Prepared in cooperation with the U.S. Army Corps of Engineers, Fort Worth District

Estimation of Evaporation from Open Water—A Review of Selected Studies, Summary of U.S. Army Corps of Engineers Data Collection and Methods, and Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas

Scientific Investigations Report 2012–5202

U.S. Department of the Interior
U.S. Geological Survey

Front cover, Benbrook Lake, December 2011. Photograph by Glenn Harwell, U.S. Geological Survey.

Background, Canyon Lake, November 2008. Photograph by Sam Price, U.S. Army Corps of Engineers.

Back cover:

Top, Hords Creek, September 2012. Photograph by Anna Reinhardt, U.S. Army Corps of Engineers.
Middle, Granger Lake, September 2012. Photograph by Ben Bohac, U.S. Army Corps of Engineers.
Bottom, Sam Rayburn Lake, September 2012. Photograph by David LaRue, U.S. Army Corps of Engineers.

Estimation of Evaporation from Open Water—A Review of Selected Studies, Summary of U.S. Army Corps of Engineers Data Collection and Methods, and Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas

By Glenn R. Harwell

Prepared in cooperation with the U.S. Army Corps of Engineers, Fort Worth District

Scientific Investigations Report 2012–5202

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

This and other USGS information products are available at http://store.usgs.gov/

U.S. Geological Survey
Box 25286, Denver Federal Center
Denver, CO 80225

To learn about the USGS and its information products visit http://www.usgs.gov/
1-888-ASK-USGS

Suggested citation:
Harwell, G.R., 2012, Estimation of evaporation from open water—A review of selected studies, summary of U.S. Army Corps of Engineers data collection and methods, and evaluation of two methods for estimation of evaporation from five reservoirs in Texas: U.S. Geological Survey Scientific Investigations Report 2012–5202, 96 p.

Acknowledgments

The author recognizes the contributions of many U.S. Army Corps of Engineers staff from five districts including Roberta Ball, Albuquerque District; Jerry Cotter, Paul Lauderdale, Lynne Rednour, Michael Schwind, Stephen Pilney, Ron Hula, and Clinton Greb, Fort Worth District; Matthew Moix, Little Rock District; Kellie Bergman and Steven Daly, Omaha District; and Greg Estep, Tulsa District. The author is especially appreciative of consultation and advice from U.S. Geological Survey Research Hydrologist, David Stannard, and Scientist Emeritus, Thomas Winter, prior to his passing.

Contents

Figures

Tables

Conversion Factors and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
inch per day(in/d)	25.4	millimeter per day (mm/d)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
foot per second (ft/s)	0.3048	meter per second (m/s)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Energy	
kilowatthour (kWh)	3,600,000	joule (J)
	Energy flux	
Watts per square foot (W/ft^2)	10.7643	Watts per square meter (W/m^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Estimation of Evaporation from Open Water—A Review of Selected Studies, Summary of U.S. Army Corps of Engineers Data Collection and Methods, and Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas

By Glenn R. Harwell

Abstract

Organizations responsible for the management of water resources, such as the U.S. Army Corps of Engineers (USACE), are tasked with estimation of evaporation for water-budgeting and planning purposes. The USACE has historically used Class A pan evaporation data (pan data) to estimate evaporation from reservoirs but many USACE Districts have been experimenting with other techniques for an alternative to collecting pan data. The energy-budget method generally is considered the preferred method for accurate estimation of open-water evaporation from lakes and reservoirs. Complex equations to estimate evaporation, such as the Penman, DeBruin-Keijman, and Priestley-Taylor, perform well when compared with energy-budget method estimates when all of the important energy terms are included in the equations and ideal data are collected. However, sometimes nonideal data are collected and energy terms, such as the change in the amount of stored energy and advected energy, are not included in the equations. When this is done, the corresponding errors in evaporation estimates are not quantifiable. Much simpler methods, such as the Hamon method and a method developed by the U.S. Weather Bureau (USWB) (renamed the National Weather Service in 1970), have been shown to provide reasonable estimates of evaporation when compared to energy-budget method estimates. Data requirements for the Hamon and USWB methods are minimal and sometimes perform well with remotely collected data. The Hamon method requires average daily air temperature, and the USWB method requires daily averages of air temperature, relative humidity, wind speed, and solar radiation. Estimates of annual lake evaporation from pan data are frequently within 20 percent of energy-budget method estimates. Results of evaporation estimates from the Hamon method and the USWB method were compared against historical pan data at five selected reservoirs in Texas (Benbrook Lake, Canyon Lake, Granger Lake, Hords Creek Lake, and Sam Rayburn Lake) to evaluate their performance and to develop coefficients to minimize bias for the purpose of estimating reservoir evaporation with accuracies similar to estimates of evaporation obtained from pan data. The modified Hamon method estimates of reservoir evaporation were similar to estimates of reservoir evaporation from pan data for daily, monthly, and annual time periods. The modified Hamon method estimates of annual reservoir evaporation were always within 20 percent of annual reservoir evaporation from pan data. Unmodified and modified USWB method estimates of annual reservoir evaporation were within 20 percent of annual reservoir evaporation from pan data for about 91 percent of the years compared. Average daily differences between modified USWB method estimates and estimates from pan data as a percentage of the average amount of daily evaporation from pan data were within 20 percent for 98 percent of the months. Without any modification to the USWB method, average daily differences as a percentage of the average amount of daily evaporation from pan data were within 20 percent for 73 percent of the months. Use of the unmodified USWB method is appealing because it means estimates of average daily reservoir evaporation can be made from air temperature, relative humidity, wind speed, and solar radiation data collected from remote weather stations without the need to develop site-specific coefficients from historical pan data. Site-specific coefficients would need to be developed for the modified version of the Hamon method.

Introduction

Estimation of evaporation from open water, such as lakes and reservoirs, has been the subject of many studies and publications dating back to the early 1900s. At first, estimation of evaporation might seem like a straightforward task. However, the methods for estimating evaporation are generally not straightforward and typically require intensive data collection and subsequent analysis and interpretation.

Examples of complex methods for estimating evaporation include energy-budget methods and data-intensive semiempirical equations. Some methods seem straightforward (such as Class A pan evaporation data [pan data] and certain empirical equations) but are complex in practice because of the need to apply corrective pan coefficients or the uncertainty in the applicability of a particular empirical equation based on study-specific coefficients that likely were developed for different hydrologic and climatic conditions of the studied water body.

Many organizations responsible for the management of water resources, such as the U.S. Army Corps of Engineers (USACE), are tasked with estimation of evaporation for water-budgeting and planning purposes. The USACE historically has used Class A pan data to estimate evaporation losses from reservoirs for the purposes of water-resources management. The Class A pan is defined as an unpainted circular galvanized iron pan that is 4 feet (ft) in diameter and 10 inches (in.) deep. The operation and maintenance of a Class A pan is explained in a National Weather Service handbook (National Oceanic and Atmospheric Administration, National Weather Service, 1972). The collection of daily Class A pan data requires appreciable effort by USACE staff, and records are sometimes incomplete because of staff unavailability or problems associated with equipment maintenance, such as freezing water during cold weather. Throughout this report, the term pan data will always refer to Class A pan evaporation data because other types of pans are not considered.

There are many published equations for estimating evaporation (Kohler and others, 1955; Winter and others, 1995; Rosenberry and others, 2004; Dalton and others, 2004; Rosenberry and others, 2007). Some equation estimates are attractive alternatives to energy-budget methods and pan data because of potential lower operation costs, automated data collection and storage, and real-time calculation capability. However, these various open-water evaporation methods can yield different results, and guidance as to what methods should be used is lacking. Accordingly, the U.S. Geological Survey (USGS), in cooperation with the USACE, reviewed selected studies in the scientific literature, summarized significant findings and methods pertaining to estimation of evaporation from open water, and evaluated two methods, the Hamon method and the U.S. Weather Bureau (USWB) method, for estimating evaporation. The USWB was renamed the National Weather Service in 1970.

Purpose and Scope

This report summarizes the results of selected studies in which various methods were used to estimate evaporation from open water, focusing particular attention on studies where equation estimates and pan data estimates were done in conjunction with energy-budget method estimates, and summarizes open-water evaporation data from five USACE districts (Albuquerque, Fort Worth, Little Rock, Omaha, and Tulsa). Modified and unmodified versions of the Hamon and USWB methods for estimating evaporation were evaluated at five reservoirs in Texas (Benbrook, Canyon, Granger, Hords Creek, and Sam Rayburn Lakes) using meteorological data collected by other agencies. Comparisons were made between the results of the Hamon and USWB methods and historical pan estimates of evaporation.

A Review of Selected Studies Pertinent to Open-Water Evaporation Estimation

The energy-budget method is often considered the most accurate method for open-water evaporation estimation (Harbeck and others, 1958; Gunaji, 1968; Winter, 1981; Brutsaert, 1982; Sturrock and others, 1992; Winter and others, 2003; Rosenberry and others, 2004; Dalton and others, 2004; Westenburg and others, 2006). Estimates of evaporation using the energy-budget method are recognized as a standard by which other estimates are compared.

Appendix 1 of this report provides more detailed summaries of selected studies that are pertinent to open-water evaporation estimation and defines the individual terms of the energy budget. The studies included in appendix 1 primarily were selected because a comprehensive energy budget was determined for a water body or wetland, and energy-budget method estimates were compared with complex semiempirical equation estimates, simple empirical equation estimates, and estimates of evaporation from pan data. Some comparisons with water-budget estimates of evaporation also are included in appendix 1. Conclusions drawn from the review of the selected studies in appendix 1 are summarized in the following discussion.

Complex semiempirical equations are defined as those that some investigators have classified as Penman-based or combination equations (Rosenberry and others, 2004; Shuttleworth, 1993). The equations are complex with respect to data requirements because the energy required for evaporation, such as net radiation over the water body, change in the amount of stored energy, and the change in the amount of advected energy over some period of time, are taken into account. The equations are semiempirical because they contain a physically based aerodynamic term with empirically derived coefficients that describe the diffusion mechanism by which water vapor is removed from the surface of the water body (Shuttleworth, 1993). The combination of the energy required for evaporation with the aerodynamic term is the reason for the reference to combination equations. These include (but are not limited to) the Penman, DeBruin-Keijman, and Priestley-Taylor equations (Penman, 1948; Brutsaert, 1982; DeBruin and Keijman, 1979; Stewart and Rouse, 1976).

Simple empirical equations are defined as equations with minimal data requirements compared to the complex equations because net radiation over the water body, change in the amount of stored energy, or the change in the amount of advected energy over some period of time are not required.

These equations require only one or more of the following meteorological data: (1) incoming short-wave solar radiation; (2) air temperature; or (3) atmospheric pressure. The simple empirical equations are often referred to as solar radiation or temperature-based equations and contain empirically derived coefficients (Rosenberry and others, 2004). The equations include (but are not limited to) the Hamon, Makkink, Jensen-Haise, Thornthwaite (or Mather), and Papadakis equations (Hamon, 1961; McGuinness and Bordne, 1972; Mather, 1978).

Complex equations to estimate evaporation, such as the Penman, DeBruin-Keijman, and Priestley-Taylor, have performed well with comparisons of energy-budget method estimates when all of the important energy terms are included and ideal data are collected (Winter and others, 1995; Rosenberry and others 2004; Rosenberry and others, 2007). The net radiation term should ideally be measured over the surface of the water but may not be possible in some locations where water recreation activities prohibit installation of a monitoring station in the middle of the water body. The change in the amount of stored energy and the advected energy terms require appreciable effort and expense to collect and include in the equations (Winter and others, 1995; Rosenberry and others 2004; Rosenberry and others, 2007; Dalton and others, 2004). Given these difficulties in collecting ideal data, sometimes nonideal data are collected and terms, such as the stored energy and advected energy, are not included in the equations. When this is done, the corresponding errors in evaporation estimates are not quantifiable without accurate energy-budget or water-budget estimates for comparison.

The simple empirical equations, such as the Hamon, Makkink, Jensen-Haise, Thornthwaite, and Papadakis equations, have been shown to provide reasonable estimates of evaporation when compared to energy-budget method estimates (Winter and others, 1995; Rosenberry and others 2004; Rosenberry and others, 2007; Dalton and others, 2004). However, when applying these equations to various water bodies, their performance remains questionable without accurate energy-budget or water-budget estimates for comparison because of the empirical origin of their coefficients.

A method to estimate average daily lake evaporation was published as equation 10 in a USWB research paper (Kohler and others, 1955, p. 14) and is based directly on the Penman equation. The USWB was renamed the National Weather Service in 1970 (National Oceanic and Atmospheric Administration, National Weather Service, 2012). The Penman approach was applied to daily Class A pan evaporation data from stations throughout the United States to empirically derive coefficients to estimate the amount of daily evaporation from a Class A pan and, ultimately, the amount of average daily lake evaporation from air temperature, relative humidity, wind speed, and solar radiation data. Average daily lake evaporation is estimated as the product of the Penman estimated evaporation from a Class A pan and a 0.70 coefficient. The USWB method assumes that the change in the amount of stored energy and the amount of advected energy are negligible. Therefore, the USWB method is intended to estimate average daily lake evaporation such that the sum of the daily estimates should approximate annual evaporation if the annual change in the amount of stored energy and advected energy are negligible.

To estimate the amount of evaporation from a water body, a pan coefficient is multiplied by the amount of evaporation from the pan. Pan coefficients are usually less than one and, therefore, the amount of evaporation from a pan is usually greater than the amount of evaporation from a nearby water body. Kohler and others (1959) reported that annual pan coefficients vary regionally from 0.60 to 0.80 throughout the United States, with values being the highest near the coast and the lowest inland. Hounam (1973) showed that for 13 lakes, annual pan coefficients varied from 0.52 for the Salton Sea in California to 0.86 for Lake Eucumbene in Australia.

Despite this variability, estimates of annual lake evaporation from pan data and application of published pan coefficients have been shown to frequently be within 20 percent of energy-budget and water-budget estimates (Kohler and others, 1955; Harbeck and others, 1958; Kohler and others, 1959; Ficke, 1972; Swancar and others, 2000). Estimates of annual lake evaporation from pan data frequently compare well with accurate energy-budget and water-budget estimates because annually the changes in the amount of stored energy and the advected energy become negligible. However, the advected energy may also be appreciable on an annual time step but will vary between water bodies and may be influenced by how water-supply reservoirs are managed.

The USWB method estimates of annual lake evaporation also have been shown to frequently be within 20 percent of energy-budget and water-budget estimates (Kohler and others, 1955; Harbeck and others, 1958; Kohler and others, 1959; Ficke, 1972). Computed pan estimates from the USWB method annually perform well for the same reason as pan estimates.

Results of evaporation estimates from simple methods, such as the Hamon method and USWB method, could be compared with historical pan data at a given lake or reservoir where pan data have been collected. If bias between the Hamon and USWB method estimates and historical pan data are fairly consistent, then corrective coefficients could be applied to reduce bias and tune each method to estimate the amount of evaporation from a reservoir within the amount of error frequently associated with a pan estimate of evaporation.

The last section of this report focuses on evaluating the two methods and their ability to estimate evaporation from Benbrook, Canyon, Granger, Hords Creek, and Sam Rayburn Lakes in Texas using meteorological data collected by other agencies. However, before presenting the results of that evaluation, the following discussion is included to summarize various ways in which five different USACE Districts currently (2012) estimate evaporation from reservoirs.

Summary of U.S. Army Corps of Engineers Data Collection and Methods for Estimating Evaporation from U.S. Army Corps of Engineers Reservoirs in Five Districts

Over the years, the USACE has pursued different methods of estimating evaporation losses from its reservoirs because of the difficulties associated with the collection of daily pan data. The purpose of the following discussion is to summarize evaporation data collection and methods within five USACE Districts. Summaries of operations are included for the Albuquerque, Fort Worth, Little Rock, Omaha, and Tulsa Districts of the USACE.

Albuquerque District

The USACE Albuquerque District, which includes New Mexico and parts of Texas and Colorado, manages nine reservoirs. Historically, pan data have been used to estimate evaporation from its reservoirs with the universal application of a 0.70-pan coefficient. Pan data currently (2012) are collected at six of the nine reservoirs. Data usually are not collected during the winter because of freezing water in the pans. The Albuquerque District has been investigating the use of automated methods for estimating evaporation from its reservoirs (Roberta Ball, U.S. Army Corps of Engineers, written commun., 2011).

From July 2009 to November 2010, meteorological data were collected concurrently from an automated weather station and a manual weather station at Jemez Canyon Reservoir in north central New Mexico to determine if the data from an automated weather station could be used to estimate reservoir evaporation. Data collected from the automated weather station included air temperature, atmospheric pressure, net radiation, incoming short-wave solar radiation, precipitation, relative humidity, wind speed, and wind direction. Data collected from the manual weather station included maximum and minimum air temperature, precipitation, wind speed, and daily pan evaporation.

Data from the automated weather station were used as input data into different forms of the Penman-Monteith equation. The two forms were the Food and Agriculture Organization (FAO) of the United Nations Penman-Monteith equation, frequently referred to as the FAO-56 Penman-Monteith equation, and the American Society of Civil Engineers (ASCE) standardized reference equation based on the Penman-Monteith method (Allen and others, 1998; Jensen and others, 1990; Allen and others, 2005).

The results showed that both forms of the Penman-Monteith method could estimate pan evaporation after applying different "adjustment" coefficients to the output of the two forms of the Penman-Monteith equations. A single adjustment coefficient was determined for each method to estimate the amount of pan evaporation. The adjusted FAO-56 Penman-Monteith equation predicted pan evaporation with an average error of 6.2 percent and the adjusted ASCE equation predicted pan evaporation with an average error of 10.1 percent.

To estimate evaporation from a particular reservoir, a 0.70-pan coefficient was applied to the Penman-Monteith method (modified with the appropriate coefficient) estimate of pan evaporation. Currently, the Albuquerque District is still evaluating different methods of estimating evaporation from its reservoirs (Roberta Ball, U.S. Army Corps of Engineers, written commun., 2011).

Fort Worth District

The USACE Fort Worth District manages 25 reservoirs throughout Texas (fig. 1; table 1). Many of these are water supply reservoirs for densely populated, major metropolitan areas with growing populations.

The Fort Worth District currently (2012) collects pan data at 19 of its 25 reservoirs (table 1) and uses those data to estimate daily evaporation. Evaporation estimates for the remaining six are made from pan data collected at nearby reservoirs (table 1). Monthly pan coefficients from the Texas Water Development Board (TWDB) are applied to all of the pan data throughout the State. The coefficients for January through December are 0.77, 0.67, 0.64, 0.64, 0.68, 0.73, 0.79, 0.84, 0.88, 0.91, 0.92, and 0.89, respectively (Kane, 1967). The coefficients average annually to a coefficient of 0.78, which is higher than the typical annual average coefficient of about 0.70 that was published later for many parts of Texas (Farnsworth and others, 1982). In 1998, the TWDB released a document that explains a Geographic Information Systems (GIS) program entitled ThEvap 1.0 that incorporates revised pan coefficients by Farnsworth and others (1982) that vary seasonally (by month) and spatially (Tschirhart and Rodriguez, 1998). Monthly and spatially distributed pan coefficients are available from the TWDB website for different regions (or quadrants) of Texas (Texas Water Development Board, 1998). The quadrants are displayed in another TWDB website (Texas Water Development Board, 2012). The revised monthly and spatially revised pan coefficients have annual averages that more closely reflect the typical annual average of about 0.70 for many parts of Texas.

In 2007, the Fort Worth District began using different forms of the Penman equation to estimate daily evaporation from meteorological data collected at six reservoirs. Currently (2012) the Fort Worth District operates and maintains three stations that collect meteorological data at Grapevine Lake, Hords Creek Lake, and Canyon Lake. The Fort Worth District cooperates with the USGS in funding the operation and maintenance of two stations, one at Lewisville Lake and one at Wright Patman Lake. Lastly, one station at Joe Pool Lake in Cedar Hill State Park is part of the Remote Automatic Weather Station (RAWS) network and is operated and maintained by

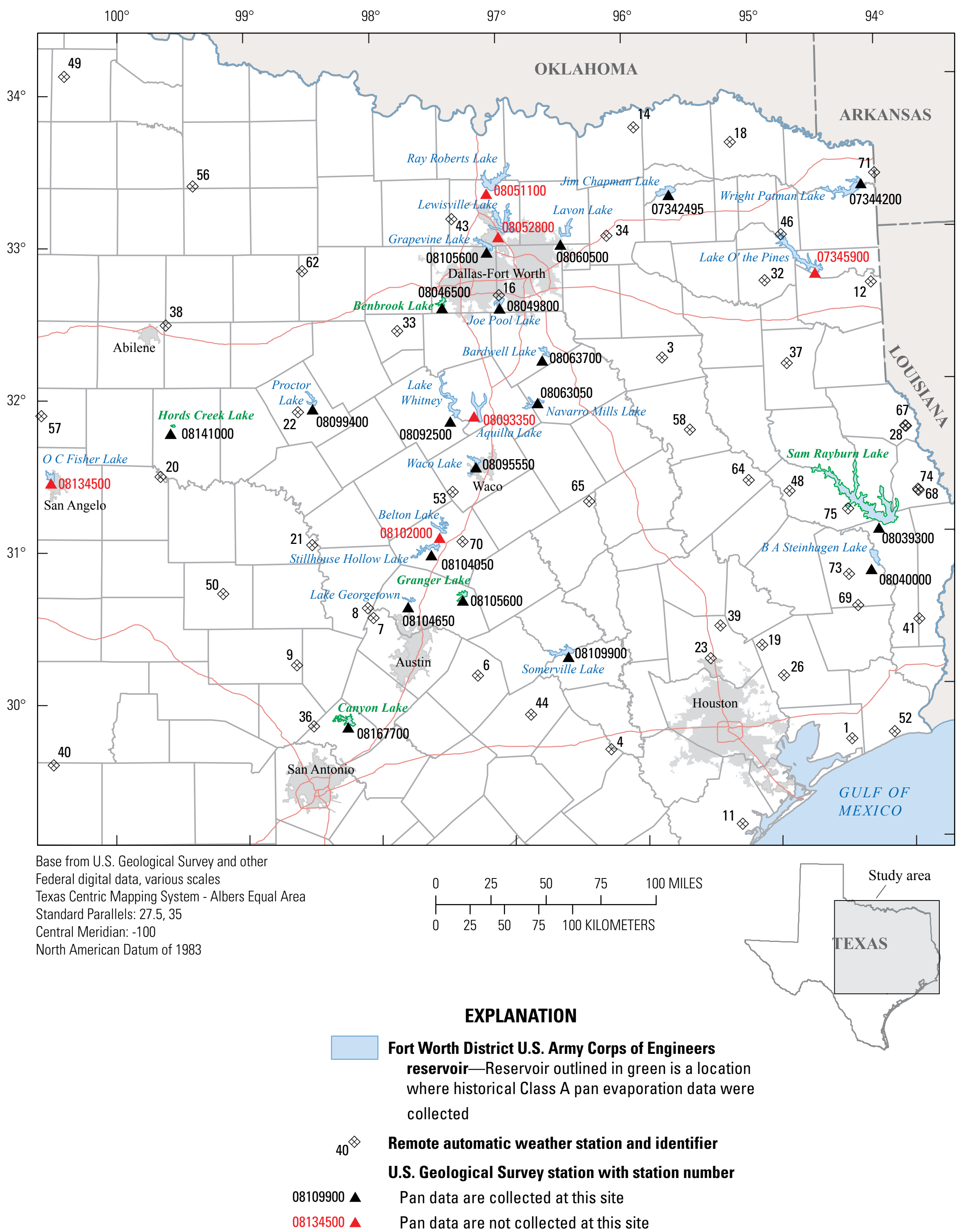


Figure 1. Location of Fort Worth District U.S. Army Corps of Engineers reservoirs and Remote Automatic Weather Stations in Texas.

