow values had positive SOI values.

Relations between monthly inflow volumes to monthly Oceanic Niño Index and Pacific Decadal Oscillation

Several reports indicate precipitation or runoff in the Highland Lakes area to be related to ONI. Although ONI values precede 1942, periods defining El Niño and La Niña conditions based on ONI values since 1950 are available online by the National Weather Service (NWSCPC n.d.). Based on the period 1950–2013, percentiles were calculated for monthly total inflow volumes to the Highland Lakes and for inflow volumes during El Niño conditions, La Niña conditions, and all periods. Figure 16 shows, for percentiles up to the 90^{th}, monthly inflow volumes for each of the three periods (El Niño, La Niña, and all). El Niño inflow volumes slightly exceed La Niña inflow volumes for low inflow percentiles, but the difference between El Niño and La Niña inflow volumes increases substantially as inflow percentile increases. Based on the data (the 768 months from 1950 through 2013), El Niño conditions occurred during 202 months (26% of the time) and produced 27.2 million acre-feet of inflow to the Highland Lakes (34% of total inflow). La Niña conditions occurred 216 months (28% of the time) and produced 16.2 million acre-feet of inflow (20% of total inflow). Based on these data, the mean of the monthly total inflow during El Niño conditions

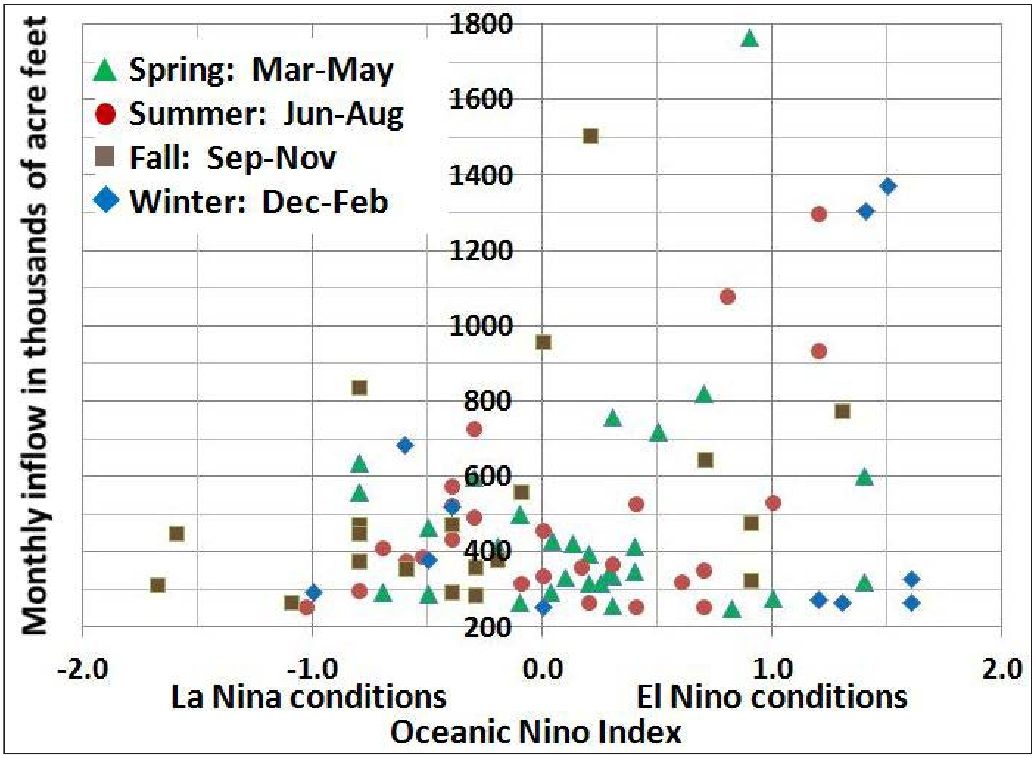

Figure 17. Relation between monthly Oceanic Niño Index and 90th-or-greater percentile monthly inflow volumes to the Highland Lakes, 1942–2013.

(134,600 acre-feet) exceeded that during La Niña conditions (75,000 acre-feet) by 79%.