Table 1. Fort Worth District U.S. Army Corps of Engineers reservoirs in Texas.

[USGS, United States Geological Survey; --, indicates Class A pan data are collected at the reservoir]

USGS station number	Reservoir	Latitude	Longitude	Class A pan data collected at reservoir	Class A pan data location used to estimate evaporation at indicated reservoir
08093350	Aquilla Lake	31° 53′ 59″	97° 12′ 09″	No	Whitney Lake
08040000	B A Steinhagen Lake	30° 47′ 43″	94° 10′ 48″	Yes	--
08063700	Bardwell Lake	32° 15′ 00″	96° 38′ 49″	Yes	--
08102000	Belton Lake	31° 06′ 22″	97° 28′ 28″	No	Stillhouse Hollow Lake
08046500	Benbrook Lake	32° 39′ 02″	97° 26′ 54″	Yes	--
08167700	Canyon Lake	29° 52′ 07″	98° 11′ 55″	Yes	--
08104650	Lake Georgetown	30° 40′ 03″	97° 43′ 38″	Yes	--
08105600	Granger Lake	30° 41′ 34″	97° 19′ 34″	Yes	--
08105600	Grapevine Lake	32° 58′ 21″	97° 03′ 22″	Yes	--
08141000	Hords Creek Lake	31° 49′ 58″	99° 33′ 38″	Yes	--
07342495	Jim Chapman Lake	33° 20′ 00″	95° 37′ 30″	Yes	--
08049800	Joe Pool Lake	32° 38′ 36″	97° 00′ 03″	Yes	--
07345900	Lake O’ The Pines	32° 45′ 18″	94° 29′ 57″	No	Wright Patman Lake
08060500	Lavon Lake	33° 01′ 54″	96° 28′ 56″	Yes	--
08052800	Lewisville Lake	33° 04′ 09″	96° 57′ 51″	No	Grapevine Lake
08063050	Navarro Mills Lake	31° 57′ 27″	96° 41′ 21″	Yes	--
08134500	O C Fisher Lake	31° 29′ 04″	100° 28′ 53″	No	National Weather Service office in San Angelo, Texas
08099400	Proctor Lake	31° 58′ 07″	98° 29′ 09″	Yes	--
08051100	Ray Roberts Lake	33° 21′ 19″	97° 02′ 59″	No	Grapevine Lake
08039300	Sam Rayburn Lake	31° 03′ 38″	94° 06′ 21″	Yes	--
08109900	Somerville Lake	30° 19′ 20″	96° 31′ 32″	Yes	--
08104050	Stillhouse Hollow Lake	31° 01′ 20″	97° 31′ 57″	Yes	--
08095550	Waco Lake	31° 34′ 46″	97° 11′ 51″	Yes	--
08092500	Whitney Lake	31° 51′ 55″	97° 22′ 18″	Yes	--
07344200	Wright Patman Lake	33° 18′ 16″	94° 09′ 38″	Yes	--

the Texas Forest Service (map identifier 16, fig. 1; table 2). The RAWS network is a national network consisting of about 2,200 stations, and about 70 stations are in Texas (Remote Automatic Weather Stations, 2012*)*. The Texas stations are strategically located to provide the data necessary to assist land-management agencies like the Texas Forest Service with fire danger ratings. RAWS stations, including the one at Joe Pool Lake, monitor incoming short-wave solar radiation, wind speed, wind direction, precipitation, air temperature, relative humidity, fuel moisture, soil moisture, and soil temperature (Remote Automatic Weather Stations, 2012).

The six stations are similar in many respects but there are important differences. The Grapevine Lake, Hords Creek Lake, and Canyon Lake stations collect net radiation, wind speed, wind direction, air temperature, relative humidity, and barometric pressure data. These stations are land-based stations adjacent to the reservoirs and the USACE project offices.

The Lewisville Lake station is accessible only by boat and is on top of a narrow piece of land that is part of an old dam that formed Lake Dallas that was breached when Lewisville Dam was built to form Lewisville Lake. The Wright Patman Lake station is located on a small peninsula that extends from an island in the main body of the reservoir and is accessible only by boat. The Wright Patman and Lewisville Lake stations collect net radiation, wind speed,

Table 2. Summary information for Remote Automatic Weather Stations in Texas.

[RAWS, Remote Automatic Weather Stations; NWSID, National Weather Service Identification Number; --, indicates NWSID not available or station is currently active]

Map identifier	RAWS station name[1]	NWSID	Latitude	Longitude	Year data collection began	Year solar radiation data collection began	Year station discontinued
1	Anahuac National Wildlife Refuge	416099	29° 40′ 09″	94° 26′ 18″	1994	2003	--
2	Aransas	418502	28° 15′ 00″	96° 45′ 00″	1999	2001	--
3	Athens	--	32° 13′ 16″	95° 45′ 58″	2002	2002	--
4	Attwater National Wildlife Refuge	416601	29° 39′ 42″	96° 15′ 35″	2002	2002	--
5	Barnhart	417701	30° 59′ 08″	101° 09′ 28″	2003	2003	--
6	Bastrop	415501	30° 10′ 27″	97° 15′ 23″	2003	2003	--
7	Balcones	417902	30° 33′ 58″	98° 02′ 20″	2000	2000	--
8	Balcones Flying X	--	30° 37′ 48″	98° 04′ 55″	2010	2010	--
9	Bird	417901	30° 15′ 45″	98° 37′ 44″	2001	2002	--
10	Bootleg	418801	34° 49′ 43″	102° 48′ 34″	2004	2004	--
11	Brazoria NWR	418301	29° 08′ 30″	95° 17′ 30″	1994	2001	--
12	Caddo Lake	411901	32° 39′ 30″	94° 06′ 59″	2002	2002	--
13	Caprock	418901	34° 24′ 38″	101° 02′ 57″	2004	2004	--
14	Caddo	410202	33° 44′ 28″	95° 55′ 19″	2000	2005	--
15	Cedar	418701	35° 40′ 00″	101° 34′ 00″	1997	2006	--
16	Cedar Hill State Park	419701	32° 36′ 33″	96° 59′ 35″	2003	2003	--
17	Chisos Basin	417403	29° 16′ 00″	103° 18′ 00″	2000	2005	--
18	Clarksville	410401	33° 37′ 08″	95° 10′ 00″	2001	2003	--
19	Coldsprings	414201	30° 18′ 38″	95° 05′ 12″	2001	2004	--
20	Coleman	419502	31° 30′ 22″	99° 39′ 34″	2003	2003	--
21	Colorado Bend	419501	31° 03′ 08″	98° 30′ 01″	2000	2002	--
22	Comanche	419403	31° 55′ 27″	98° 35′ 50″	2007	2007	--
23	Conroe	415109	30° 14′ 11″	95° 28′ 58″	1995	2004	--
24	Caprock State Park	--	34° 12′ 36″	101° 01′ 48″	2000	Never collected	2003
25	Davis	--	30° 36′ 00″	103° 53′ 00″	2001	Never collected	2004
26	Dayton	415201	30° 06′ 18″	94° 55′ 53″	2003	2003	--
27	Dog Canyon	--	31° 59′ 46″	104° 50′ 02″	2010	2010	--
28	Dreka	--	31° 42′ 05″	93° 54′ 19″	2000	Never collected	2004
29	Falcon Lake	418604	26° 33′ 17″	99° 08′ 08″	2002	2002	--
30	Fort Davis	417201	30° 36′ 02″	103° 53′ 12″	2004	2004	--
31	George West	418201	28° 22′ 00″	98° 07′ 00″	2002	2010	--
32	Gilmer	411401	32° 42′ 06″	94° 56′ 41″	2002	2002	--
33	Granbury	419702	32° 26′ 49″	97° 49′ 01″	2004	2004	--
34	Greenville	419602	33° 02′ 07″	96° 09′ 50″	2002	2002	--
35	Guadalupe Peak	417103	31° 55′ 30″	104° 49′ 31″	1985	2006	--
36	Guadalupe River State Park	418101	29° 51′ 34″	98° 30′ 19″	2003	2003	--
37	Henderson	412202	32° 09′ 00″	94° 48′ 00″	2000	2003	--
38	Hamby	419401	32° 30′ 00″	99° 37′ 00″	2000	2004	--
39	Huntsville	414102	30° 27′ 00″	95° 24′ 00″	2000	2003	--

Table 2. Summary information for Remote Automatic Weather Stations in Texas.—Continued

[RAWS, Remote Automatic Weather Stations; NWSID, National Weather Service Identification Number; --, indicates NWSID not available or station is currently active]

Map identifier	RAWS station name[1]	NWSID	Latitude	Longitude	Year data collection began	Year solar radiation data collection began	Year station discontinued
40	Kickapoo Caverns State Park	418001	29° 36′ 33″	100° 28′ 23″	2006	2006	--
41	Kirbyville	414501	30° 26′ 00″	93° 53′ 00″	2001	2003	2010
42	Laguna Atascosa	418603	26° 13′ 42″	97° 20′ 54″	2002	2002	--
43	LBJ Road	419601	33° 10′ 22″	97° 22′ 32″	2000	2004	--
44	La Grange	415602	29° 54′ 27″	96° 51′ 36″	2000	2004	--
45	Linn-San Manuel	418605	26° 32′ 06″	98° 05′ 09″	2002	2002	--
46	Linden	411102	33° 00′ 00″	94° 48′ 00″	2003	2003	--
47	Santa Ana National Wildlife Refuge	418602	26° 05′ 02″	98° 08′ 13″	1998	2003	--
48	Lufkin	413509	31° 18′ 47″	94° 49′ 34″	1995	2004	--
49	Matador Wildlife Management Area	418902	34° 08′ 00″	100° 25′ 00″	2000	2005	--
50	Mason	417801	30° 44′ 09″	99° 11′ 10″	2003	2003	--
51	Matagorda Island	418503	28° 07′ 22″	96° 48′ 08″	2003	2003	--
52	McFadden	419901	29° 42′ 00″	94° 07′ 00″	1998	2004	--
53	McGregor	419802	31° 23′ 02″	97° 24′ 46″	2003	2003	--
54	McKittrick	--	31° 58′ 39″	104° 45′ 06″	2009	2009	--
55	Midland	419202	32° 00′ 00″	102° 00′ 00″	2000	2004	--
56	Miller Creek	419301	33° 24′ 49″	99° 24′ 02″	2003	2010	--
57	Paint Creek	419203	31° 54′ 22″	100° 34′ 54″	2006	2006	--
58	Palestine	412601	31° 44′ 33″	95° 34′ 18″	2002	2002	--
59	Panther Junction	417401	29° 19′ 00″	103° 12′ 00″	2003	2003	--
60	Pearsall	418102	28° 53′ 06″	99° 06′ 38″	2007	2007	--
61	Pinery	417101	31° 53′ 40″	104° 47′ 52″	2001	2001	--
62	Possum Kingdom	419402	32° 51′ 00″	98° 33′ 00″	2000	2003	--
63	PX Well	--	31° 58′ 20″	104° 56′ 52″	2010	2010	--
64	Ratcliff	413302	31° 23′ 42″	95° 08′ 10″	2001	2005	--
65	Round Prairie	413101	31° 17′ 44″	96° 21′ 56″	2007	2007	--
66	San Bernard	418302	28° 51′ 53″	95° 34′ 04″	2002	2002	--
67	Sabine North	412901	31° 42′ 15″	93° 54′ 35″	2004	2004	--
68	Sabine South	413701	31° 16′ 49″	93° 50′ 19″	2000	2003	--
69	Southern Rough	416101	30° 32′ 25″	94° 20′ 28″	1999	Never collected	--
70	Temple	419801	31° 03′ 23″	97° 20′ 49″	2003	2003	--
71	Texarkana	410501	33° 22′ 26″	94° 02′ 44″	2002	2002	--
72	Victoria	418202	28° 50′ 46″	96° 55′ 18″	2003	2003	--
73	Woodville	414402	30° 45′ 00″	94° 24′ 00″	2000	2003	--
74	Yellowpine	--	31° 16′ 33″	93° 50′ 10″	2003	2003	2003
75	Zavalla	413503	31° 10′ 38″	94° 23′ 02″	2010	2010	--

[1]RAWS station name taken from RAWS website at http://www.raws.dri.edu/wraws/txF.html and accessed February 15, 2012.

wind direction, air temperature, and relative humidity data. Atmospheric pressure is assumed constant at these two stations and is calculated from station elevation. The net radiation data collected at all of the stations are impacted by the surrounding land. The location of the Lewisville and Wright Patman Lake stations were selected to try to minimize the effects of the land on net radiation measurements.

Two different forms of the Penman equation are used to estimate daily evaporation from the data collected at the six reservoirs, and the Fort Worth District also collects pan data at these reservoirs or nearby reservoirs. The Pruitt and Doorenbos Modified Penman, referred to as the Modified Penman equation, is used for Grapevine Lake, Hords Creek Lake, Canyon Lake, and Joe Pool Lake (Pruitt and Doorenbos, 1977). The California Irrigation Management Information System (CIMIS) also uses the equation to estimate reference evapotranspiration from well-watered actively growing and closely-clipped grass and the CIMIS website explains the steps involved in making the calculations (California Irrigation Management Information System, 2012). An alternative form of the Penman equation is used for Lewisville Lake and Wright Patman Lake. The alternative form for these two reservoirs is equation number 4.4.10 from Shuttleworth (1993, p. 4.36). Both forms of the Penman equation for estimating evaporation from Grapevine Lake, Hords Creek Lake, Canyon Lake, Joe Pool Lake, Lewisville Lake, and Wright Patman Lake are configured to ignore the effects of changes in stored energy and advection on estimates of evaporation from the reservoirs.

Little Rock District

The USACE Little Rock District manages 23 reservoirs in Arkansas and Missouri, 11 of which are on the Arkansas River. Pan data are used to estimate evaporation from all of the reservoirs for water-budgeting purposes. Pan data were historically collected at three locations throughout the district. One pan is located at Millwood Lake in the southwestern part of Arkansas, and these data are used to estimate evaporation from four reservoirs with an average pan to reservoir distance of 25 miles (mi). Another pan is located at Blue Mountain Lake in the western part of Arkansas, and these data are used to estimate evaporation from the 11 reservoirs on the Arkansas River and 2 additional reservoirs. The average distance from pan site to reservoir is about 70 mi. The third pan site, near Mountain Home, Ark., in the northern part of the State, has been discontinued and historical daily average pan data are used to estimate evaporation from the remaining six reservoirs in the Little Rock District. Average distance from pan site (when active) to reservoir is about 54 mi. To convert pan evaporation to reservoir evaporation, a pan coefficient of 0.70 is applied to pan data during all months of the year at all reservoirs (Matthew Moix, U.S. Army Corps of Engineers, written commun., 2011).

Omaha District

The USACE Omaha District manages 32 reservoirs throughout Nebraska, Colorado, Wyoming, South Dakota, North Dakota, and Montana. Six more large reservoirs on the main stem of the Missouri River also are managed by the Northwestern Division of the USACE, of which the Omaha District is included. Historically, pan data have been used to estimate evaporation from the reservoirs. For the six reservoirs on the Missouri River, water budgets are done on a daily time step and on a monthly time step for the other reservoirs. Pan evaporation records are usually incomplete during the winter months because of water freezing in the pans in the colder climates of the States where these reservoirs are located.

The Omaha District has moved away from using pan data to estimate evaporation from its reservoirs (Kellie Bergman, U.S. Army Corps of Engineers, written commun., 2011). Researchers at the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire, have been developing an automated method to estimate reservoir evaporation from data collected at nearby National Weather Service (NWS) stations on a 1-hour time step. Currently (2012), the Omaha District uses an automated method to estimate daily evaporation from the 6 reservoirs on the main stem of the Missouri River and 22 of the other 32 reservoirs with intention of expanding to include the remaining 10 reservoirs.

A report that describes the method used by the Omaha District was published in the proceedings of the Conference on Hydrology of the American Meteorological Society in January 2002 (Andreas and others, 2002). The method is based on a “bulk flux algorithm” that includes predictions of the three turbulent fluxes of momentum, sensible heat, and latent heat. It is beyond the scope of this report to discuss in detail the Andreas and others (2002) method and the complex equations that are iteratively solved to ultimately estimate evaporation under various atmospheric conditions of stability and instability and under various surface roughness conditions.

Two of the key input variables of the method are surface-water temperature of the reservoir and the saturation-specific humidity of the surface at that temperature (Andreas and others, 2002). Because the data are remotely collected meteorological data, surface-water temperature of the reservoir and saturation-specific humidity at the surface must be estimated. Andreas and others (2002) describe the “bootstrap” method employed to predict these variables from available meteorological data collected at the NWS stations. The authors also show comparisons of the estimates of surface-water temperature and measured water temperature (deployed temporarily for comparative purposes) at one of the reservoirs and conclude that the estimate of surface-water temperature closely follows the air temperature and, therefore, displays much more diurnal variability than measured water temperature.

To date (2012), a comprehensive comparison of estimates of evaporation by the Andreas and others (2002) method used in the Omaha District against evaporation estimates from traditional energy-budget methods has not been done. Some comparisons have been made against pan data, but these comparisons were for small time periods (one month) (Andreas and others, 2002). The accuracy of the evaporation estimates will likely depend upon the accuracy of the surface-water temperature and saturation-specific humidity estimates and the representativeness of conditions at the nearby NWS stations to conditions just above the surface of the water in the reservoir for which estimates are being made.

Tulsa District

The USACE Tulsa District manages 49 reservoirs throughout Texas, Oklahoma, and Kansas. Historically, pan data have been used to estimate daily evaporation. In 1996, the Tulsa District began using empirical and semiempirical equations to estimate daily evaporation from meteorological data including air temperature, relative humidity, wind speed, and incoming short-wave solar radiation. By about 1998, the Tulsa District discontinued the use of evaporation pans and began relying exclusively on equation estimates (Greg Estep, U.S. Army Corps of Engineers, written commun., 2011). Tulsa District, U.S. Army Corps of Engineers (2012) is a list of the 49 reservoirs and the daily estimates of evaporation found at each reservoir.

For 42 of the 49 reservoirs, meteorological data are collected from stations on top of the dams and usually adjacent to the gate towers, or outlet control works. These stations are listed as data collection platform (DCP) stations at the reference given above. For the other seven reservoirs, meteorological data are collected from weather stations offsite and vary with respect to distance away from the reservoir for which data are used to estimate evaporation. Average distance from reservoir to remote weather station is 12.4 mi and ranges from 1.1 to 21.8 mi. These seven stations are part of the Oklahoma Mesonet (MESO) network (Mesonet, 2012). The MESO network consists of 120 automated stations throughout the State of Oklahoma with at least one station in each county. The network is managed jointly by Oklahoma State University and the University of Oklahoma. Air temperature, relative humidity, wind speed, and incoming short-wave solar radiation are reported for all of the stations as hourly averages, and daily averages are used to calculate a daily estimate of evaporation from the reservoirs (Tulsa District, U.S. Army Corps of Engineers, 2012).

The method used by the Tulsa District to estimate average daily lake evaporation was published as equation 10 in a USWB research paper (Kohler and others, 1955, p. 14) and is based directly on the Penman equation. The Penman equation was applied to daily Class A evaporation pan data from stations throughout the United States to empirically derive coefficients to estimate the amount of daily evaporation from a Class A pan and ultimately the amount of average daily lake evaporation from air temperature, relative humidity, wind speed, and solar radiation data. Average daily lake evaporation is estimated as the product of the Penman estimated evaporation from a Class A pan and a 0.70 coefficient. The USWB method assumes that the change in the amount of stored energy and the amount of advected energy are negligible. Therefore, the USWB method is intended to estimate average daily lake evaporation such that the sum of the daily estimates should approximate annual evaporation if the annual change in the amount of stored energy and advected energy are negligible.

The Tulsa District uses empirical equations to calculate the input data to the USWB method from the meteorological data collected at the DCP and MESO stations. These equations are referenced in chapters two and five of “Hydrology for Engineers” (Linsley and others, 1982, p. 31–174). The equations and the steps to calculate average daily lake evaporation with the USWB method are shown on the Tulsa District websites for each of the reservoirs (http://www.swt-wc.usace.army.mil/evap/calcevap.shtml) and are included in appendix 2 of this report.

Kohler and others (1955) compared lake evaporation estimates from the USWB method with lake evaporation as determined from water budgets for Lake Hefner, Oklahoma, Lake Okeechobee, Florida, and Red Bluff Reservoir, Texas. Percentage errors between the USWB method and water-budget estimates at the three locations ranged from 4.4 percent at Lake Hefner to 14.4 percent at Lake Okeechobee. The time periods compared were 1 year for Lake Hefner, 1 year for Lake Okeechobee, and 8 years for Red Bluff Reservoir. Similarly, Kohler and others (1955) compared lake evaporation as determined from pan data and application of a 0.70-pan coefficient to lake evaporation as determined from water budgets and found percentage errors ranged from 2.4 percent at Lake Hefner to 6.5 percent at Lake Okeechobee. Percentage errors between lake evaporation determined from pan data and application of a 0.70-pan coefficient and the USWB method averaged about 12.0 percent and ranged from about 6.6 to 22.0 percent with three of the four percentage errors less than 10 percent. Other comparisons reported in the scientific literature between the USWB method estimates and other method estimates, such as energy budgets, are discussed in appendix 1 of this report for reference.

In 1996, the Tulsa District compared daily pan estimates with daily estimates using the USWB method at 14 different reservoirs for an average of 24 days at each reservoir at various times during July, August, September, October, and November. The percentage difference between the total amounts of evaporation by the two methods for all of the reservoirs was about 20 percent with the USWB calculated amount exceeding the pan amount. The average and median daily differences between the two methods were 0.05 and 0.04 inches per day (in/d), respectively.

The USWB method by Kohler and others (1955) is appealing because it allows for estimation of average daily lake evaporation in an automated way with instrumentation that is fairly robust and with minimal data input (four parameters) from land-based meteorological stations. The method could be evaluated in a more comprehensive way by retrieving historical meteorological data from MESO stations (and other stations with the required data) throughout the State of Oklahoma and estimating evaporation with the USWB method and comparing the estimates with historical evaporation pan estimates from the different reservoirs. This would provide a more comprehensive comparison of the differences between the two methods and would identify the presence of any seasonal bias in the differences with respect to historical pan estimates.

Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas

Modified and unmodified versions of two methods (Hamon method and the USWB method) used to estimate evaporation from five reservoirs operated by the USACE in Texas (Benbrook Lake, Canyon Lake, Granger Lake, Hords Creek Lake, and Sam Rayburn Lake) (hereinafter, the five reservoirs) were evaluated by comparing results from these methods with pan evaporation data that was also collected at each reservoir. These five reservoirs are operated and maintained by the Fort Worth District of the USACE. The Hamon method was developed for the estimation of potential evapotranspiration on a daily time step (Hamon, 1961). Evaporation from open water is equivalent to potential evapotranspiration, primarily because in both conditions the supply of water is nonlimiting, meaning there is an infinite supply of water for the evaporation process. The USWB method was explained in the previous section because it is the method currently (2012) used by the Tulsa District of the USACE.

All of the supporting equations required for the two methods are included in appendix 2. Appendix 2 also includes the calculation steps and limitations of the equations, when appropriate. The two methods were selected because of simplicity, minimal data requirements, and ability to use remotely collected data.

The Hamon method requires only average daily air temperature and maximum number of daylight hours calculated from the latitude of the reservoir and the Julian day. The USWB method requires daily averages of air temperature, relative humidity, wind speed, and incoming short-wave solar radiation. The required data (in real time) for both methods are available from RAWS stations distributed throughout Texas (fig. 1), which makes additional instrumentation and data collection unnecessary. Average daily values from the stations are available from the internet (Remote Automatic Weather Stations, 2012).

The National Wildfire Coordinating Group (2009) has published a document that specifies the standards and guidelines for operation and maintenance of the weather stations in the RAWS network. The document is available from the internet (National Wildfire Coordinating Group, 2009). Every RAWS station receives at least one annual site visit to ensure sensors are within calibration standards and to verify site conditions by maintaining vegetation growth or mitigating other activities that reduce data integrity. Other site visits during the annual period are made as necessary to repair or replace equipment. As a matter of standard procedure, the air temperature and humidity sensors are replaced annually, wind speed and direction sensors are replaced every 2 years, and solar radiation sensors are replaced every 3 years. The temperature sensors are accurate to within 1 degree Fahrenheit (°F) (range of -58 to 140°F) and humidity sensors are accurate to within 2 percent from 0 to 80 percent humidity and within 5 percent from 80 to 100 percent humidity at 77°F. The wind speed sensors are accurate to within 5 percent of the reading within the range of zero to 100 miles per hour (mi/h). Lastly, solar radiation sensors are accurate to within 5 percent of the reading within the range of zero to 1,800 watts per square meter.

The five reservoirs (fig. 1) were selected because of their spatial distribution across Texas, varying climatic setting, and presumably varying amounts of evaporation. The average amounts of monthly pan evaporation collected at each of the reservoirs by the USACE are shown in figure 2. Monthly pan evaporation refers to the published monthly Class A pan evaporation data in appendix tables 3.1–3.5 (National Oceanic and Atmospheric Administration, 1953–2010). Average monthly pan evaporation is highest at Hords Creek Lake (the westernmost and most arid climate of the five reservoirs) and lowest at Sam Rayburn Lake (the easternmost and most humid climate of the five reservoirs), with similar amounts at Canyon Lake and Granger Lake in the center of the State. Monthly pan evaporation amounts at Benbrook Lake in north Texas are less than Hords Creek Lake for all months of the year and usually less than Canyon Lake and Granger Lake.

The time period for which comparisons were made between the Hamon and the USWB method estimates with pan evaporation estimates covers a broad range of wet and dry periods. The amount of deviation from average annual precipitation amounts for the five reservoirs in Texas is listed in table 3. Positive deviation in the table indicates periods with precipitation above average and negative deviation indicates periods with precipitation below average.

Data Compilation

For each of the five reservoirs, a RAWS “base station” was selected to provide the necessary meteorological data. Base stations for Benbrook Lake, Canyon Lake, Granger Lake, Hords Creek Lake, and Sam Rayburn Lake were

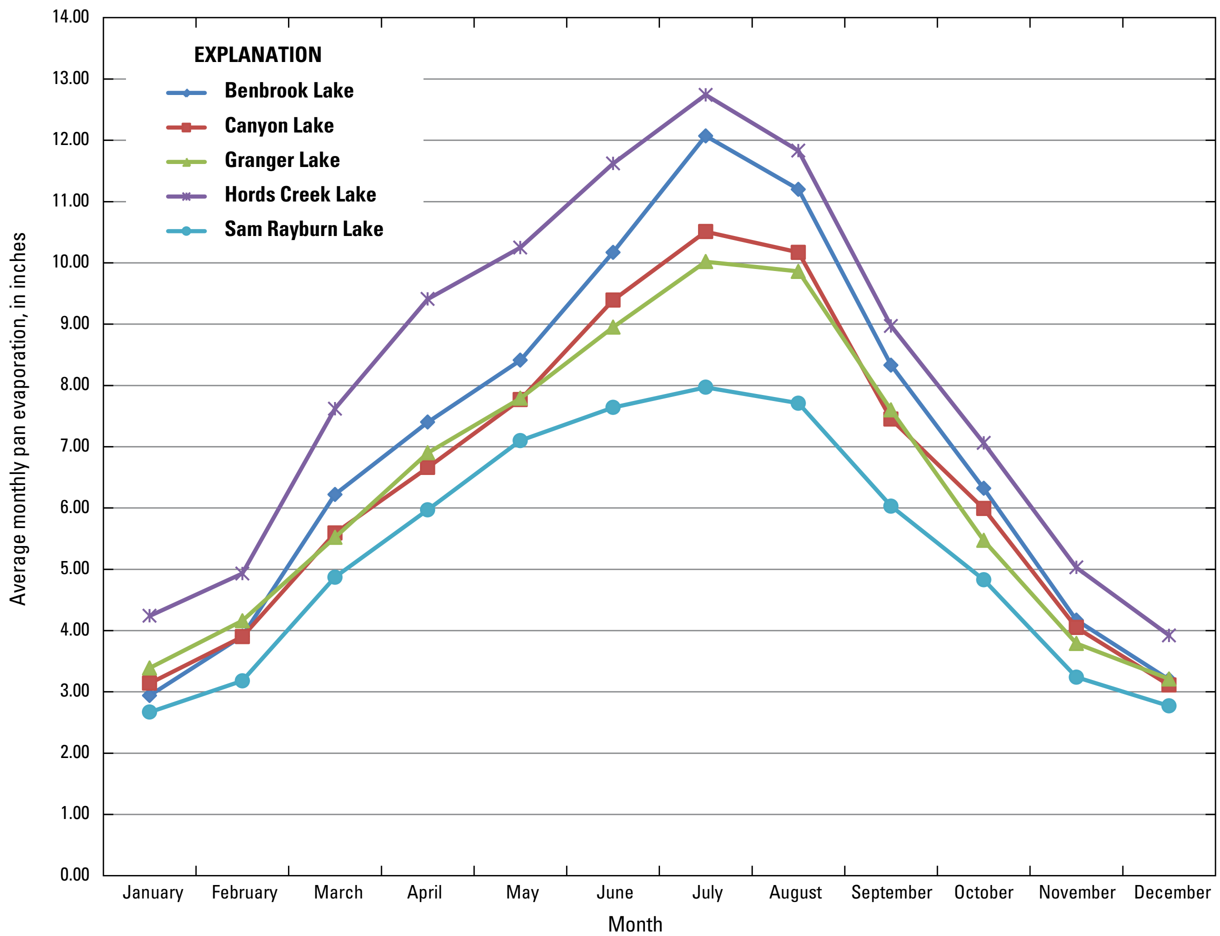


Figure 2. Average monthly historical Class A pan evaporation from five reservoirs in Texas, 1953–2010.

Cedar Hill State Park, Guadalupe River State Park, Temple, Coleman, and Woodville, respectively (fig. 1; table 4). The RAWS station names listed here and in tables 2 and 4 are the station names listed on the RAWS website (Remote Automatic Weather Stations, 2012). Base stations were selected primarily for their proximity to a reservoir and for having the longest period of complete record. Distances from a RAWS base station to its corresponding reservoir ranged from 18 to 27 mi. Distances and periods of record for each RAWS station and meteorological data in the study are listed in table 4.

Other stations within the RAWS network were used to fill data gaps at base stations when average daily values at the base stations were not available because of maintenance, repair, or equipment malfunction. These stations are referred to as "satellite stations" in this report (fig. 1; table 4). Satellite stations included Granberry, LBJ Road, Balcones, Bastrop, Mason, Hamby, Lufkin, Sabine South, and Southern Rough. The Southern Rough station does not collect solar radiation data. Data from Southern Rough were only used to fill in gaps for air temperature data at the Woodville base station.

Linear regression equations for air temperature, relative humidity, wind speed, and solar radiation were developed to estimate average daily values at the base station using satellite station data. The equations were used to fill in data gaps when the base station values were missing or when the daily average from the base station was calculated from less than 22 of 24 hourly values (or 91.7 percent). When there was missing data or a data gap at a base station, the corresponding daily value from a satellite station was only used to fill in the data at a base station if at least 22 of its 24 hourly values were available from the satellite station. The linear regression equations are included in appendix tables 4.1–4.4. To develop the equations, only days with complete periods of record (24 hourly averages) at both the base station and the satellite station were used to minimize potential bias in the linear regression equations. The percentage of days with data filled in using the linear regression equations at each base station are included in tables 4.1–4.4. Air temperature, relative humidity, and wind speed data at base stations were similar with respect to the percentage of days with estimated values derived from

Table 3. Amount of deviation from average annual precipitation amounts for five Texas reservoirs, 2001–10.

Reservoir	Year	Precipitation deviation from average (inches)[1]	Reservoir, or station, where precipitation data were collected
Benbrook Lake	2004	11.20	Benbrook Lake
	2005	-15.83	Benbrook Lake
	2006	-3.16	Grapevine Lake[2]
	2007	15.66	Grapevine Lake[2]
	2008	-9.05	Benbrook Lake
	2009	14.63	Benbrook Lake
	2010	0.13	Benbrook Lake
Canyon Lake	2004	19.72	Canyon Lake
	2005	-8.61	Canyon Lake
	2006	-7.55	Canyon Lake
	2007	27.61	Canyon Lake
	2008	-16.70	Canyon Lake
	2009	3.61	Canyon Lake
	2010	4.20	Canyon Lake
Granger Lake	2004	29.89	Granger Lake
	2005	-6.22	Stillhouse Hollow Lake[2]
	2006	-1.66	Lake Georgetown[2]
	2007	12.21	Granger Lake
	2008	-17.05	Lake Georgetown[2]
	2009	3.19	Granger Lake
	2010	-10.25	Granger Lake
Hords Creek Lake	2003	0.69	Hords Creek Lake
	2004	16.57	Hords Creek Lake
	2005	-10.56	Proctor Lake[2]
	2006	-9.73	Burkett[2]
	2007	18.39	Proctor Lake[2]
	2008	-4.69	Burkett[2]
	2009	0.19	Proctor Lake[2]
	2010	0.48	Hords Creek Lake
Sam Rayburn Lake	2001	17.62	B A Steinhagen Lake[2]
	2002	8.88	B A Steinhagen Lake[2]
	2003	-10.26	Sam Rayburn Lake
	2004	20.24	Sam Rayburn Lake
	2005	-5.74	Sam Rayburn Lake
	2006	10.57	Sam Rayburn Lake
	2007	-7.49	Sam Rayburn Lake
	2008	-9.51	Sam Rayburn Lake
	2009	-3.64	Sam Rayburn Lake
	2010	-18.08	B A Steinhagen Lake[2]

[1]Positive deviation means amount of precipitation above average and negative deviation means amount of precipitation below average. Data are published by the National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas (2001–10).

[2]When data were incomplete, data from a nearby reservoir or National Weather Service station were used.

the linear regression equations. For air temperature, relative humidity, and wind speed, an average of 2.3, 2.6, and 2.8 percent, respectively, of the daily values was missing and needed to be estimated from the linear regression equations. For solar radiation, an average of about 8.9 percent of the days was estimated, mainly influenced by the large amount of estimated data at the Temple and Coleman stations (22.4 and 18.2 percent, respectively).

The strength of the linear relations and the estimating power of the linear regression equations (Helsel and Hirsch, 2002) were greatest for air temperature, as evidenced by the relatively large adjusted R-squared values greater than about 97 percent, the statistical significance of all of the slope and intercept terms (p-values less than 0.05), and the relatively small standard error of the estimates (less than 1.3 degrees Celsius). Relative humidity and wind speed equations varied among satellite stations. Although some of the adjusted R-squared values were low (less than about 50 percent) for these two variables, most were greater than about 70 percent and all of the slope and most of the intercept terms were statistically significant (p-values less than 0.05), and the standard error of the estimates was relatively low. Regression equations for relative humidity at the Woodville station from data collected at the Lufkin and Sabine South stations were developed according to wind direction. Regression equations for relative humidity were stronger when wind direction was taken into account, probably resulting from the close proximity of these stations to the Gulf of Mexico and its inherent influence on relative humidity. Adjusted R-squared values for solar radiation equations ranged from about 74 to 88 percent and all of the slope terms were significant and only one intercept term had a p-value greater than 0.05 because of outliers exerting leverage.

To estimate the amount of evaporation from a water body, a pan coefficient is multiplied by the amount of evaporation from the pan. Pan coefficients are usually less than one and, therefore, the amount of evaporation from a pan is usually greater than the amount of evaporation from a nearby water body. Average annual pan coefficients generally range from 0.60 to 0.80 across the United States (Kohler and others, 1959). Part-year, or monthly, pan coefficients for a particular reservoir are more variable because they attempt to account for changes in energy storage throughout the year. Monthly pan coefficients will usually be lower in the spring because heat is going into storage (warming the water) and not available for evaporation, and monthly pan coefficients will usually be higher during the fall because as the warm water in the reservoir cools energy is released from the reservoir through evaporation (Farnsworth and others, 1982; Spahr and Ruddy, 1983; Masoner and others, 2008).

The TWDB has published pan coefficients for Texas that vary monthly and spatially (Farnsworth and others, 1982; Tschirhart and Rodriguez, 1998). The TWDB monthly pan coefficients are included in appendix tables 3.1–3.5. The amount of monthly reservoir evaporation from published pan data (appendix tables 3.1–3.5) and application of the TWDB

Table 4. Remote Automatic Weather Station descriptive information for stations used in data analyses of five reservoirs in Texas.

[RAWS, Remote Automatic Weather Station; --, indicates no data collected; B, base station to reservoir; S, satellite station to base station for prediction of meteorological data]

Reservoir	RAWS station name	Distance to reservoir (miles)	Earliest air temperature, relative humidity, and wind speed data used in analyses	Earliest solar radiation data used in analyses
Benbrook Lake	Cedar Hill State Park (B)	27	December 2003	December 2003
	Granbury (S)	26	July 2004	July 2004
	LBJ Road (S)	36	December 2003	March 2004
Canyon Lake	Guadalupe River State Park (B)	18	November 2003	November 2003
	Balcones (S)	49	May 2000	December 2000
Granger Lake	Temple (B)	25	December 2003	December 2003
	Balcones (S)	43	May 2000	December 2000
	Bastrop (S)	36	April 2003	April 2003
Hords Creek Lake	Coleman (B)	23	April 2003	July 2005
	Mason (S)	79	January 2003	June 2005
	Hamby (S)	45	November 2000	June 2004
Sam Rayburn Lake	Woodville (B)	27	December 2000	January 2003
	Lufkin (S)	46	March 2000	July 2004
	Sabine South (S)	22	January 2000	November 2003
	Southern Rough (S)	38	January 2000	--

monthly pan coefficients are considered the “best available estimates” of monthly reservoir evaporation for the analysis described in this report.

Unmodified Hamon and U.S. Weather Bureau Method Estimates to Predict Monthly and Annual Evaporation

To avoid confusion in the following discussion, some terms previously defined in the section “Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas” are defined again in this section. Monthly pan evaporation refers to the published monthly Class A pan evaporation data in appendix tables 3.1–3.5. Monthly reservoir evaporation from pan data refers to monthly estimates of reservoir evaporation calculated from monthly Class A pan evaporation multiplied by the monthly pan coefficient recommended by the TWDB for the five reservoirs (Tschirhart and Rodriguez, 1998).

The average daily meteorological data required by the unmodified Hamon and USWB methods were used to calculate an estimate of daily reservoir evaporation. These daily estimates were summed to provide monthly estimates of reservoir evaporation. The monthly estimates of reservoir evaporation from the unmodified forms of the Hamon and USWB methods were compared with monthly reservoir evaporation from pan data for the five reservoirs. The results of these comparisons are displayed in figure 3 and summarized in table 5. Monthly estimates of evaporation along with percentage errors at all five reservoirs are included in appendix tables 5.1–5.5.

The unmodified Hamon method estimates of monthly reservoir evaporation were different from monthly reservoir evaporation from pan data. Average errors for all five reservoirs were greater than 20 percent and greater than 30 percent for four of the five reservoirs. The unmodified Hamon method tended to underestimate (with some exceptions) the amount of reservoir evaporation from pan data during all months of the year, but especially during the colder months of the year, for all except Sam Rayburn Lake (fig. 3E). For Sam Rayburn Lake, the unmodified Hamon method tended to underestimate during the colder months of the year, but during the warmer months there was more variability with respect to under- or overestimating monthly reservoir evaporation from pan data.

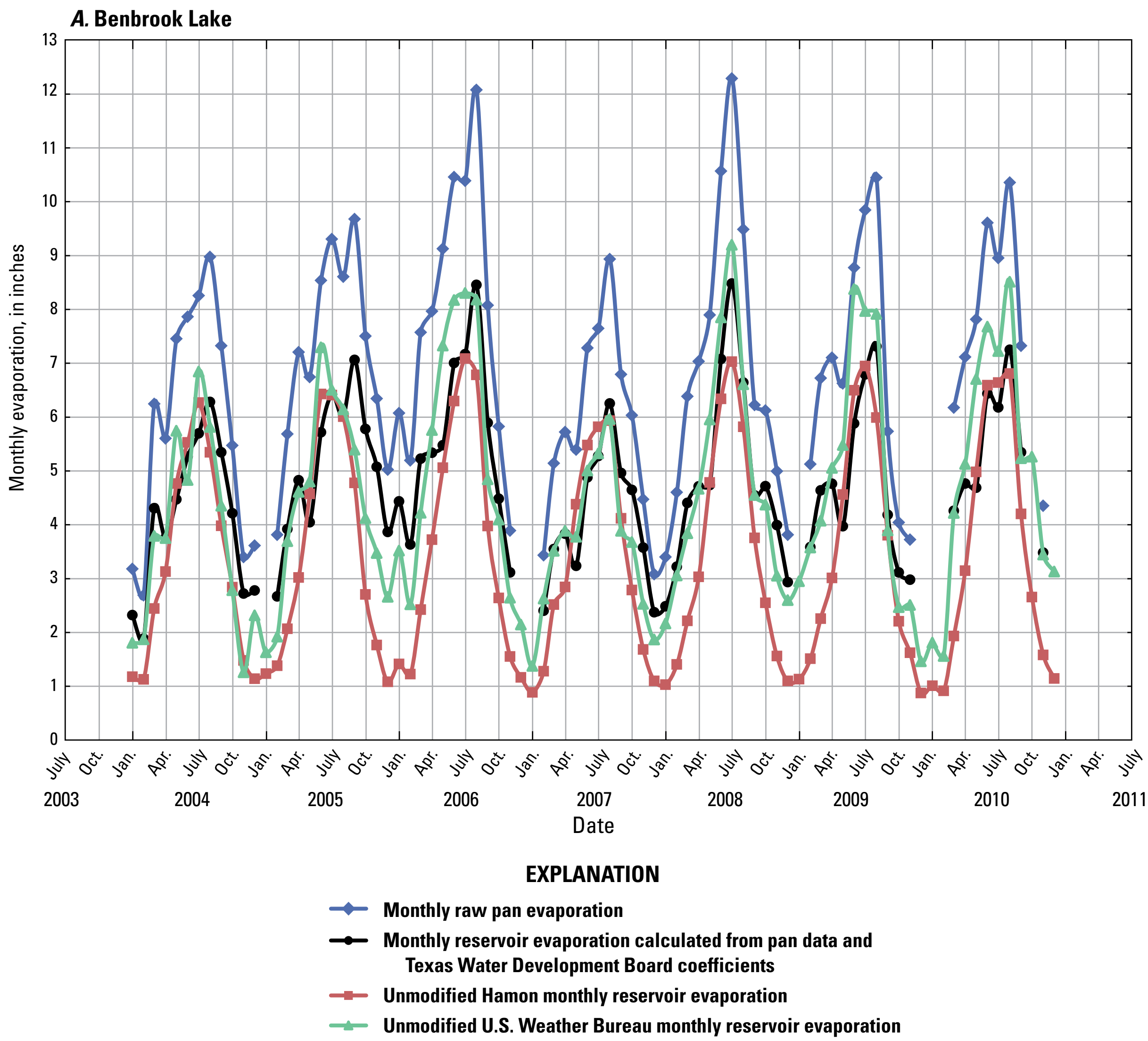


Figure 3. Comparison of monthly pan evaporation with unmodified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.