The 90th percentile for the 1942–2013 and 1950–2013 monthly inflow volumes is about 250,000 acre-feet. Based on the 1942–2013 dataset for ONI values, the ONI value for each month exceeding 250,000 acre-feet of inflow (85 months) is presented in Figure 17. The correlation coefficient between the two datasets is 0.28. As shown, most of the largest monthly inflow volumes (those greater than 800,000 acre-feet) occurred during periods with positive ONI values. Eight of the 10 largest monthly inflow volumes occurred during periods with positive ONI values, one occurred during a period with a negative ONI value, and one occurred during neither condition (index equals zero). Additionally, based on the 85 values, for all but the fall season, the number of months with positive ONI values exceeded the number of months with negative ONI values. For the non-fall months, 37 months occurred during positive ONI conditions, 24 months occurred during negative ONI conditions, and four months occurred during neither condition. However, 14 of the 20 fall-season months occurred during negative ONI conditions, while only five fall-season months occurred during positive conditions; one fall-season month occurred during neither condition. The National Weather Service Climate Prediction Center forecasts ONI index values several months in advance. The site is online at http://www.cpc.ncep.noaa.gov/products/predictions/90day/tools/briefing/unger.pri.php.

As noted previously in describing the ONI, positive ONI indicate El Niño conditions, and negative ONI indicate La Niña conditions. That the majority of fall-season months occurred during negative ONI months (per Figure 17) is consistent with the finding of Slade and Chow (2011) that during the fall La Niña flows generally exceed El Niño flows at each of the two USGS stations, Pedernales River near Johnson City and Llano River at Llano. (See section "Reports relating streamflow in the Highland Lakes area to climatic indices.") Large volumes of runoff associated with hurricanes often occur during fall, and many reports have concluded that hurricanes tend to be associated with La Niña conditions.

However, the indices that best predict the driest monthly inflow volumes is the PDO. For example, the monthly PDO index is negative for 67 of the 85 driest months—those with inflow volumes less than the 10th percentile. The PDO index is, therefore, negative for 79% of the driest months even though the PDO monthly index is negative for only 54% of its 1942–2013 database. The ONI index is negative for 57 of the 85 driest months; therefore it is considered to be less predictive of the driest months than is the PDO index.

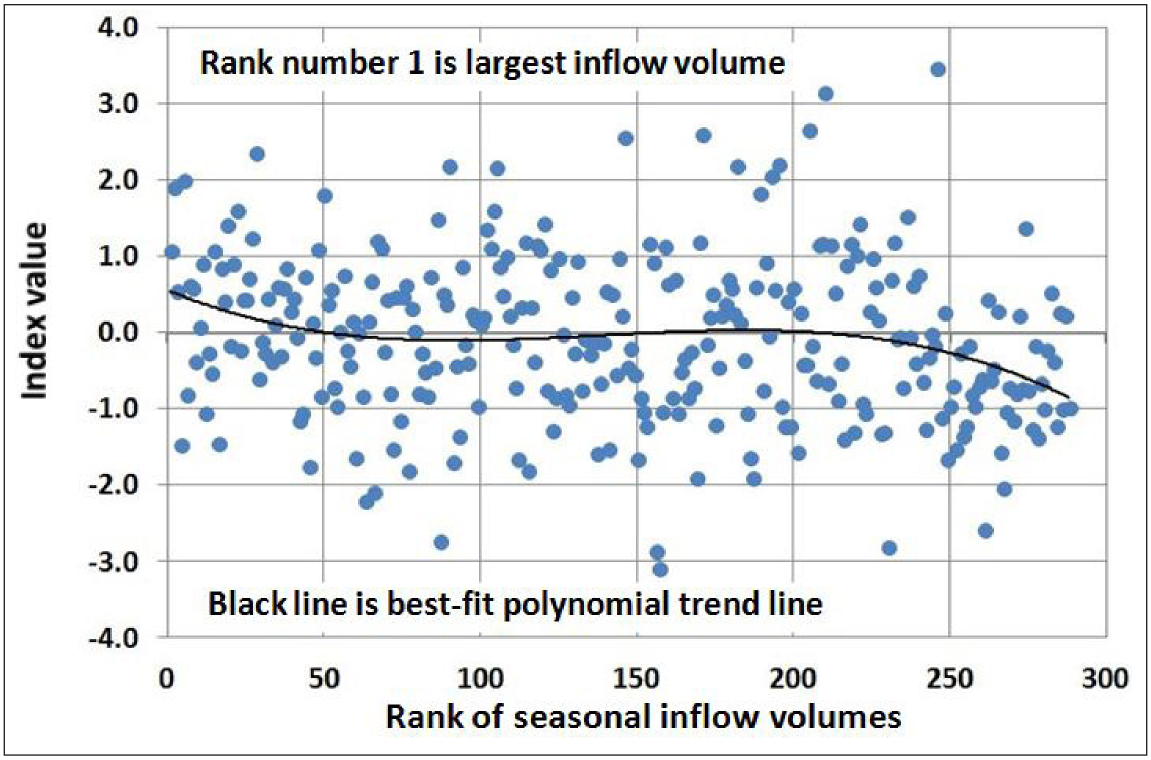

Figure 18. Relation between combination of AMO and ONI indices and ranks of seasonal inflow volumes to the Highland Lakes, 1942–2013.