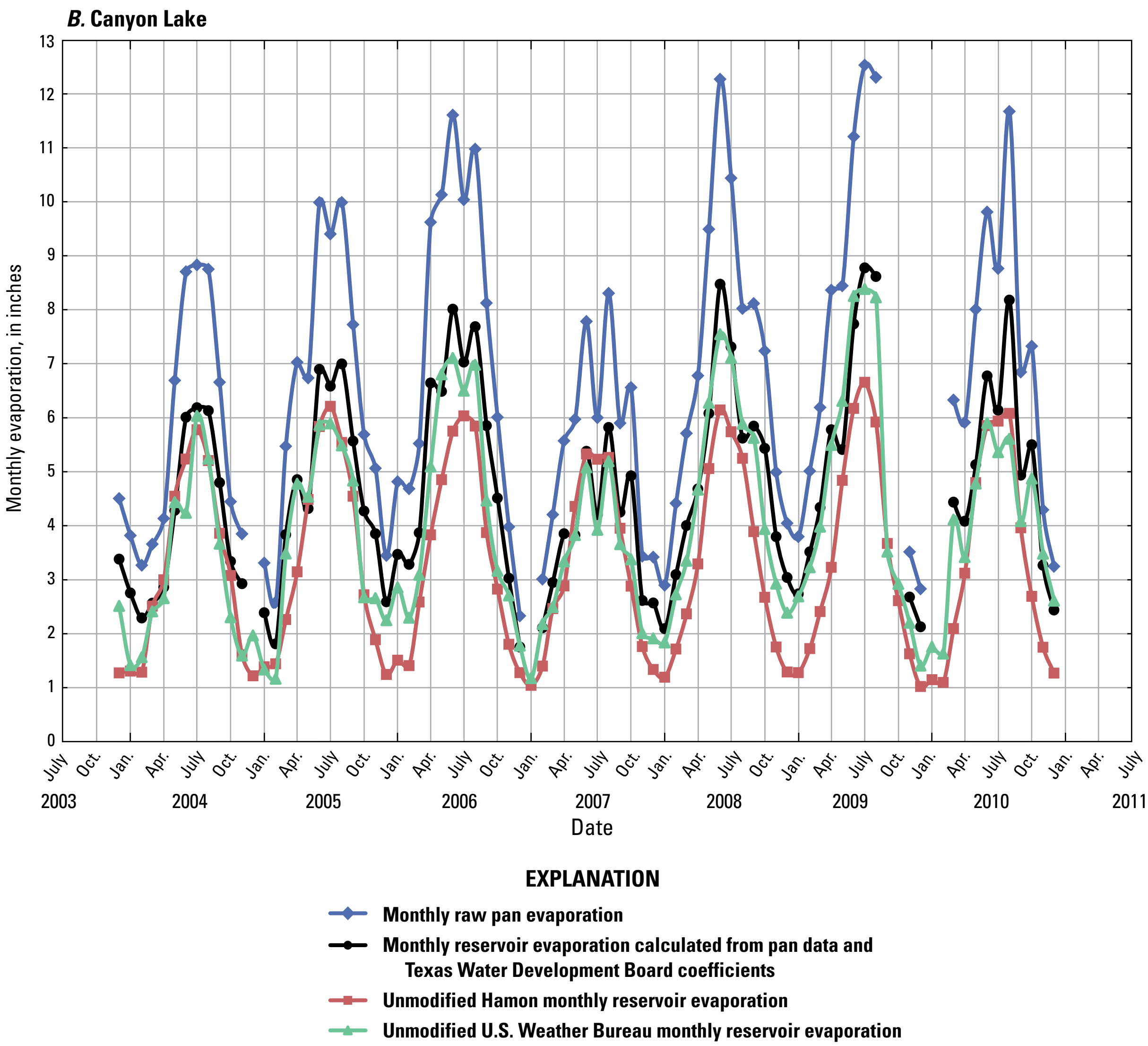


Figure 3. Comparison of monthly pan evaporation with unmodified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.—Continued

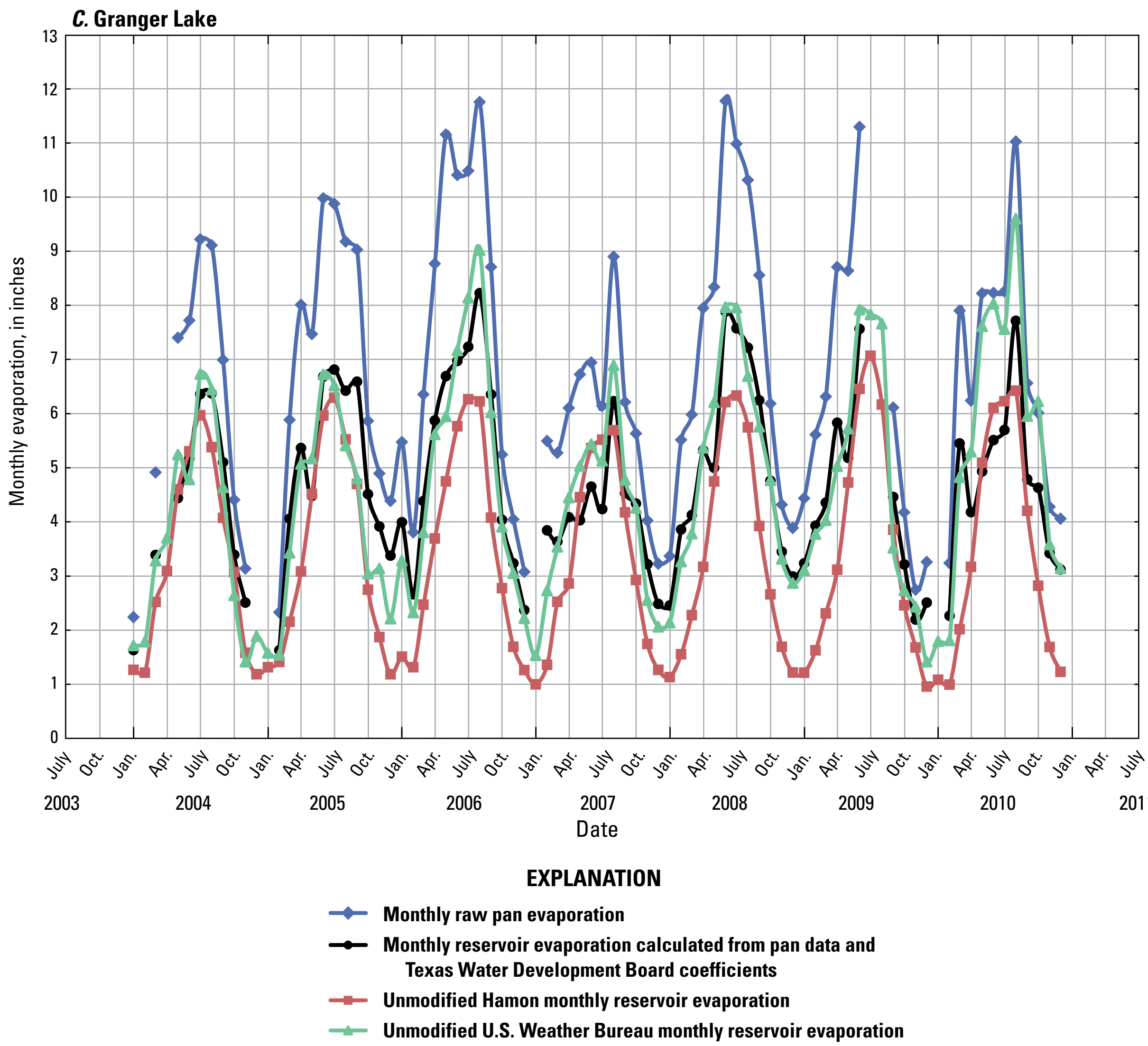


Figure 3. Comparison of monthly pan evaporation with unmodified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.—Continued

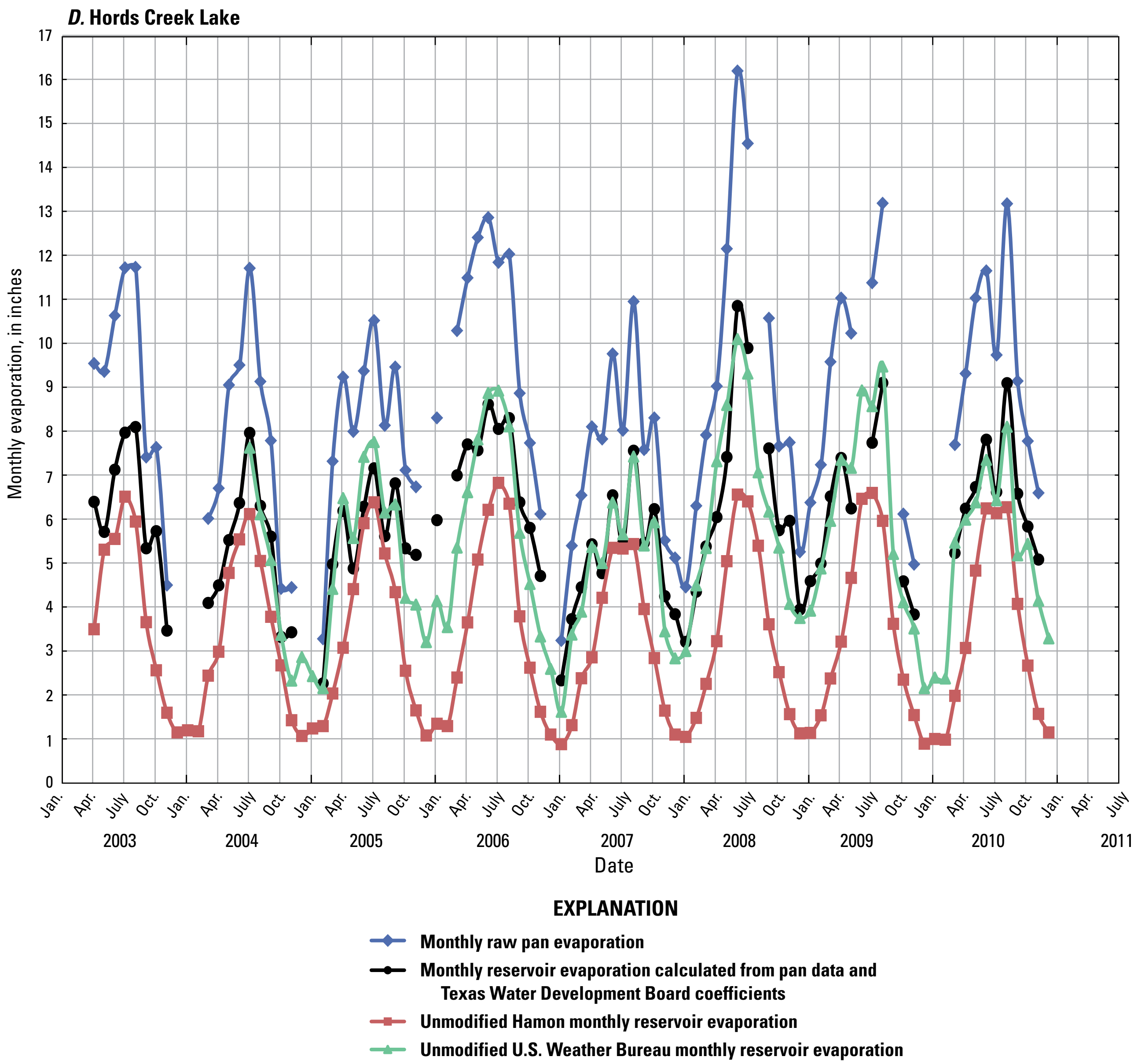


Figure 3. Comparison of monthly pan evaporation with unmodified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.—Continued

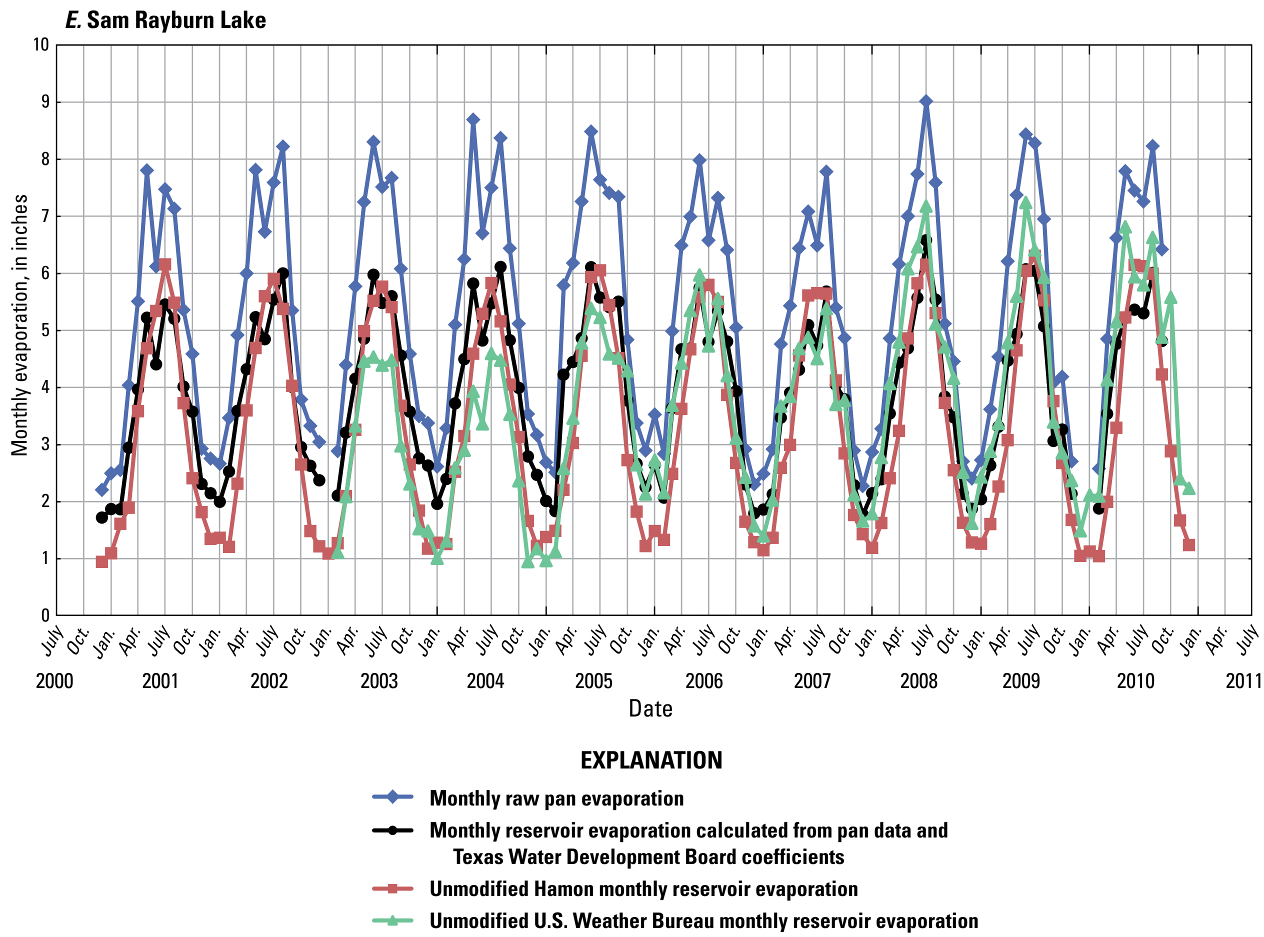


Figure 3. Comparison of monthly pan evaporation with unmodified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.—Continued

Table 5. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for five Texas reservoirs.

[USWB, U.S. Weather Bureau]

Reservoir	Percentage error[1]	Unmodified Hamon	Modified Hamon	Unmodified USWB	Modified USWB
Benbrook Lake	Average	31.0	10.7	15.2	8.6
	25th percentile	11.4	4.3	5.5	3.7
	Median	32.4	8.7	15.1	7.7
	75th percentile	49.5	14.3	21.4	10.9
Canyon Lake	Average	30.3	13.3	15.5	9.8
	25th percentile	16.0	4.4	6.6	3.5
	Median	29.8	10.9	12.7	6.7
	75th percentile	44.5	17.5	23.4	13.7
Granger Lake	Average	31.3	13.7	13.9	11.3
	25th percentile	13.9	4.5	4.9	4.0
	Median	30.1	10.0	10.7	7.4
	75th percentile	46.8	16.3	20.1	16.8
Hords Creek Lake	Average	41.2	12.4	10.8	7.4
	25th percentile	23.9	4.3	4.1	3.5
	Median	41.8	8.6	8.4	6.1
	75th percentile	58.3	15.6	15.7	11.4
Sam Rayburn Lake	Average	22.0	8.7	17.7	17.6
	25th percentile	8.7	3.6	6.5	7.7
	Median	21.4	7.1	13.6	15.2
	75th percentile	32.0	11.4	24.7	24.7

[1]The complete list of monthly percentage errors for each method are available in appendix tables 5.1–5.5. Summary statistics of percentage error are calculated from the absolute value of the difference between the method estimate and the reservoir evaporation from pan data divided by the reservoir evaporation from pan data and multiplied by 100. Reporting the absolute value of the errors reduces the cancelling effects of positive and negative numbers.

The tendency of the unmodified Hamon method to underestimate monthly reservoir evaporation is also evident in the comparisons of annual amounts of evaporation in table 6. The unmodified Hamon method monthly estimates were summed annually to compare with annual reservoir evaporation from pan data. The unmodified Hamon method underestimates the annual amount of reservoir evaporation from pan data for every year at all five reservoirs and average errors range from about 12.9 percent at Sam Rayburn Lake to about 38.1 percent at Hords Creek Lake.

Estimates of monthly reservoir evaporation calculated using the unmodified USWB method were more similar to pan evaporation data than those calculated using the unmodified Hamon method. Average errors for all five reservoirs were less than 18 percent, median errors for all five reservoirs were less than 16 percent, and the 75th percentile values of the percentage errors were less than 25 percent for all five reservoirs. The same tendency to underestimate the amount of reservoir evaporation, particularly during the colder months of the year, was also true for the unmodified USWB method but not as consistent.

The unmodified USWB method monthly estimates were summed annually to compare with annual reservoir evaporation from pan data. Average percentage errors on an annual basis ranged from 4.7 percent at Hords Creek Lake to 14.1 percent at Sam Rayburn Lake. The unmodified USWB method estimated annual reservoir evaporation from pan data the best at Benbrook Lake, Granger Lake, and Hords

Table 6. Percentage error between unmodified and modified Hamon and modified U.S. Weather Bureau method estimates of annual reservoir evaporation with annual reservoir evaporation from the sum of published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for five Texas reservoirs, 2001–10.

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available; bold values indicate precentage errors less than or equal to 20 percent]

Reservoir	Year	Number of months[1]	Annual reservoir evaporation (A) (inches)	Unmodified Hamon (B) (inches)	Unmodified Hamon percentage error[2] ([B-A]/A) *100)	Modified Hamon (C) (inches)	Modified Hamon percentage error[2] ([C-A]/A) *100)	Unmodified USWB (D) (inches)	Unmodified USWB percentage error[2] ([D-A]/A) *100)	Modified USWB (E) (inches)	Modified USWB percentage error[2] ([E-A]/A) *100)
Benbrook Lake	2004	12	49.02	39.22	**-20.0**	53.46	**9.0**	45.15	**-7.9**	45.42	**-7.3**
	2005	11	55.38	40.20	-27.4	52.97	**-4.4**	50.60	**-8.6**	51.46	**-7.1**
	2006	11	60.19	42.16	-30.0	55.31	**-8.1**	59.56	**-1.0**	59.33	**-1.4**
	2007	11	44.96	37.92	**-15.7**	50.68	**12.7**	42.04	**-6.5**	42.87	**-4.6**
	2008	12	57.91	40.60	-29.9	54.49	**-5.9**	57.89	**-0.0**	58.53	**1.1**
	2009	10	47.19	38.39	**-18.7**	48.79	**3.4**	51.29	**8.7**	50.20	**6.4**
	2010	8	42.38	35.87	**-15.4**	42.79	**1.0**	48.12	**13.5**	46.48	**9.7**
	Average error[3]	--	--	--	22.4	--	6.4	--	6.6	--	5.4
Canyon Lake	2004	11	44.09	37.33	**-15.3**	50.50	**14.6**	35.48	**-19.5**	39.88	**-9.5**
	2005	12	53.91	40.62	-24.7	55.72	**3.4**	44.89	**-16.7**	50.75	**-5.9**
	2006	12	61.60	41.51	-32.6	57.10	**-7.3**	52.80	**-14.3**	59.54	**-3.4**
	2007	11	42.43	36.78	**-13.3**	50.02	**17.9**	36.91	**-13.0**	41.93	**-1.2**
	2008	12	59.44	40.28	-32.2	55.22	**-7.1**	54.23	**-8.8**	61.36	**3.2**
	2009	10	51.69	34.82	-32.6	46.86	**-9.3**	50.16	**-3.0**	55.62	**7.6**
	2010	10	50.85	37.49	-26.3	49.77	**-2.1**	44.20	**-13.1**	50.26	**-1.2**
	Average error[3]	--	--	--	25.3	--	8.8	--	12.6	--	4.6
Granger Lake	2004	9	38.49	33.89	**-11.9**	43.67	**13.5**	37.03	**-3.8**	35.68	**-7.3**
	2005	11	54.00	39.60	-26.7	53.05	**-1.8**	47.21	**-12.6**	46.40	**-14.1**
	2006	12	62.21	41.96	-32.6	57.73	**-7.2**	60.69	**-2.4**	59.96	**-3.6**
	2007	11	45.43	38.03	**-16.3**	51.44	**13.2**	47.01	**3.5**	46.48	**2.3**
	2008	12	61.08	40.82	-33.2	55.71	**-8.8**	60.27	**-1.3**	59.72	**-2.2**
	2009	10	42.61	28.52	-33.1	41.65	**-2.3**	39.82	**-6.6**	40.30	**-5.4**
	2010	11	51.87	40.12	-22.6	53.05	**2.3**	63.82	23.0	62.58	20.7
	Average error[3]	--	--	--	25.2	--	7.0	--	7.6	--	7.9
Hords Creek Lake	2003	8	49.86	34.66	-30.5	52.54	**5.4**	--	--	--	--
	2004	9	47.12	34.81	-26.1	54.85	**16.4**	--	--	--	--
	2005	10	54.72	36.88	-32.6	59.47	**8.7**	54.58	**-0.3**	57.05	**4.3**
	2006	10	70.16	39.92	-43.1	65.44	**-6.7**	63.42	**-9.6**	66.63	**-5.0**
	2007	12	60.08	37.31	-37.9	65.05	**8.3**	56.36	**-6.2**	59.71	**-0.6**
	2008	11	70.46	34.86	-50.5	61.80	**-12.3**	67.56	**-4.1**	71.34	**1.2**
	2009	9	55.03	29.40	-46.6	51.68	**-6.1**	54.97	**-0.1**	57.59	**4.6**
	2010	9	59.26	36.87	-37.8	57.46	**-3.0**	54.52	**-8.0**	57.06	**-3.7**
	Average error[3]	--	--	--	38.1	--	8.4	--	4.7	--	3.2
Sam Rayburn Lake	2001	12	43.02	39.20	**-8.9**	45.39	**5.5**	--	--	--	--
	2002	12	46.05	39.48	**-14.3**	45.73	**-0.7**	--	--	--	--
	2003	11	44.93	37.69	**-16.1**	43.02	**-4.3**	32.74	-27.1	33.80	-24.8
	2004	12	48.91	39.20	**-19.9**	45.65	**-6.7**	32.25	-34.1	33.41	-31.7
	2005	12	48.70	40.42	**-17.0**	46.78	**-3.9**	41.74	**-14.3**	43.45	**-10.8**
	2006	12	46.47	40.01	**-13.9**	46.63	**0.4**	45.96	**-1.1**	47.69	**2.6**
	2007	12	43.13	39.78	**-7.8**	46.30	**7.3**	41.69	**-3.3**	43.30	**0.4**
	2008	12	46.25	39.84	**-13.9**	46.17	**-0.2**	51.30	**10.9**	53.07	**14.7**
	2009	11	43.08	38.89	**-9.7**	44.28	**2.8**	47.30	**9.8**	48.49	**12.6**
	2010	8	36.90	34.08	**-7.6**	36.79	**-0.3**	41.46	**12.4**	42.14	**14.2**
	Average error[3]	--	--	--	12.9	--	3.2	--	14.1	--	14.0

[1]The number of months for which complete pan data were available and comparisons could be made.

[2]Because percentage errors for each year reported in the table are calculated by subtracting the annual reservoir evaporation from pan data from the method estimate, negative percentage errors mean the method underestimates evaporation and positive numbers mean the method overestimates evaporation.

[3]Average of yearly errors reported in the table are the sums of the absolute values of the yearly errors divided by the number of years.

Creek Lake. Most of the annual percentage errors at these three reservoirs were less than 10 percent. For Canyon Lake and Sam Rayburn Lake, most of the annual percentage errors were within 15 percent. For all of the reservoirs and all of the years compared, the unmodified USWB method estimates of annual reservoir evaporation from pan data were within 20 percent for 32 of the combined 35 years compared (about 91 percent), within 15 percent for 30 of the 35 years (about 86 percent), and within 10 percent for 22 of the 35 years (about 63 percent). During 3 years (2 years at Sam Rayburn Lake and 1 year at Granger Lake) the percentage errors were greater than 20 percent.

Modified Hamon and U.S. Weather Bureau Method Estimates to Predict Monthly and Annual Evaporation

The Hamon and USWB methods were modified with the goal of reducing bias and "tuning" each method to estimate reservoir evaporation from pan data for the five reservoirs. To do this, the unmodified monthly totals from the two methods were the independent variables, and the published monthly pan data were the dependent variables in regression analyses. Regression of published monthly pan data and unmodified monthly Hamon and USWB method totals was performed, and intercepts were forced through zero. Forcing the intercepts through zero produces monthly coefficients (termed HM_c and $USWB_c$ in appendix 2 for Hamon and USWB method monthly coefficients) that minimize bias between published monthly pan data and method estimates such that a single coefficient can be used to adjust method estimates. Therefore, the methods were modified to predict the pan data that could ultimately be used to estimate reservoir evaporation with the application of the TWDB monthly pan coefficients. The decision was made to model the pan data so that if any future modifications were made to monthly pan coefficients, the modified methods and derived coefficients would not be affected. The monthly coefficients for both methods are summarized in appendix table 2.1. All p-values were less than 0.05 except for the December USWB coefficient for Hords Creek Lake, which had a p-value less than 0.10.

The unmodified and modified monthly estimates of evaporation were plotted against published monthly pan data in figures 4–5. If the modified methods were perfect predictors of the published pan data, then the modified values would plot on an equal value line and the regression line would have slope and y-intercepts equal to one and zero, respectively. As evidenced in figures 4–5, the modified Hamon and USWB method regression lines have slopes nearer to one and intercepts nearer to zero than their unmodified counterparts, except for the modified USWB method regression equation for Sam Rayburn Lake. It is also worth noting that the monthly coefficients (HM_c and $USWB_c$ in appendix table 2.1) effectively shift the unmodified regression lines from left to right (close to the equal value lines) in figures 4–5 because bias is minimized.

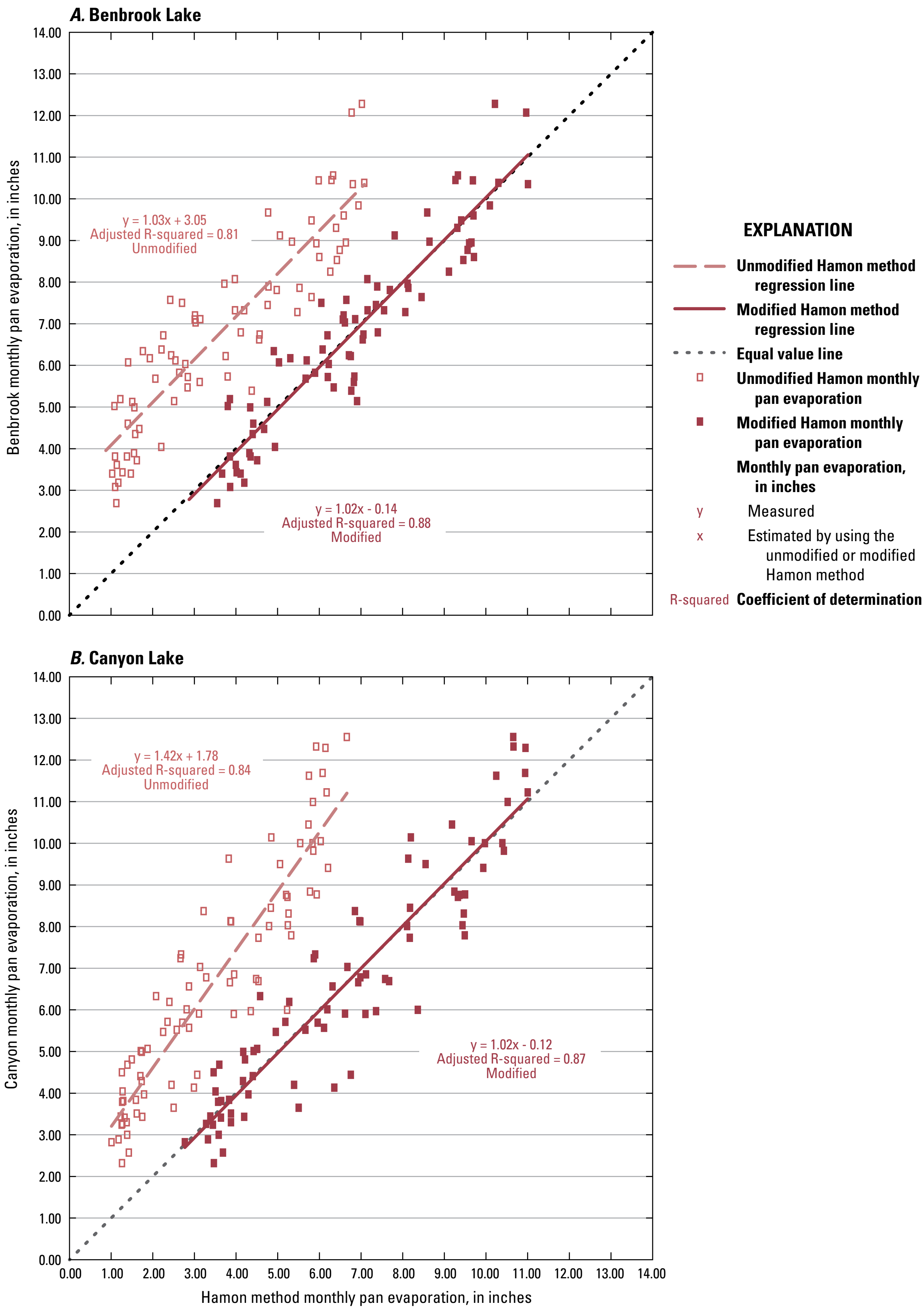


Figure 4. Unmodified and modified Hamon method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.

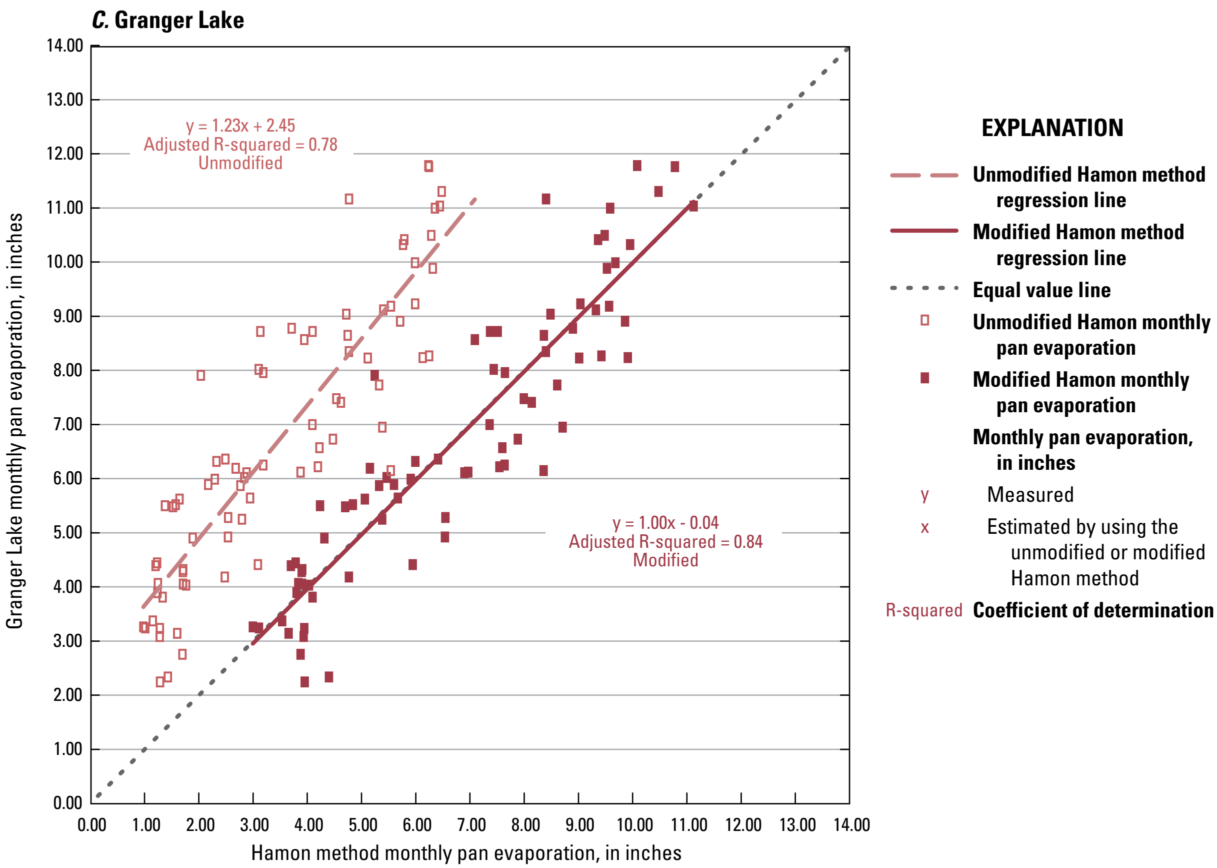


Figure 4. Unmodified and modified Hamon method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

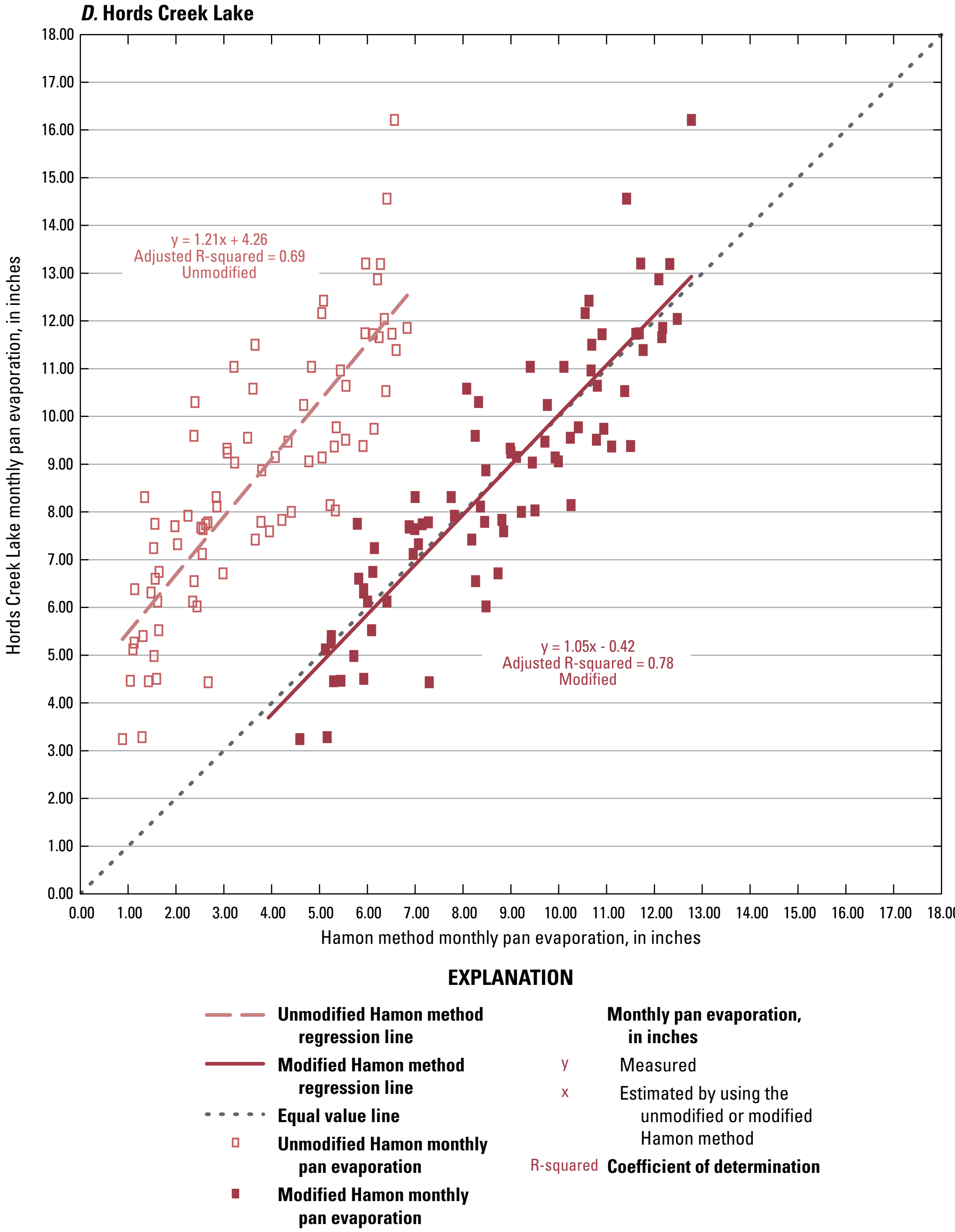


Figure 4. Unmodified and modified Hamon method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

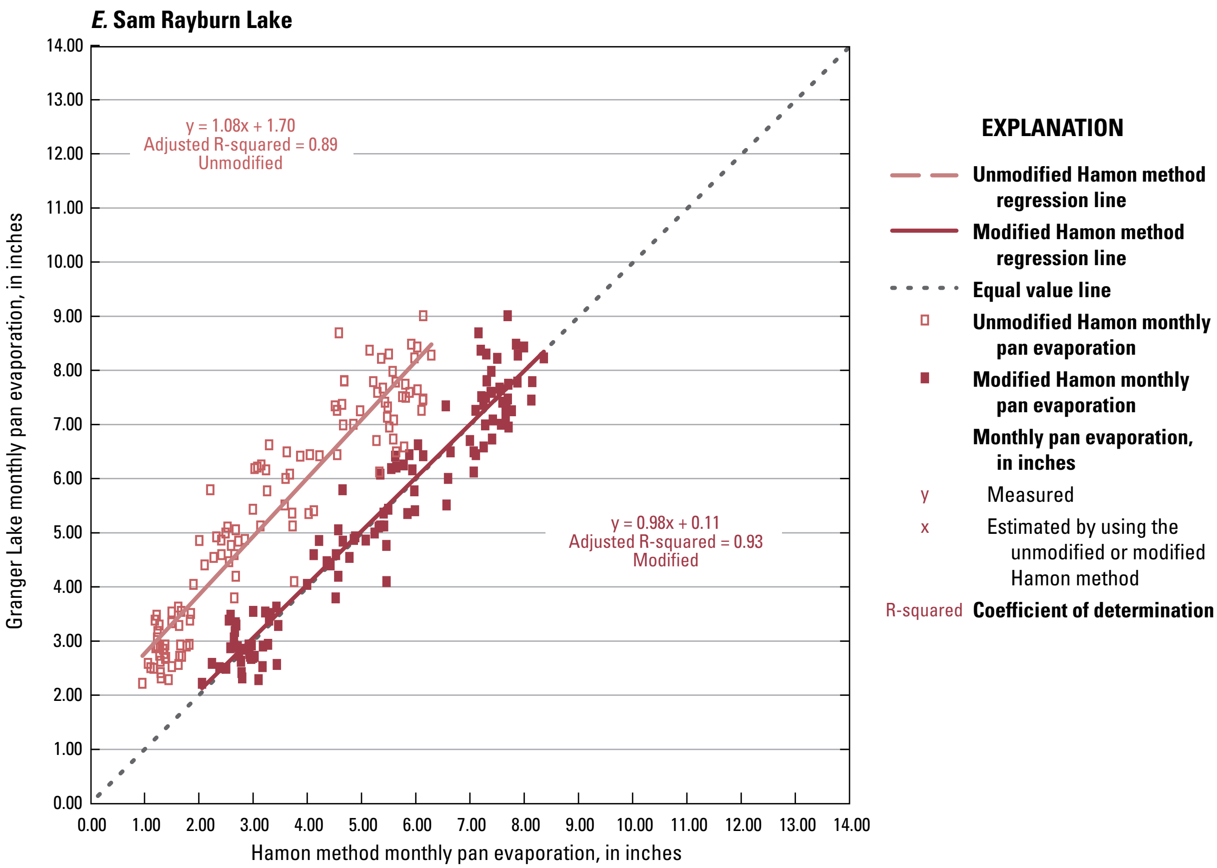


Figure 4. Unmodified and modified Hamon method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

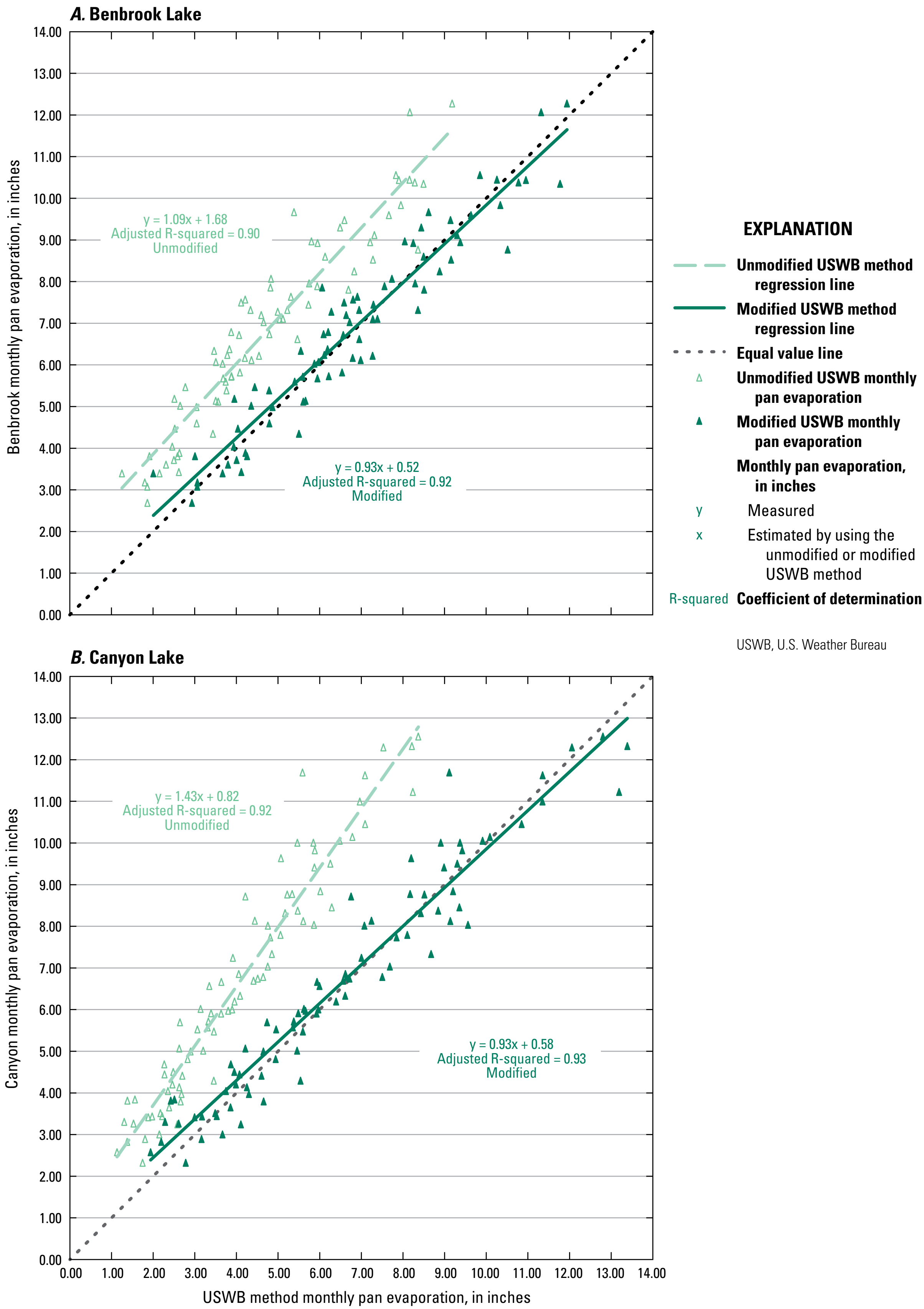


Figure 5. Unmodified and modified U.S. Weather Bureau method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.

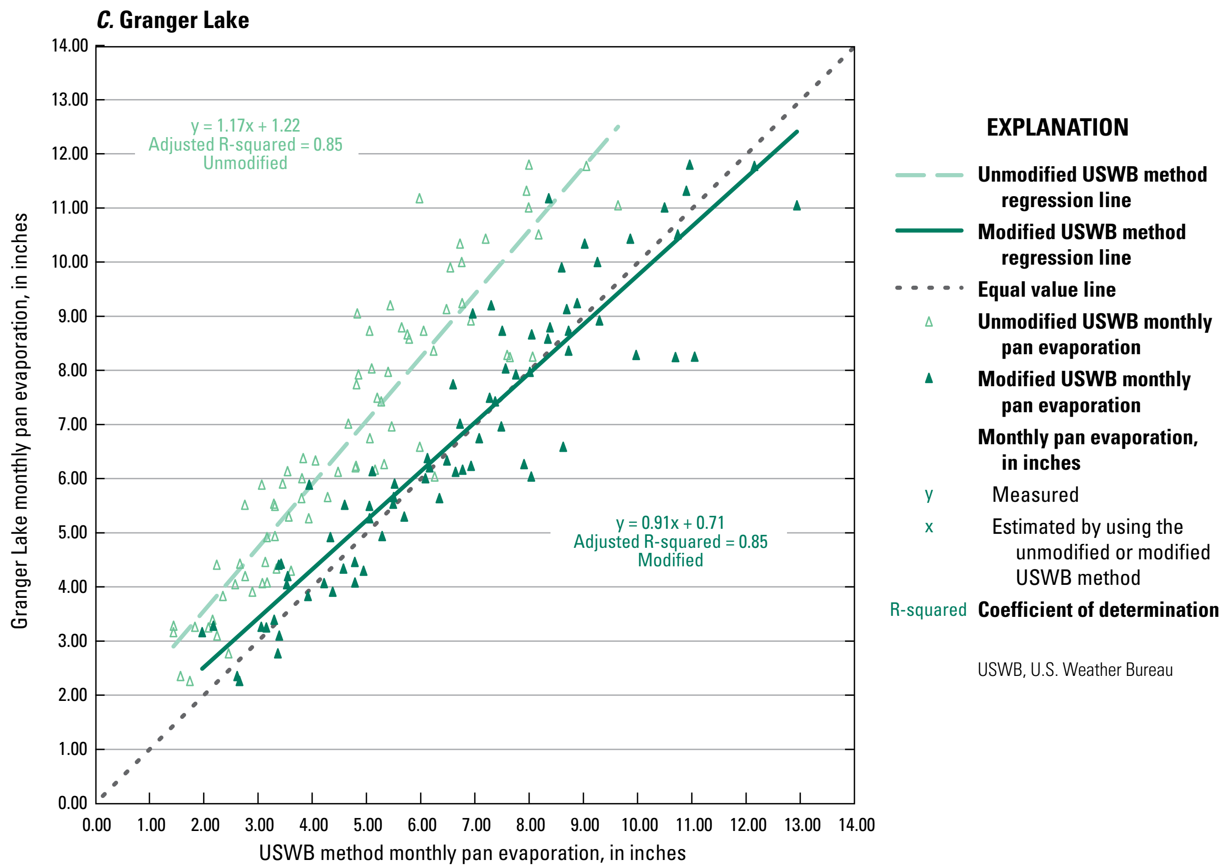


Figure 5. Unmodified and modified U.S. Weather Bureau method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