Relations between seasonal inflow volumes and seasonal climatic indices

The 1942–2013 seasonal (three-month period) inflow volumes to the Highland Lakes and associated seasonal (three-month period) indices were computed and evaluated to minimize the carryover volumes from monthly storm runoff and to create a longer period for the atmospheric pressure cycles related to climatic variations and the resulting weather conditions associated with runoff to the lakes. An evaluation was made, without regard to particular seasons (i.e., winter), of the statistical relations between the three-month period inflow volumes to the Highland Lakes and each of the eight associated three-month period climatic indices.

To evaluate the indices as a prediction tool one season in advance, a second seasonal database was created for which the indices for each season were grouped with the inflow values for the following season (three-month period). Likewise, a third seasonal database was prepared for which the indices for each season were grouped with the inflow values two seasons later. A fourth database was created for which the seasonal indices were grouped with inflow values three seasons later, and finally, a fifth database was created for which the seasonal indices were grouped with seasonal inflows four seasons (one year) later.

The analysis is based on relations between inflow values for the wettest and driest seasonal inflow volumes and indices. For each of the five databases, the 288 seasonal inflow volumes for the 72 years 1942–2013 were sorted on the basis of inflow volume magnitude—the associated value for each of the indices remained grouped with each inflow value. The greatest and least 10% of the inflow volumes were then analyzed for comparisons with their associated indices. Therefore, the 29 periods with the greatest inflow volumes and the 29 periods with the least inflow volumes were analyzed. The signs (positive or negative) and values for each index relative to the associated inflow volumes were examined. Attention also was given to seeking a combination of two or more indices that might accurately predict wet and dry inflow seasons.

The two indices most closely associated with the 90th-or-greater percentile seasonal inflow volumes are the AMO and ONI. The ONI represents sea surface temperature for an equatorial region of the Pacific Ocean (Niño 3.4 region), and the AMO represents sea surface temperature for the Atlantic Ocean. Each has a weak relations with the inflow volumes. However, a combination of the two indices provides a better predictor of wet inflow seasons than either index by itself. Combining the two indices also provides the best predictor of dry inflow seasons. Thus, the AMO and ONI seasonal indices were combined to develop a single index that would be closely associated with the wet and dry inflow seasons. Combinations of most of the indices above were tested for predictability of wet and dry inflow conditions, but the combination of the AMO and ONI produced the best estimations of wet and dry inflow conditions.

Additionally, the PDO index provides a good indicator for the driest inflow seasons. The PDO represents sea surface temperatures for the northern Pacific Ocean.

Summaries of the PDO values and the combined AMO and ONI in each dataset are provided below to describe the relations with inflow volumes for each of the five seasonal databases. The correlation coefficient between seasonal values of AMO and ONI is only 0.06; thus, the values are considered to be independent indicators of inflow values.

As shown in Table 3, the seasonal (and monthly) mean for each index is near zero. Likewise, the percentiles for each index indicate that the values are almost normally distributed about the mean, and thus the skew coefficient approaches zero for each index. However, the standard deviations for the AMO and ONI indices are 0.20 and 0.77, respectively; so the ONI standard deviation is 3.85 times greater than that of the AMO. Also, negative AMO values indicate wet inflow seasons, and positive AMO values indicate dry inflow seasons. For the ONI index, positive values indicate wet periods and negative values indicate dry periods.

Therefore, to maximize the ability of the combined indices to predict wet and dry inflow seasons, the sign for each AMO value was changed, and each AMO value was multiplied by 3.85 so it would have a distribution of values similar to that of the ONI. Each revised AMO value was then added to its associated ONI value, resulting in a single combined value. Based on the combined indices, positive values indicate wet seasons and negative values indicate dry seasons.