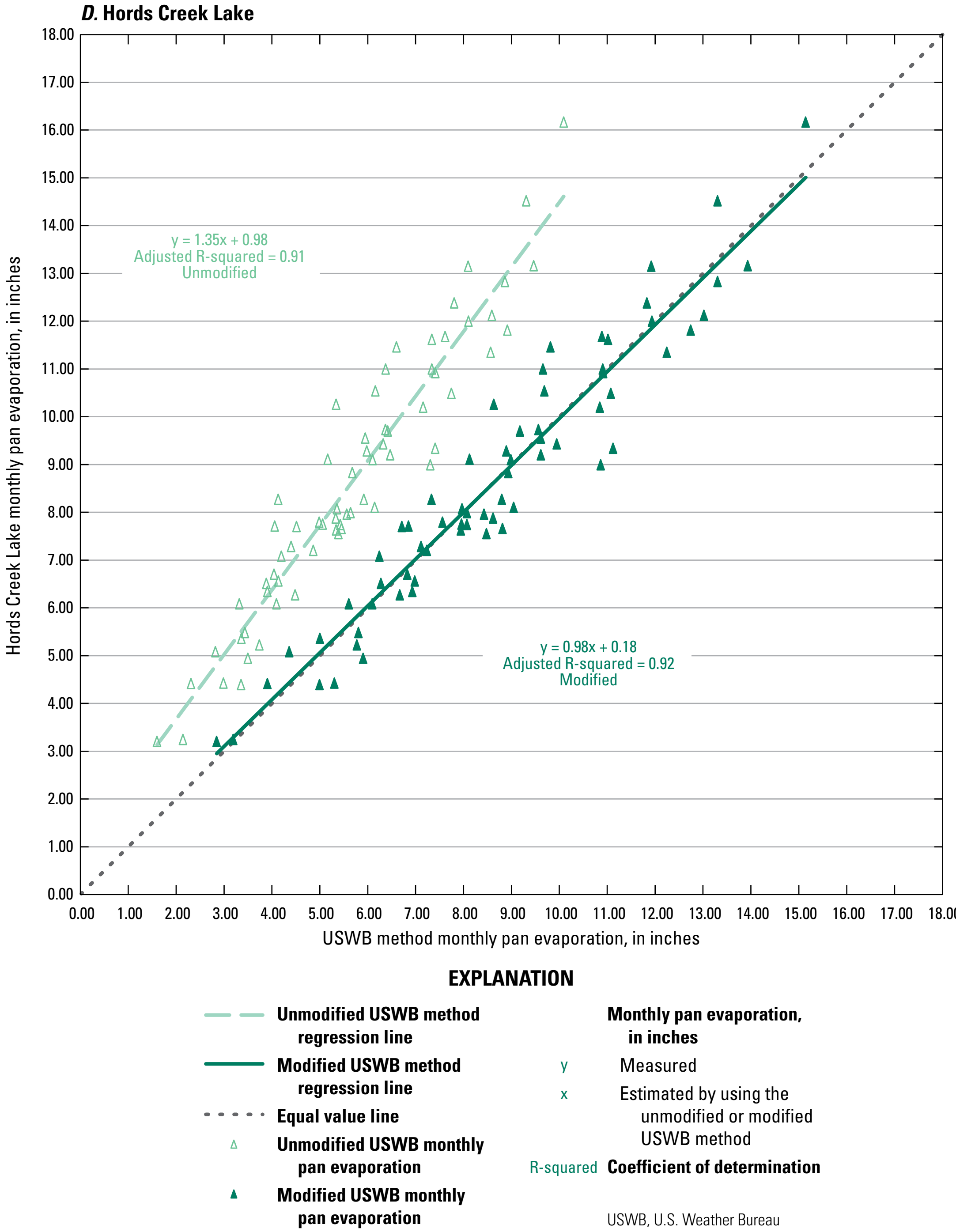


Figure 5. Unmodified and modified U.S. Weather Bureau method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

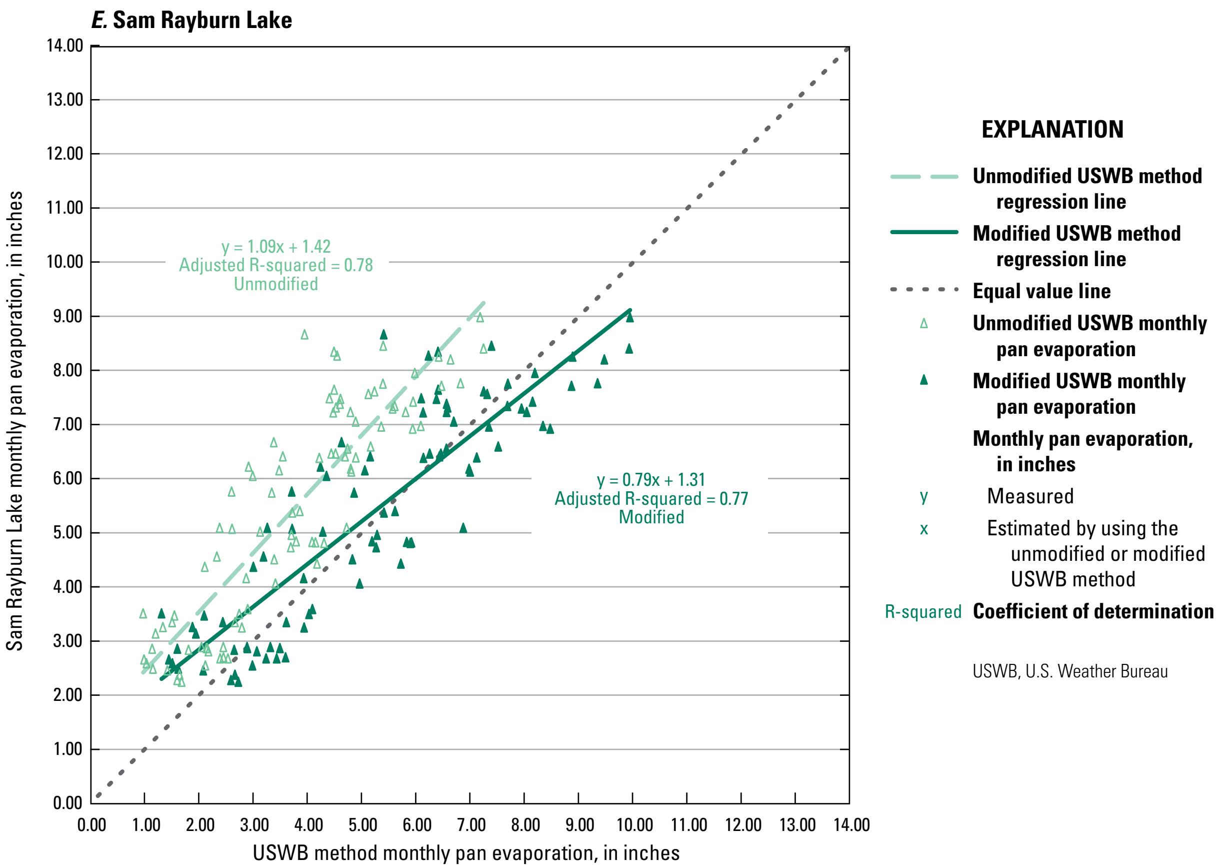


Figure 5. Unmodified and modified U.S. Weather Bureau method estimates of evaporation and regression lines with pan evaporation data at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

The modified Hamon and USWB method estimates of monthly reservoir evaporation and monthly reservoir evaporation from pan data are plotted for the five reservoirs in figure 6 and summarized in table 5 with the unmodified estimates already discussed.

Compared to the unmodified Hamon method estimates of monthly reservoir evaporation, modified Hamon method estimates were generally more similar to monthly reservoir evaporation from pan data (fig. 6). This was the case for all of the reservoirs and further evidenced in the summary statistics of percentage error (table 5). For all five reservoirs the average errors for monthly estimates of evaporation determined from the modified Hamon method were less than 14 percent and the 75th percentile values of the percentage errors were less than 18 percent.

The modified Hamon method estimates of annual reservoir evaporation were also much better than the unmodified Hamon counterparts, with average errors on an annual basis ranging from 3.2 percent at Sam Rayburn Lake to 8.8 percent at Canyon Lake for the modified Hamon method compared to average errors ranging from 12.9 percent at Sam Rayburn Lake to 38.1 percent at Hords Creek Lake for the unmodified Hamon method. The modified Hamon method estimates of annual reservoir evaporation were within plus or minus 20 percent of annual reservoir evaporation from pan data for 39 of the combined 39 years compared (100 percent), within plus or minus 15 percent for 37 of the 39 years (about 95 percent), and within plus or minus 10 percent for 32 of the 39 years (about 82 percent) (table 6).

Compared to the unmodified USWB method estimates of monthly reservoir evaporation, modified USWB method estimates were generally more similar to monthly reservoir evaporation from pan data, except for Sam Rayburn Lake, where modified USWB method estimates were essentially the same as the unmodified USWB counterparts (fig. 6; table 5). The modified USWB method estimates at Sam Rayburn Lake were influenced by the changing bias from 2003–10 between unmodified USWB method estimates and pan evaporation (fig. 3E). The changing bias from 2003–10 was likely attributable to uncertainties in the solar radiation data that affected the USWB method estimates. For example, an incorrect solar radiation sensor calibration coefficient during one period and a correct calibration coefficient during another period would cause a change in the bias because the USWB method is strongly influenced by the average solar radiation data. For the other four reservoirs, the average errors for monthly estimates of evaporation determined from the modified USWB method were less than 12 percent and 75th percentile values of the percentage errors were less than 17 percent. Average errors for monthly estimates of evaporation determined from the unmodified USWB method at the same four reservoirs were less than 16 percent and 75th percentile values of the percentage errors were less than 24 percent.

For all of the reservoirs and all of the years compared, the modified USWB method estimates of annual reservoir evaporation were within plus or minus 20 percent of monthly reservoir evaporation from pan data for 32 of the combined 35 years compared (about 91 percent) (table 6). These are the same results obtained from the unmodified USWB method, indicating that although modifications to the USWB method with the coefficients improve the estimates of evaporation when compared to monthly reservoir evaporation from pan data, the annual estimates of evaporation are not always appreciably improved because monthly bias is not consistent from year to year. The only exception to this was at Canyon Lake, where the average annual percentage error from the unmodified USWB was 12.6 percent and improved to 4.6 percent with the modified USWB. However, all 7 years at Canyon Lake had annual percentage errors for the unmodified USWB method less than 20 percent and 5 out of the 7 years were less than 15 percent.

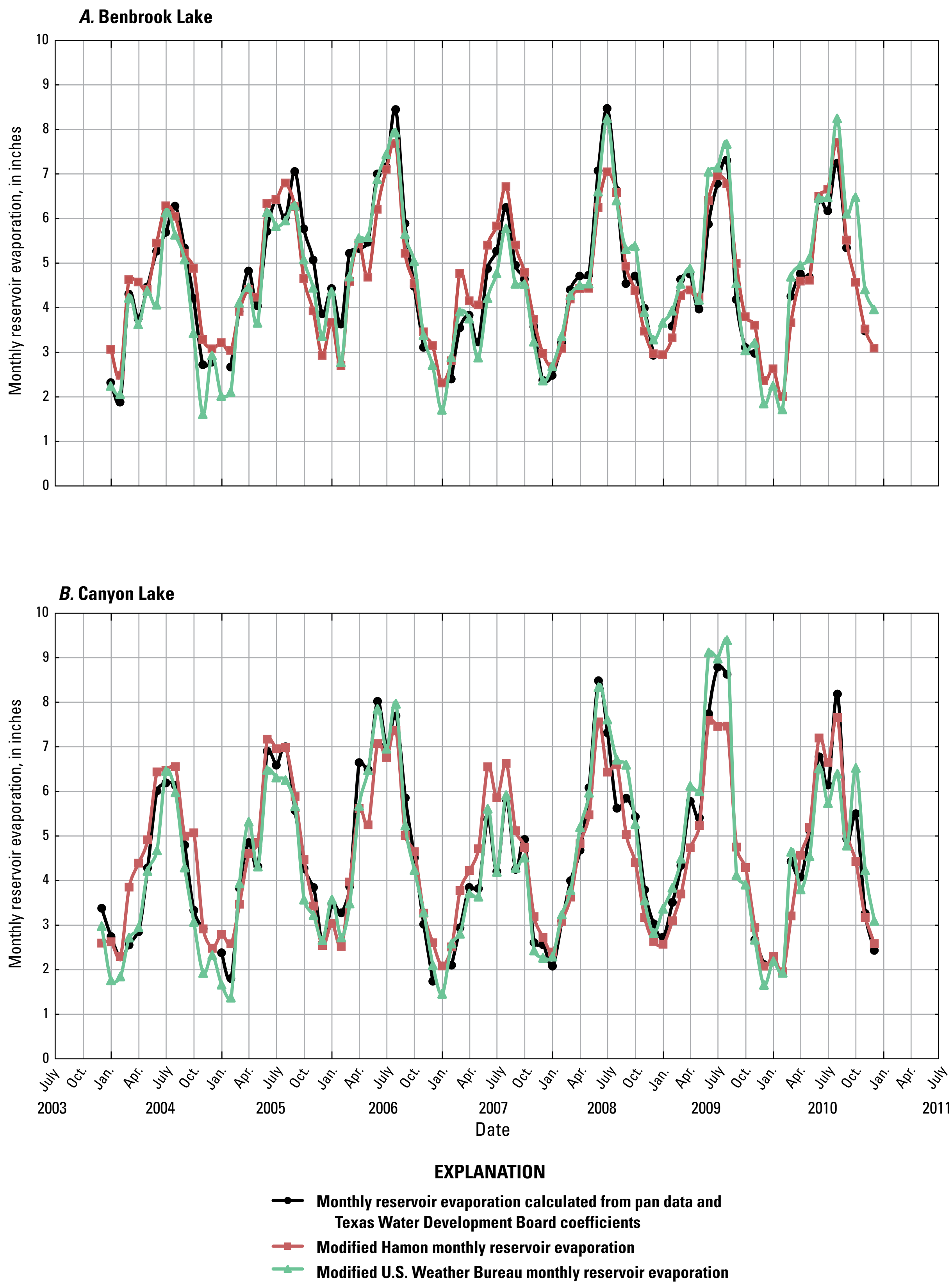


Figure 6. Comparison of monthly pan evaporation with modified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.

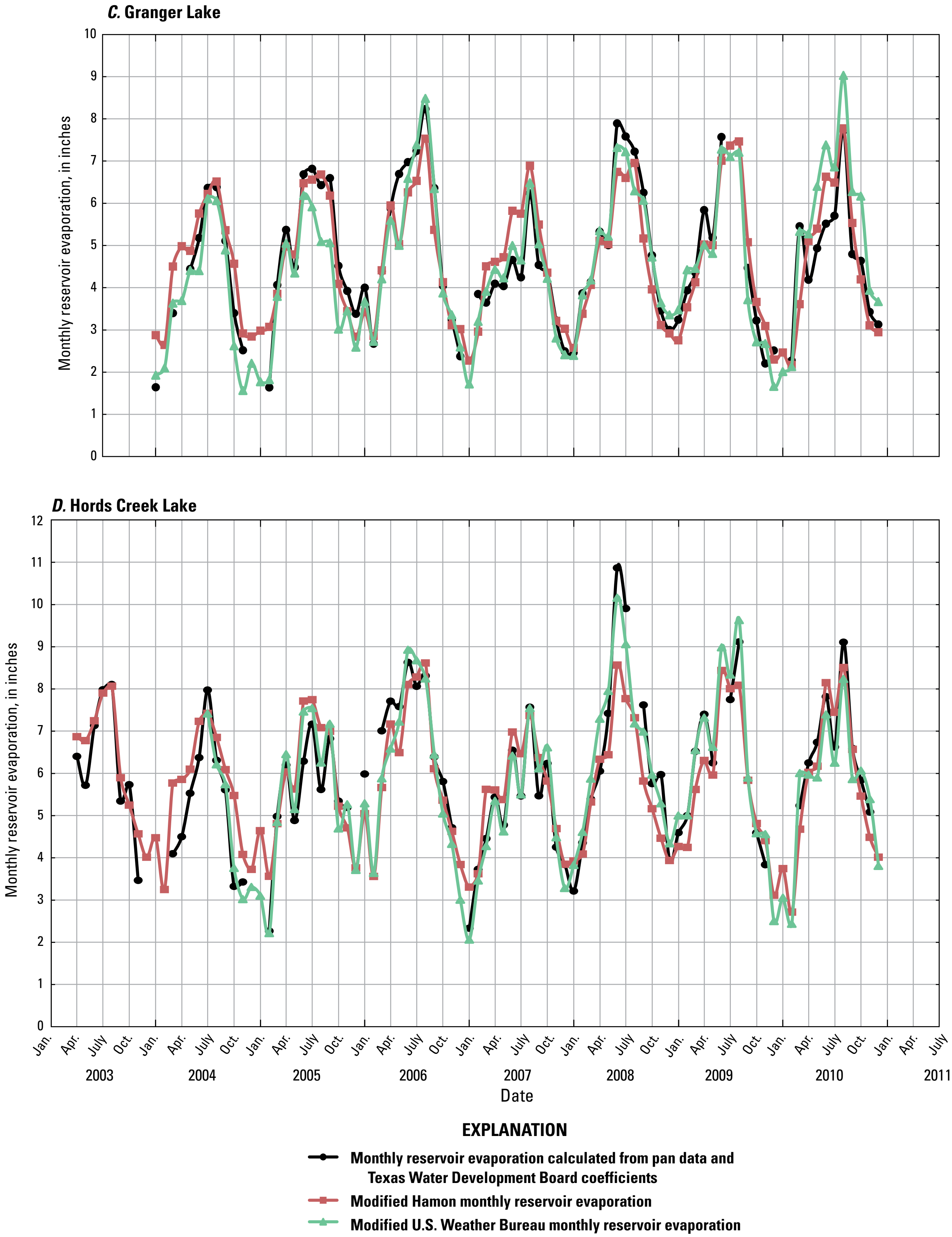


Figure 6. Comparison of monthly pan evaporation with modified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.—Continued

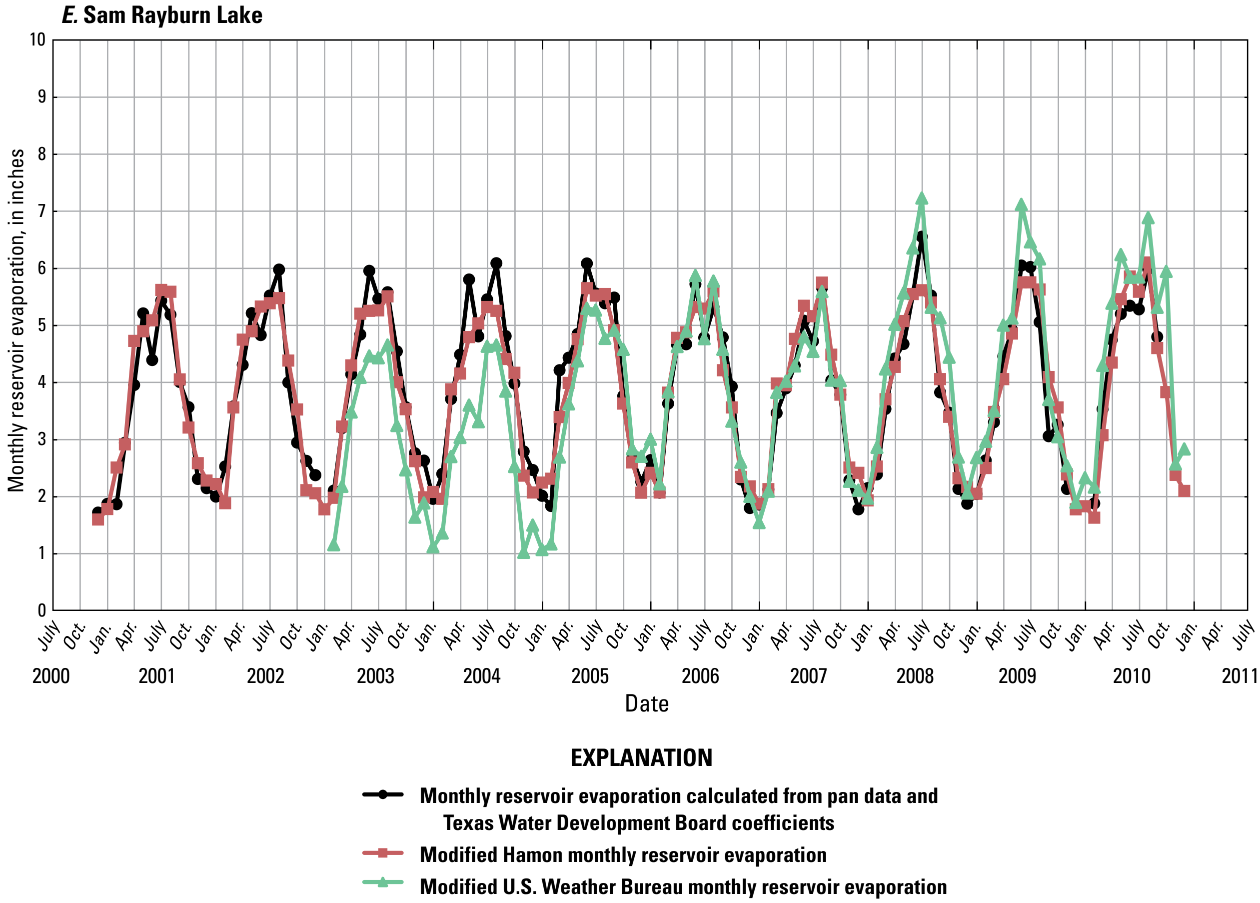
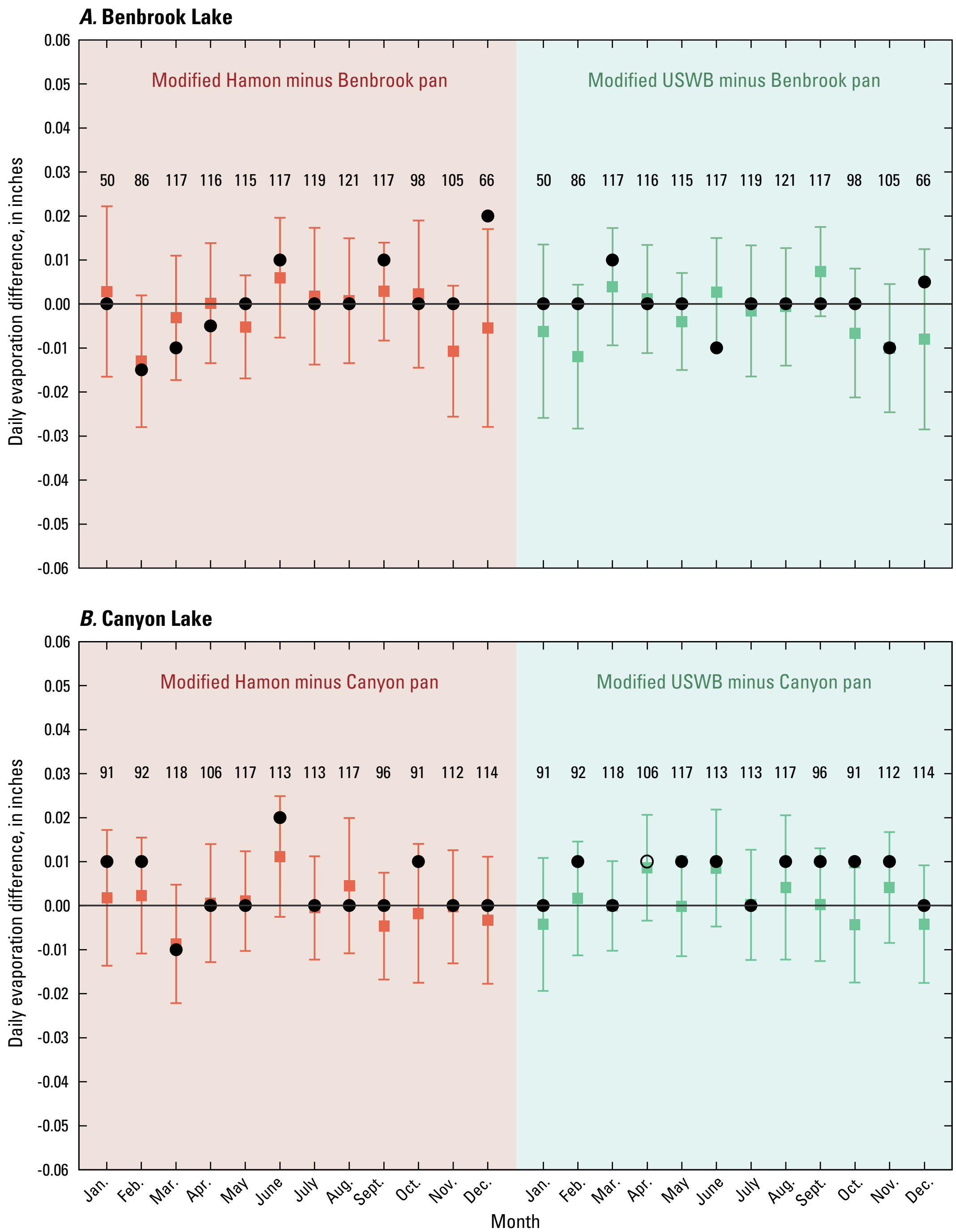


Figure 6. Comparison of monthly pan evaporation with modified Hamon and U.S. Weather Bureau method estimates at *A*, Benbrook Lake, Texas, from January 2004 to December 2010, *B*, Canyon Lake, Tex., from December 2003 to December 2010, *C*, Granger Lake, Tex., from January 2004 to December 2010, *D*, Hords Creek Lake, Tex., from April 2003 to December 2010, and *E*, Sam Rayburn Lake, Tex., from December 2000 to December 2010.—Continued

Comparison of Hamon and U.S. Weather Bureau Method Estimates of Daily Evaporation

The daily pan data were evaluated to account for multiday totals before making comparisons with the Hamon and USWB method daily estimates. Pan data are not always collected on a daily basis by USACE staff, particularly during weekends when staff may not be available. Therefore, the pan data collected on Monday morning may represent the amount of evaporation from the pan over a 3-day period including Friday, Saturday, and Sunday. Daily pan data reported on Monday morning were not used when making comparisons to eliminate the comparison of daily method estimates with multiday pan estimates. Other multiday totals (when identified) were also removed before making comparisons. Because daily pan data are collected at 8:00 a.m., the value is more representative of the amount of evaporation from the pan on the day before the data were collected. Therefore, data-collection times associated with pan data were adjusted back by 1 day so that the same daily values would be compared.

Differences between the modified Hamon and USWB method estimates of daily reservoir evaporation and daily estimates of reservoir evaporation from pan data were calculated by subtracting the daily estimate of reservoir evaporation from pan data from the modified Hamon and USWB method estimate of daily reservoir evaporation, and these differences were aggregated on a monthly basis. Mean and median daily differences and the 95-percent confidence intervals about the mean for each month are included in figure 7. If the mean difference is above the zero line then, on average, the respective method overestimates daily pan estimates for a given month and if the mean is below the zero line, the method underestimates daily pan estimates for a given month. Not all of the data in the figure 7 are from normal distributions, as partly evidenced by the differences



EXPLANATION

117 **Number of values**

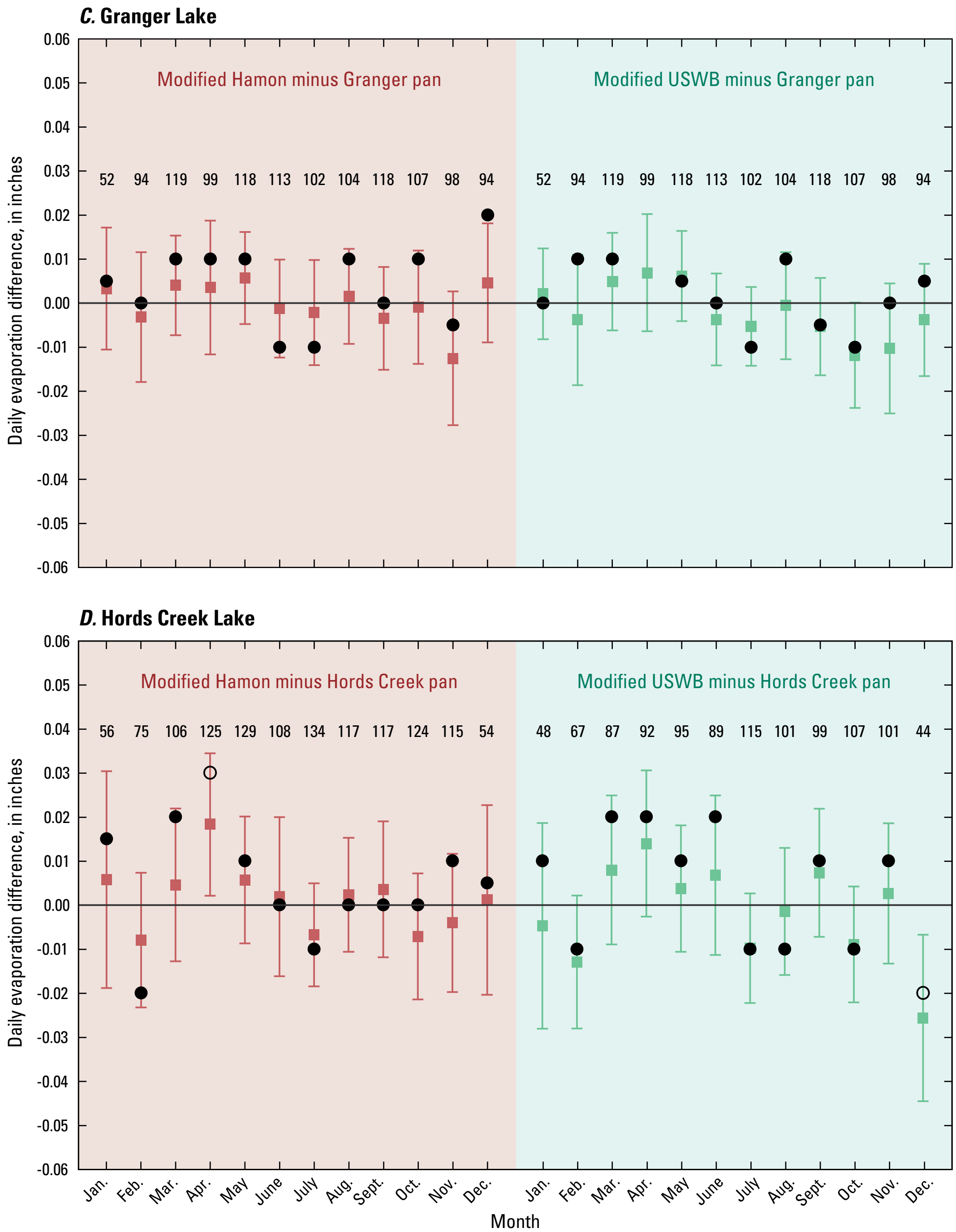
Mean difference between modified method estimate and estimate from daily pan data

95 percent confidence above the mean
Mean difference between modified Hamon method evaporation estimate and estimate from daily pan data
95 percent confidence below the mean

95 percent confidence above the mean
Mean difference between modified U.S. Weather Bureau (USWB) method evaporation estimate and estimate from daily pan data
95 percent confidence below the mean

Median difference between modified method estimate and estimate from daily pan data—Filled circle indicates the median difference is not statistically different from zero at the 95 percent confidence level

Figure 7. Daily mean and median differences for each month between modified Hamon and U.S. Weather Bureau method evaporation estimates and daily pan evaporation estimates from pan data collected at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.



EXPLANATION

117 **Number of values**

Mean difference between modified method estimate and estimate from daily pan data

95 percent confidence above the mean
Mean difference between modified Hamon method evaporation estimate and estimate from daily pan data
95 percent confidence below the mean

95 percent confidence above the mean
Mean difference between modified U.S. Weather Bureau (USWB) method evaporation estimate and estimate from daily pan data
95 percent confidence below the mean

Median difference between modified method estimate and estimate from daily pan data—Filled circle indicates the median difference is not statistically different from zero at the 95 percent confidence level

Figure 7. Daily mean and median differences for each month between modified Hamon and U.S. Weather Bureau method evaporation estimates and daily pan evaporation estimates from pan data collected at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

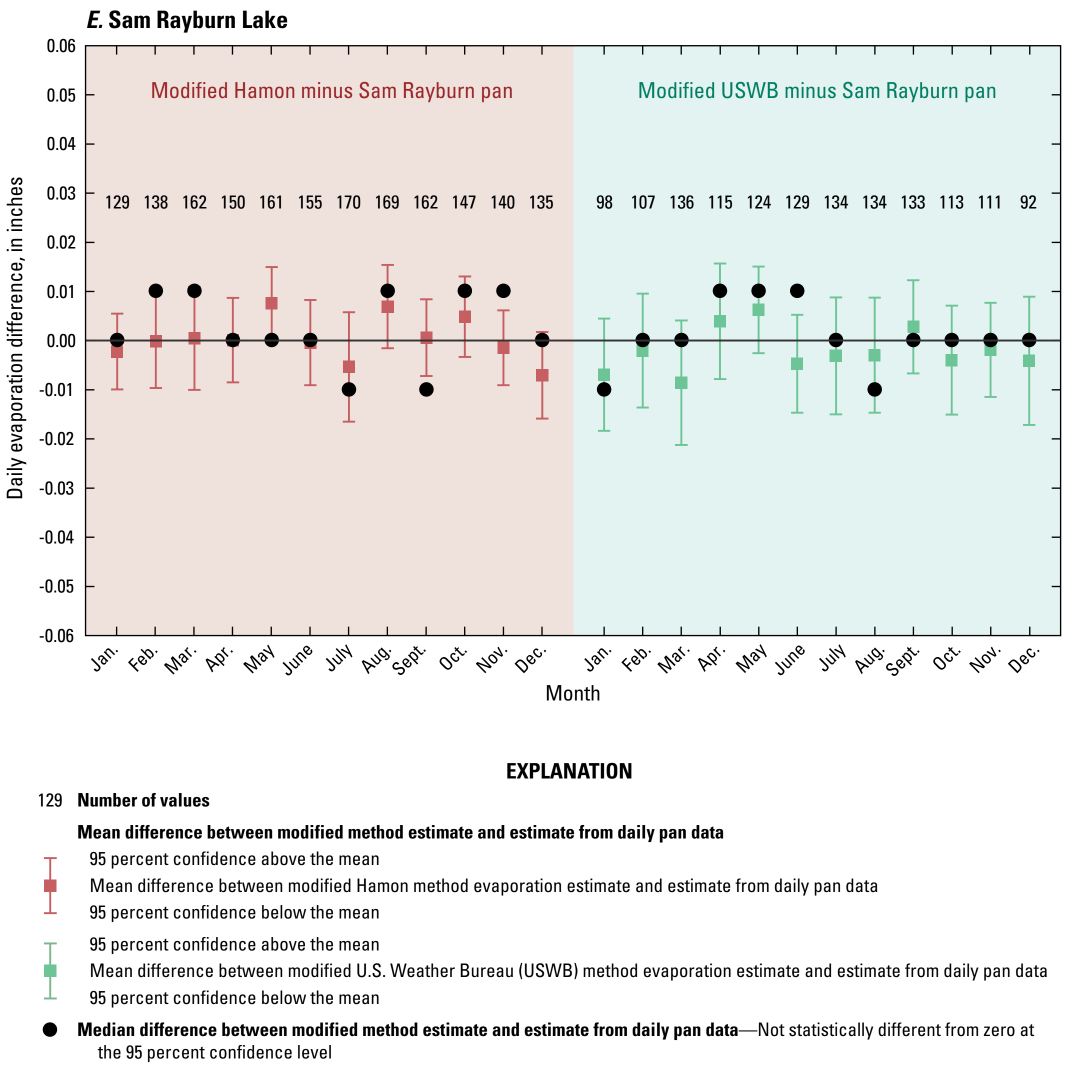


Figure 7. Daily mean and median differences for each month between modified Hamon and U.S. Weather Bureau method evaporation estimates and daily pan evaporation estimates from pan data collected at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

between the mean and the median differences for some of the months. The nonparametric Wilcoxon signed-rank test (Helsel and Hirsch, 2002) was used to determine whether the null hypothesis that the median differences between the paired observations for the aggregation of data from a given month were not significantly different from zero at the 95-percent confidence level (fig. 7; indicated by a filled circle). An unfilled circle (fig. 7) indicates the median difference is different from zero.

For Benbrook Lake and Sam Rayburn Lake, the median differences for all months between modified Hamon and USWB method daily estimates and daily pan estimates were not significantly different from zero. For Canyon Lake and Granger Lake, median differences between the paired observations were significantly different from zero for only 1 month (USWB method estimates during April). For Hords Creek Lake, median differences between the paired observations were significantly different from zero for 2 months (Hamon method estimates during April and USWB method estimates during December).

The ability of the modified Hamon method, requiring only measurements of air temperature at remote weather stations, to estimate reservoir evaporation similarly to pan estimates of evaporation is probably because of a strong relation between air temperature and pan water temperature. The small volume of water in the pan responds to day-to-day fluctuations in air temperature and, therefore, a strong relation exists between average daily air temperature and the amount of evaporation from the pan.

The relative magnitude of the differences between the modified Hamon and USWB method daily estimates and daily pan estimates are presented in table 7. This table summarizes the differences as a percentage of the average daily reservoir evaporation from pan data and application of the TWDB coefficients by month for each reservoir. For example, the average amount of daily reservoir evaporation as estimated from pan data during January at Benbrook Lake is 0.07 in. This is calculated by multiplying the average January pan evaporation of 2.94 in. by 0.73 (TWDB pan coefficient for January) and dividing by the number of days in January (appendix 3.1). The average difference between the modified Hamon method daily estimate and the pan estimate for January at Benbrook Lake is 0.0028 in. (fig. 7A). Therefore, the average difference as a percentage of the average daily reservoir evaporation from pan data during January (4.0 percent) at Benbrook Lake is small (table 7).

For the modified Hamon method, the percentages in table 7 are within plus or minus 5 percent for 49 of the 60 months (12 months of data collected at each of the five Texas reservoirs), which is about 82 percent, within plus or minus 10 percent for 57 of the 60 months (95 percent) and within plus or minus 14 percent for all months at all of the reservoirs. For the modified USWB method, the percentages in table 7 are within plus or minus 5 percent for 45 of the 60 months (about 75 percent), within plus or minus 10 percent for 54 of the 60 months (90 percent), and within plus or minus 20 percent for all months at all reservoirs except December at Hords Creek Lake (about 98 percent), where the difference is 27.1 percent.

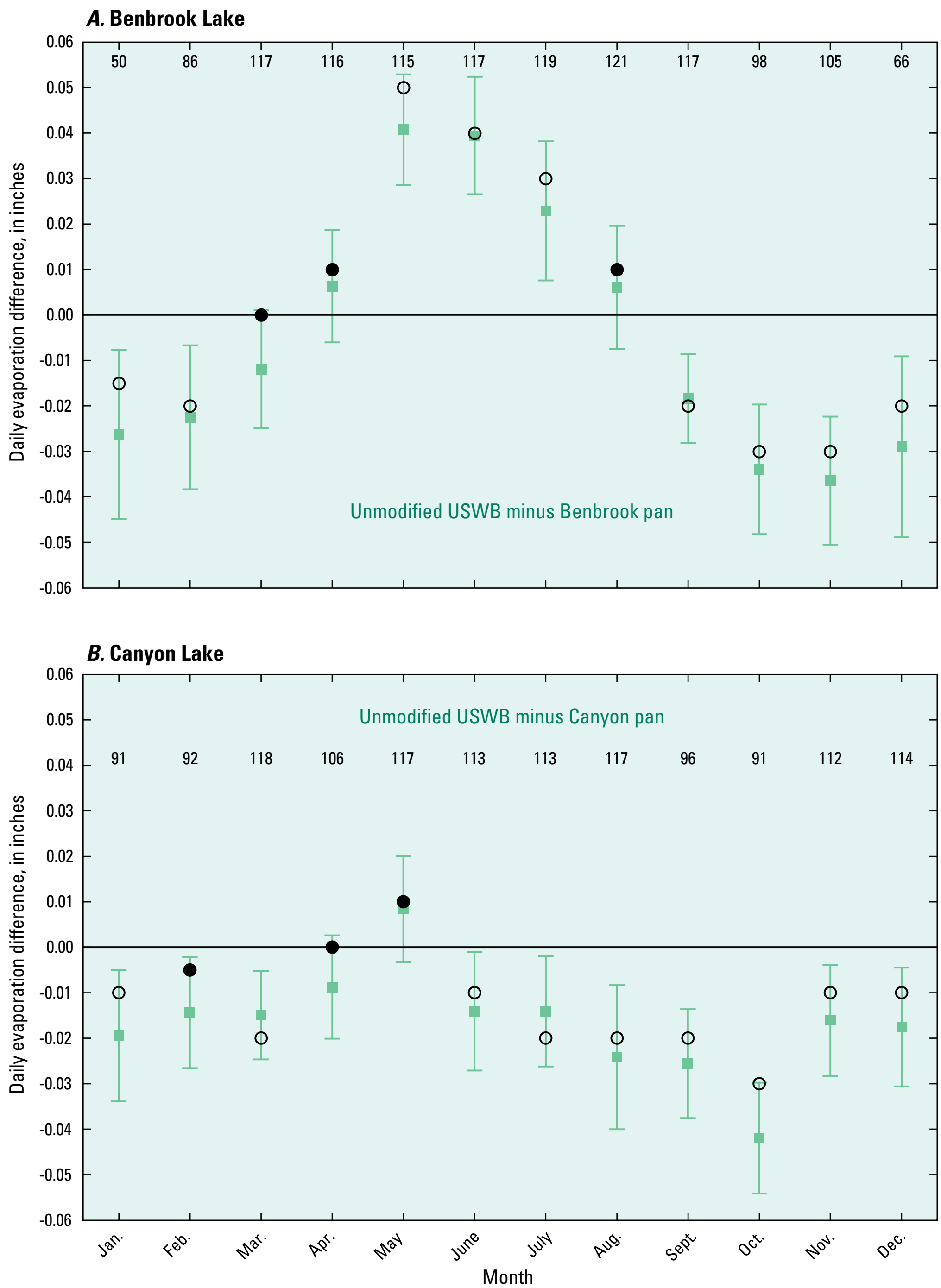
Seasonal bias was evident between the unmodified USWB daily evaporation estimates and the daily pan evaporation estimates at each of the five lakes in Texas (fig. 8). Positive seasonal bias, indicating a tendency to overestimate evaporation, was most prevalent during the warmer spring and summer months, and negative seasonal bias was most prevalent during the cooler fall and winter months. However, without any modification to the USWB method, the percentages in table 7 are within plus or minus 10 percent for 31 of the 60 months (about 52 percent) and within plus or minus 20 percent for 44 of the 60 months (about 73 percent). Therefore, the differences are greater than 20 percent for only 16 of the 60 months (about 27 percent).

The modified Hamon and modified USWB method daily estimates of reservoir evaporation typically were similar to daily pan evaporation estimates, as evidenced by almost all of the median differences not being significantly different from zero for all months at the five reservoirs. The differences that do exist between the estimates were small with respect to the percentage of average daily evaporation. The unmodified USWB method daily estimates frequently had median differences with daily pan evaporation estimates significantly different from zero, but the relative magnitudes of the differences as a percentage of average daily evaporation were small (less than 20 percent) most of the time.

Table 7. Summary of the differences between the modified daily Hamon and modified and unmodified U.S. Weather Bureau method estimates as a percentage of the average amount of daily evaporation by month for five reservoirs in Texas.