The mean seasonal inflow for the positive-value combined indices is 373,000 acre-feet, and the mean seasonal inflow for the negative-value combined indices is 244,000 acre-feet. Therefore, the mean inflow volume for the positive indices values exceeds that for the negative indices values by 53%. A summary of the number of positive-value and negative-value combined indices associated with the wet and dry seasons is presented in Table 4. The relation between the combined indices and the ranks of seasonal inflow volumes is presented in Figure 18. The number 1 rank represents the greatest seasonal (three-month) inflow volume, and the number 288 rank represents the lowest inflow volume. A best-fit polynomial curve trend line on the graph indicates that positive values for the indices predict about the 45 wettest inflow seasons, and negative values for the indices indicate about the 70 driest inflow seasons.

Based on the results above, the combined AMO and ONI indices can be effectively used to estimate the wettest 10th percentile of seasonal inflow volumes for a current season and for only one season in advance. However, the combined AMO and ONI indices can effectively be used to estimate the driest 10th percentile of seasonal inflow volumes for as many as four seasons in advance and to estimate the driest 20th percentile of seasonal inflow volumes as many as two seasons in advance. The PDO can effectively be used to estimate the driest 10th percentile of seasonal inflow volumes for as many as four seasons (one year) in advance. The correlation coefficient between seasonal values for the combined AMO and ONI indices and values for PDO is 0.35; thus, the two indices are relatively independent. Therefore, each index could be used to estimate wet and dry seasons.

CONCLUSIONS

From 1942 to 2013, inflow volumes decreased 19% for the Highland Lakes and 59% for Lake Buchanan. The major cause for the inflow reduction to Lake Buchanan is the proliferation of 19 major reservoirs and about 69,500 minor reservoirs, which have caused, from 1942 to 2013, an increase in evaporation that represents 73% of the value for inflow reduction and an increase in transpiration and loss to groundwater that represents 51% of the value for reduced inflow. Also, the increase in stream channel transpiration due to spread of phreatophytes represents 36% of the value for inflow reduction. Although it could not be substantiated, increased evapotranspiration due to phreatophytes outside stream channels was also a probable major cause for inflow reduction. Finally, loss due to increased surface water withdrawals was probably a minor cause for inflow reduction. The sum of the losses above expressed as percentages of inflow reduction to Lake Buchanan exceed 100%. This is because most basin losses are from reservoirs—much if not most of the water loss from the reservoirs would otherwise be lost downstream as evapotranspiration in the channel before arriving at Lake Buchanan.

Based on statistical comparisons of values for climatic indices and inflow volumes, climatic indices are likely better indicators of extreme (wet or dry) inflow conditions for the Highland Lakes rather than conditions between extreme wet and dry. (Figure 18).

Climatic indices provide only fair indicators of large inflow volumes to Lake Buchanan. Larger inflow volumes are associated with the duration and extent of flooding that typically are caused by short duration timing and location of several meteorologic conditions that, for many wet periods, cannot be readily predicted by climatic indices. However, climatic indices provide better indicators of periods with low inflow volumes. Low inflow volumes are associated with drought—some climatic indices readily provide indicators of absence of moisture in the regional atmosphere and lack of sources for such moisture.

Table 4. Number of seasons with positive and negative climatic index values for various comparisons between seasonal indices and seasonal inflow volumes to Lake Buchanan.

	Temporal relation between seasonal indices and seasonal inflow volumes				
	Same season[1]	Inflow 1 season later	Inflow 2 seasons later	Inflow 3 seasons later	Inflow 4 seasons later
Combined AMO and ONI indices					
Wettest 29 seasons[2]					
number of positive values	19	19	16	15	10
number of negative values	10	10	13	14	19
Wettest 58 seasons[3]					
number of positive values	34	34	33	32	25
number of negative values	24	24	25	26	33
Driest 29 seasons[4]					
number of positive values	7	7	5	7	8
number of negative values	22	22	24	22	21
Driest 58 seasons[5]					
number of positive values	14	16	15	18	21
number of negative values	44	42	43	40	37
PDO indices					
Wettest 29 seasons					
number of positive values	19	12	13	10	8
number of negative values	10	17	16	19	21
Wettest 58 seasons					
number of positive values	36[6]	32	30	27	28
number of negative values	21	26	28	31	30
Driest 29 seasons					
number of positive values	7	7	9	7	9
number of negative values	22	22	20	22	20
Driest 58 seasons					
number of positive values	14	16	19	18	19[6]
number of negative values	44	42	39	40	38

[1] Season defined as: Winter: January–March; Spring: April–June; Summer: July–September; Fall: October–December

[2] 1942–2013 period of record is 72 years or 288 seasons. Wettest 29 seasons are 10% of all seasons with greatest inflow volumes

[3] Wettest 58 seasons are 20% of all seasons with greatest inflow volumes

[4] Driest 29 seasons are 10% of all seasons with lowest inflow volumes

[5] Driest 58 seasons are 20% of all seasons with lowest inflow volumes

[6] Index value equal zero for one season

Due to the limited ability for any single climatic indices to predict wet or dry inflow volumes to the Highland Lakes, it is suggested that several climatic indices be evaluated in order to best predict high or low inflow volumes to the Highland Lakes. Additionally, the Pacific and Atlantic each represent potential sources of moisture to the Highland Lakes; therefore, it is suggested that climatic indices representing each of these moisture sources be used as indicators of potential extreme inflow conditions for the Highland Lakes.

NOTES

The author obtained permission from all people with whom he had personal communications.

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SUPPLEMENTAL INFORMATION

1. The ENSO, as documented by the ONI, probably represents the best-known teleconnection pattern related to precipitation and runoff in Texas. The calculated monthly indices from 1950 through 2013, along with the identification of El Niño and La Niña periods and the definition for such periods, are presented by NOAA online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. The values represent three-month running mean values for the equatorial region of the Pacific Ocean. Extended monthly ONI values from 1942 through 1949 were obtained from the International Research Institute for Climate and Society at Columbia University (http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.Niño/.EXTENDED/.NIÑO34/T+exch/). Positive ONI values indicate El Niño conditions and negative ONI values indicate La Niña conditions.

2. The Southern Oscillation is the atmospheric component of ENSO. This component is an oscillation in surface air pressure between the tropical eastern and the western Pacific Ocean waters. The strength of the Southern Oscillation is measured by the SOI. The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin, Australia. SOI values are available at http://www.bom.gov.au/climate/current/soihtm1.shtml. Negative SOI indices indicate El Niño conditions and positive SOI indices indicate La Niña conditions.
3. NOAA describes the BEST index as the combination of the ONI and SOI components of ENSO (http://www.esrl.noaa.gov/psd/people/cathy.smith/best/). NOAA believes it is a better index than ONI or SOI alone for describing ENSO because it considers sea surface temperature and atmospheric air pressure. The monthly values for this index are online at http://www.esrl.noaa.gov/psd/people/cathy.smith/best/enso.ts.1mn.txt.
4. NOAA describes the MEI as a method to characterize the climatic conditions contributing to the onset and physiology of an ENSO event. ENSO arises from a complex interaction of several climate systems; thus, MEI is regarded by NOAA as the most comprehensive index for monitoring ENSO because it combines analysis of multiple meteorologic components. The MEI is calculated as the first principal component of six different parameters: sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and cloudiness of the southern Pacific Ocean. MEI values are at https://www.esrl.noaa.gov/psd/enso/mei/, which also contains additional information regarding this index.
5. The PDO represents monthly sea surface temperature over the northern Pacific (poleward of 20° N). Several reports, some of which are listed in the section "Reports relating streamflow in the Highland Lakes area to climatic indices," indicate that the PDO index is useful for identifying trends in precipitation and runoff. The PDO index is identified as a standardized principal-component time series. PDO index values are available at http://jisao.washington.edu/pdo/PDO.latest.
6. The PNA represents, at four locations over the Pacific Ocean and North America, anomalous air pressure, which correlates with regional temperature and precipitation anomalies across North America. This pattern influences regional weather by affecting the strength and location of the East Asian jet stream and subsequently the weather it delivers to North America. PNA index values are presented at. ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh.
7. The AMO is a mode of variability occurring in the northern Atlantic Ocean that has its principal expression in sea surface temperature. The AMO signal is usually defined from the patterns of sea surface temperature variability in the North Atlantic after any linear trend has been removed. Monthly AMO values are online at http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data.
8. The NAO represents atmospheric pressure fluctuations in the northern Atlantic Ocean. The index indicates the difference in atmospheric pressure at sea level between the Icelandic low and the Azores high. The fluctuations, which vary over time and have no particular periodicity, represent the strength and direction of westerly winds and storm tracks across the North Atlantic. NAO index values are at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table.
9. Additionally, monthly and seasonal values for many indices are presented at http://www.esrl.noaa.gov/psd/data/climateindices/list/.