[USWB, U.S. Weather Bureau; D1, difference between the modified daily Hamon and daily pan as a percentage of the average amount of daily evaporation; D2, difference between the modified daily USWB and daily pan as a percentage of the average amount of daily evaporation; D3, difference between the unmodified daily USWB and daily pan as a percentage of the average amount of daily evaporation; bold values indicate a difference greater than 20 percent]

Month	Benbrook Lake			Canyon Lake			Granger Lake			Hords Creek Lake			Sam Rayburn Lake		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
January	4.0	-9.0	**-37.8**	2.4	-5.9	-26.7	4.1	2.6	-9.6	5.8	-4.9	-34.1	-3.6	-10.9	**-22.1**
February	-13.3	-12.3	**-23.0**	2.3	1.7	-14.7	-3.1	-3.7	-18.8	-6.6	-10.7	-14.5	-.3	-2.6	-5.5
March	-2.3	2.8	-8.6	-6.9	-0.1	-11.8	3.3	4.0	-6.5	2.7	4.7	-5.2	0.3	-7.6	-11.0
April	0.1	0.7	3.9	0.4	5.6	-5.7	2.3	4.5	4.9	8.7	6.6	7.2	0.0	2.7	-2.3
May	-3.2	-2.5	**25.1**	0.6	-0.1	5.2	3.8	4.0	**24.1**	2.8	1.8	10.1	4.9	4.0	13.0
June	2.6	1.2	17.4	5.2	3.9	-6.5	-0.6	-1.9	7.1	0.7	2.6	2.3	-0.3	-2.6	-1.5
July	0.7	-0.6	8.5	-0.2	0.1	-5.9	-1.0	-2.4	7.2	-2.4	-3.5	-1.1	-2.9	-1.7	-2.6
August	0.3	-0.3	2.4	2.0	1.8	-10.5	0.7	-0.3	6.1	0.9	-0.6	-2.1	3.7	-1.7	-5.6
September	1.4	3.6	-9.0	-2.6	0.1	-14.3	-1.9	-2.9	-7.9	1.6	3.4	-8.5	0.3	1.8	-6.1
October	1.4	-4.2	**-21.6**	-1.2	-3.0	**-29.0**	-0.7	-8.7	-7.9	-4.2	-5.3	-16.0	3.9	-3.3	-9.5
November	-9.7	-9.1	**-32.7**	-0.3	4.0	-15.7	-12.4	-10.2	-19.7	-3.2	2.0	**-28.1**	-1.8	-2.3	-8.0
December	-6.9	-10.1	**-36.4**	-4.4	-5.6	**-23.3**	5.7	-4.8	**-20.3**	1.2	**-27.1**	**-42.4**	-10.3	-6.1	**-26.8**



EXPLANATION

92 **Number of values**

Mean difference between unmodified method estimate and estimate from daily pan data

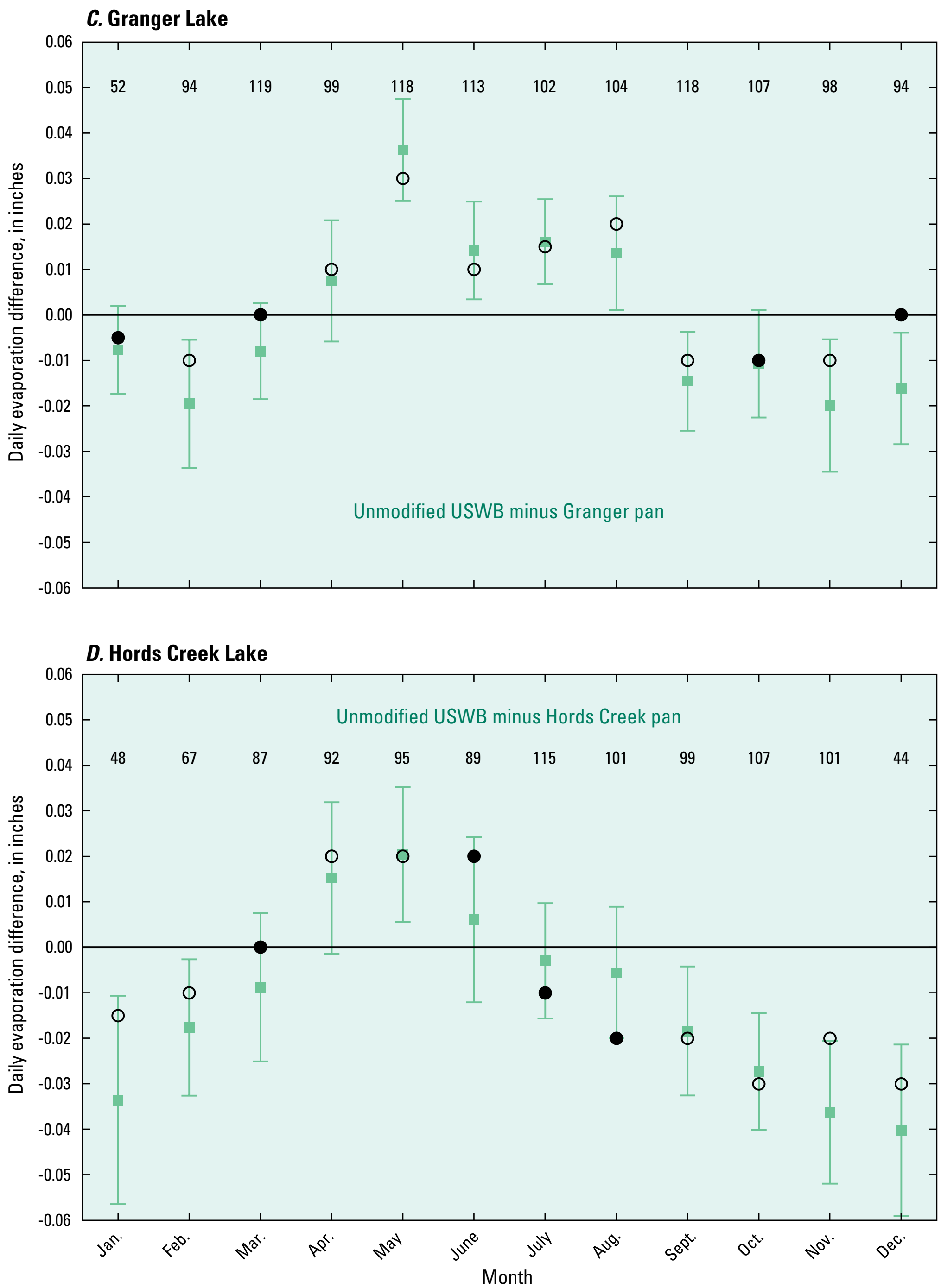
95 percent confidence above the mean

Mean difference between unmodified U.S. Weather Bureau (USWB) method evaporation estimate and estimate from daily pan data

95 percent confidence below the mean

○ **Median difference between unmodified method estimate and estimate from daily pan data**—Filled circle indicates the median difference is not statistically different from zero at the 95 percent confidence level

Figure 8. Daily mean and median differences for each month between unmodified U.S. Weather Bureau method evaporation estimates and daily pan evaporation estimates from pan data collected at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.



EXPLANATION

92 **Number of values**

Mean difference between unmodified method estimate and estimate from daily pan data

95 percent confidence above the mean

Mean difference between unmodified U.S. Weather Bureau (USWB) method evaporation estimate and estimate from daily pan data

95 percent confidence below the mean

○ **Median difference between unmodified method estimate and estimate from daily pan data**—Filled circle indicates the median difference is not statistically different from zero at the 95 percent confidence level

Figure 8. Daily mean and median differences for each month between unmodified U.S. Weather Bureau method evaporation estimates and daily pan evaporation estimates from pan data collected at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

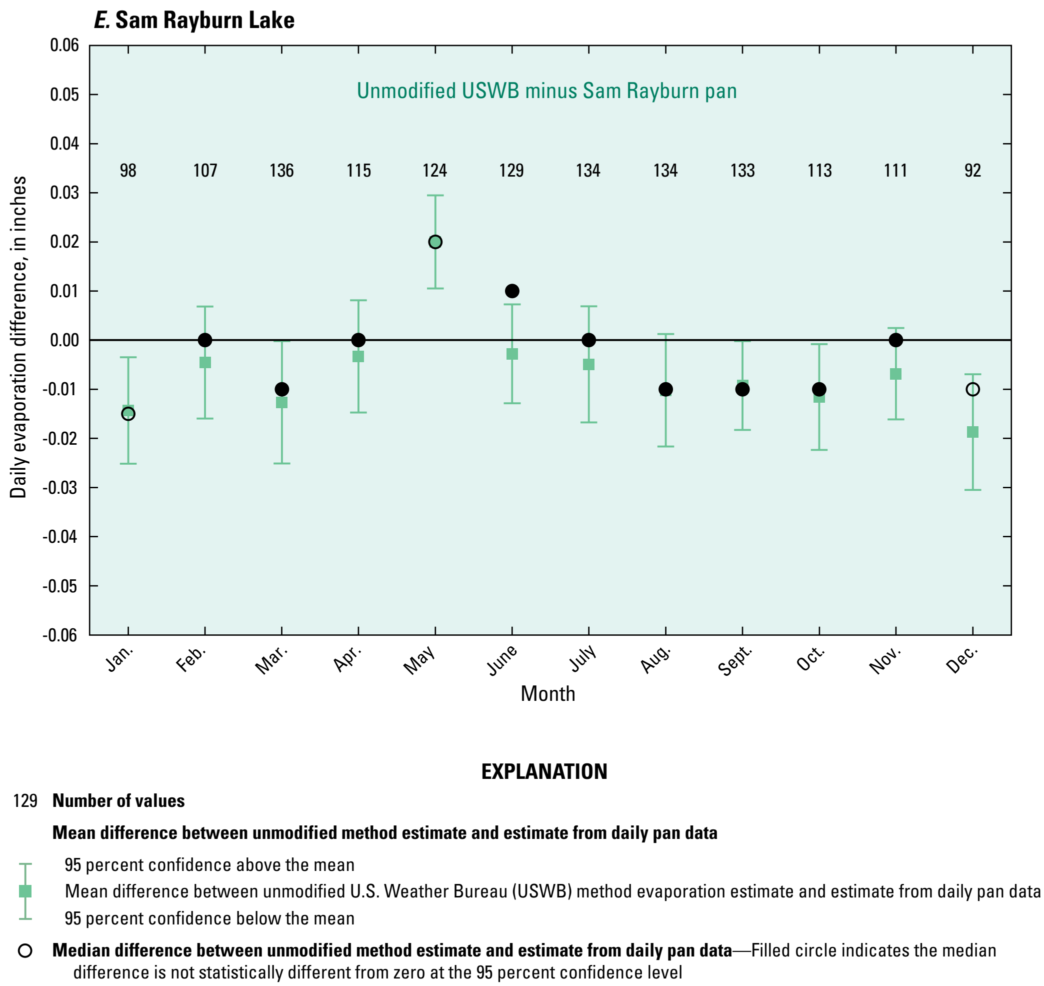


Figure 8. Daily mean and median differences for each month between unmodified U.S. Weather Bureau method evaporation estimates and daily pan evaporation estimates from pan data collected at *A*, Benbrook Lake, Texas, *B*, Canyon Lake, Tex., *C*, Granger Lake, Tex., *D*, Hords Creek Lake, Tex., and *E*, Sam Rayburn Lake, Tex.—Continued

Summary

There are many published equations for estimating evaporation. Some equation estimates are attractive alternatives to energy-budget methods and pan data because of potential lower operation costs, automated data collection and storage, and real-time calculation capability. However, these various open-water evaporation methods can yield different results, and guidance as to what methods should be used is lacking. Accordingly, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers (USACE), reviewed selected studies in the scientific literature, summarized significant findings and methods pertaining to estimation of evaporation from open water, and evaluated two methods, the Hamon method and the U.S. Weather Bureau (USWB) method, for estimating evaporation. The USWB was renamed the National Weather Service in 1970.

The energy-budget method is often considered the most accurate method for open-water evaporation estimation. Estimates of evaporation using the energy-budget method are recognized as a standard by which other estimates are compared. Complex equations to estimate evaporation, such as the Penman, DeBruin-Keijman, and Priestley-Taylor, have performed well when compared with energy-budget method estimates when all of the important energy terms, such as net radiation, change in the amount of stored energy, and advected energy, are included and ideal data are collected. However, these terms require appreciable effort and expense to collect and include in the equations. Given these difficulties in collecting ideal data, sometimes nonideal data are collected and important energy terms are not included in the equations. When this is done, the corresponding errors in evaporation estimates are not quantifiable.

The simple empirical equations, such as the Hamon, Makkink, Jensen-Haise, Thornthwaite, and Papadakis equations, have been shown to provide reasonable estimates of evaporation when compared to energy-budget method estimates. However, when applying these equations to various water bodies, their performance remains questionable without accurate energy-budget or water-budget estimates to compare against because of the empirical origin of their coefficients.

Estimates of annual lake evaporation from pan data and application of published pan coefficients have been shown to frequently be within 20 percent of energy-budget and water-budget estimates. Estimates of annual lake evaporation from pan data frequently compare well with accurate energy-budget and water-budget estimates because annually the changes in the amount of stored energy and the advected energy become negligible.

Results of evaporation estimates from two methods with minimal data requirements, the Hamon method and the USWB method, were compared against historical pan data at five reservoirs in Texas (Benbrook Lake, Canyon Lake, Granger Lake, Hords Creek Lake, and Sam Rayburn Lake) to evaluate their performance and to develop coefficients to minimize bias for the purpose of estimating reservoir evaporation with accuracies similar to estimates of evaporation obtained from pan data. The Hamon method requires average daily air temperature, and the USWB method requires daily averages of air temperature, relative humidity, wind speed, and solar radiation.

The modified Hamon method estimates of reservoir evaporation were similar to estimates of reservoir evaporation from pan data for daily, monthly, and annual time periods. Median daily differences between modified Hamon method estimates and estimates from pan data were not significantly different from zero for all months at all five reservoirs except for the month of April at Hords Creek Lake. Average daily differences between modified Hamon method estimates and estimates from pan data as a percentage of the average amount of daily evaporation from pan data were within 14 percent for all months at all five reservoirs. For all five reservoirs, the average errors for monthly estimates of evaporation determined from the modified Hamon method were less than 14 percent, and the 75th percentile values of the percentage errors were less than 18 percent. The modified Hamon method estimates of annual reservoir evaporation were always within 20 percent of annual reservoir evaporation from pan data, within 15 percent for 95 percent of the years analyzed and, therefore, within the amount of error typically associated with annual estimates of reservoir evaporation from pan data.

The ability of the modified Hamon method, requiring only measurements of air temperature at remote weather stations, to estimate reservoir evaporation similarly to pan estimates of evaporation is probably because of a strong relation between air temperature and pan water temperature. The small volume of water in the pan responds to day-to-day fluctuations in air temperature and, therefore, a strong relation exists between average daily air temperature and the amount of evaporation from the pan. The results clearly show that for application to other reservoirs, site-specific monthly coefficients need to be developed from historical pan data to adjust for bias. Site-specific monthly coefficients could probably be developed for other locations because of the tendency of the unmodified Hamon method to underpredict reservoir evaporation from pan data at all five reservoirs that vary geographically across Texas.

The unmodified and modified USWB method estimates of reservoir evaporation were similar to estimates of reservoir evaporation from pan data for annual time periods. The unmodified and modified USWB method estimates were within 20 percent of reservoir evaporation from pan data for 32 of the combined 35 years compared (about 91 percent).

Monthly estimates of reservoir evaporation from pan data with the modified USWB method were better than unmodified USWB method estimates for four of the five reservoirs. For the four reservoirs, the average errors for monthly estimates of evaporation determined from the modified USWB method were less than 12 percent and 75th percentile values of the percentage errors were less than 17 percent. Average errors for monthly estimates of evaporation determined from the unmodified USWB method at the same four reservoirs were less than 16 percent and 75th percentile values of the percentage errors were less than 24 percent. Although modifications to the USWB method with the coefficients improve the estimates of monthly reservoir evaporation from pan data, annual estimates of evaporation are not always appreciably improved because monthly bias is not consistent from year to year. Modified USWB method estimates of daily reservoir evaporation were similar to estimates of daily reservoir evaporation from pan data. Median daily differences between modified USWB method estimates and estimates from pan data were not significantly different from zero for all months at all five reservoirs except three, April at Canyon Lake and Granger Lake and December at Hords Creek Lake. Average daily differences between modified USWB method estimates and estimates from pan data as a percentage of the average amount of daily evaporation from pan data were within 20 percent for 98 percent of the months. However, without any modification to the USWB method, average daily differences as a percentage of the average amount of daily evaporation from pan data were within 20 percent for 73 percent of the months.

The similarity between annual unmodified USWB method estimates and annual estimates of reservoir evaporation from pan data at the five reservoirs is expected. The method is intended to estimate average daily lake evaporation such that the sum of the daily estimates should approximate annual evaporation if the annual change in the amount of stored energy and advected energy are negligible. Therefore, the method will underpredict and overpredict during some days and months of the year, but annually, the method will give estimates of reservoir evaporation from pan data within 20 percent for most years, which is within the amount of error typically associated with annual estimates of reservoir evaporation from pan data. Use of the unmodified USWB method is appealing because it means estimates of average daily reservoir evaporation can be made from meteorological data collected from weather stations in close proximity to a particular reservoir without the need to develop site-specific coefficients from historical pan data. However, meteorological data from nearby weather stations could be compiled and calculations of daily evaporation made and summed annually to check against historical pan estimates at a particular reservoir to increase confidence in applying the method to other reservoirs and to reveal locations where the method may not adequately predict evaporation.

References Cited

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998, Crop evapotranspiration–Guidelines for computing crop water requirements: Irrigation and Drainage Paper No. 56, Rome, Italy, United Nations Food and Agriculture Organization, 300 p.

Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., Snyder, R.L., 2005, The ASCE standardized reference evapotranspiration equation: Environmental and Water Resources Institute of the American Society of Civil Engineers, 59 p.

Anderson, E.R., 1954, Energy-budget studies, *in* Water-loss investigations, Lake Hefner studies: U.S. Geological Survey Professional Paper 269, p. 71–119.

Andreas, E.L., Daly, S.F., Koenig, G.G., and Nelson, M.E., 2002, A new method for estimating evaporation from large reservoirs, in American Meteorological Society, 16th conference on hydrology, January 2002, accessed July 17, 2012 at http://library.cma.gov.cn:8080/ams_data/AMS2002_/26925.pdf.

Bowen, I.S., 1926, The ratio of heat losses by conduction and by evaporation from any water surface: Physics Review, v. 27, p. 779–787.

Brutsaert, W.H., 1982, Evaporation into the atmosphere–Theory, history, and applications: Netherlands, D. Reidel, Dordrecht, 299 p.

California Irrigation Management Information System, 2012, CIMIS equation: California Irrigation Management Information System, Department of Water Resources, Office of Water use Efficiency, accessed February 15, 2012, at http://wwwcimis.water.ca.gov/cimis/infoEtoCimisEquation.jsp.

Crow, F.R., and Hottman, S.D., 1973, Network density of temperature profile stations and its influence on the accuracy of lake evaporation calculations: Water Resources Research, v. 9, no. 4, p. 895–899.

Dalton, M.S., Aulenbach, B.T., and Torak, L.J., 2004, Ground-water and surface-water flow and estimated water budget for Lake Seminole, southwestern Georgia and northwestern Florida: U.S. Geological Survey Scientific Investigations Report 2004–5073, 54 p.

DeBruin, H.A.R., and Keijman, J.Q., 1979, The Priestley-Taylor evaporation model applied to a large, shallow lake in the Netherlands: Journal of Applied Meteorology, v. 18, p. 898–903.

Farnsworth, R.K., and Thompson, E.S., 1982, Mean monthly, seasonal, and annual pan evaporation for the United States: National Oceanic and Atmospheric Administration Technical Report NWS 34, 85 p.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration Technical Report NWS 33, 31 p.

Ficke, J.F., 1972, Comparison of evaporation, computation methods, Pretty Lake, Lagrange County, northeastern Indiana: U.S. Geological Survey Professional Paper 686–A, 49 p.

Ficke, J.F., Adams, D.B., and Danielson, T.W., 1976, Evaporation from seven reservoirs in the Denver water-supply system, central Colorado: U.S. Geological Survey Water-Resources Investigations Report 76–114, 170 p.

Georgia Automated Environmental Monitoring Network, 2012, accessed February 15, 2012, at http://www.georgiaweather.net/.

Gunaji, N.N., 1968, Evaporation investigations at Elephant Butte Reservoir in New Mexico: International Association of Scientific Hydrology no. 78, p. 308–325.

Hamon, W.R., 1961, Estimating potential evapotranspiration: Journal of Hydraulics Division, Proceedings of the American Society of Civil Engineers, v. 87, p. 107–120.

Harbeck, G.E., Jr., Kohler, M.A., Koberg, G.E., and others, 1958, Water-loss investigations—Lake Mead studies: U.S. Geological Survey Professional Paper 298, 100 p.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources—Hydrologic analysis and interpretation: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 4, chap. A3, 510 p.

Hounam, C.E., 1973, Comparison between pan and lake evaporation: World Meteorological Organization, Technical Note 126, 52 p.

Jensen, M.E., Burman, R.D., and Allen, R.G., 1990, Evapotranspiration and irrigation water requirements: New York, American Society of Civil Engineers Manuals and Reports on Engineering Practice, No. 70, 332 p.

Kane, J.W., 1967, Monthly reservoir evaporation rates for Texas, 1940 through 1965: Texas Water Development Board, Report 64, 111 p.

Koberg, G.E., 1958, Energy-budget studies, U.S. Geological Survey Professional Paper 298, p. 20–29.

Koberg, G.E., 1964, Methods to compute long-wave radiation from the atmosphere and reflected solar radiation from a water surface: U.S. Geological Survey Professional Paper 272–F, p. 107–136.

Kohler, M.A., Nordenson, T.J., and Fox, W.E., 1955, Evaporation from pans and lakes: U.S. Weather Bureau Research Paper 38, 82 p.

Kohler, M.A., Nordenson, T.J., and Baker, D.R., 1959, Evaporation maps for the United States: U.S. Weather Bureau Technical Paper 37, 13 p.

Lamoreau, W.W., 1962, Modern evaporation formulae adapted to computer use: Monthly Weather Review, v. 90, p. 26–28.

Linsley, R.K. Jr., Kohler, M.A., Paulhus, J.L.H., 1982, Hydrology for engineers (3d ed.): New York, McGraw-Hill, 508 p.

Masoner, J.R., Stannard, D.I., and Christenson, S.C., 2008, Differences in evaporation between a floating pan and a Class A pan on land: Journal of American Water Resources Association, v. 44, p. 552–561.

Mather, J.R., 1978, The climatic water budget in environmental analysis: Lexington, Mass., Lexington Books, Heath and Company, 239 p.

McGuinness, J.L., and Bordne, E.F., 1972, A comparison of lysimeter-derived potential evapotranspiration with computed values: United States Department of Agriculture Technical Bulletin 1452, 71 p.

Mesonet, 2012, Oklahoma Mesonet network: accessed February 15, 2012, at http://www.mesonet.org/.

National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1953–2010: National Oceanic and Atmospheric Administration: v. 58–115.

National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 2001–2010: National Oceanic and Atmospheric Administration: v. 106–115.

National Oceanic and Atmospheric Administration, National Weather Service, 1972, National Weather Service observing handbook No. 2: Substation observations (revised): Washington, D.C., National Oceanic and Atmospheric Administration, 77 p.

National Oceanic and Atmospheric Administration, National Weather Service, 2012, Evolution of the National Weather Service: accessed July 6, 2012, at http://www.nws.noaa.gov/pa/history/timeline.php.

National Wildfire Coordinating Group, 2009, Interagency wildland fire weather station standards & guidelines: National Wildfire Coordinating Group PMS 426-3, 64 p. (Also available at http://raws.fam.nwcg.gov/nfdrs/Weather_station_standards_rev08_2009_FINAL.pdf.)

Parkhurst, R.S., Winter, T.C., Rosenberry, D.O., and Sturrock, A.M., 1998, Evaporation from a small prairie wetland in the Cottonwood Lake area, North Dakota—An energy-budget study: Wetlands, v. 18, p. 272–287.

Pearce, D.C., and Gold, L.W., 1959, Observations of ground temperature and heat flow at Ottawa, Canada: Journal of Geophysical Research, v. 64, p. 1293–1298.

Penman, H.L., 1948, Natural evaporation from open water, bare soil, and grass: Proceedings of the Royal Society of London, v. A193, p. 120–145.

Pruitt, W.O., and Doorenbos, J., 1977, Empirical calibration, a requisite for evapotranspiration formulae based on daily or longer mean climatic data: Budapest, Hungary, Proceedings of the International Round Table Conference on Evapotranspiration.

Remote Automatic Weather Stations, 2012, Western Regional Climate Center: accessed July 17, 2012, at http://www.raws.dri.edu/.

Remote Automatic Weather Stations, 2012, Western Regional Climate Center: accessed February 15, 2012, at http://www.raws.dri.edu/wraws/txF.html.

Rosenberry, D.O., Stannard, D.I., Winter, T.C., and Martinez, M.L., 2004, Comparison of 13 equations for determining evapotranspiration from a prairie wetland, Cottonwood Lake area, North Dakota, USA: Wetlands, v. 24, no. 3, p. 483–497.

Rosenberry, D.O., Sturrock, A.M., and Winter, T.C., 1993, Evaluation of the energy budget method of determining evaporation at Williams Lake, Minnesota, using alternative instrumentation and study approaches: Water Resources Research, v. 29, no. 8, p. 2473–2483.

Rosenberry, D.O., Winter, T.C., Buso, D.C., and Likens, G.E., 2007, Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA: Journal of Hydrology, v. 340, p. 149–166.

Sether, B.A., and Wiche, G.J., 1990, Meteorologic and hydrologic data collected for computing evaporation from Devils Lake, North Dakota, 1986–88: North Dakota State Water Commission Water-Resources Investigations Report 10, 172 p.

Shuttleworth, W.J., 1993, Handbook of hydrology: New York, McGraw-Hill, p. 4.1–4.53.

Spahr, N.E., and Ruddy, B.C., 1983, Reservoir evaporation in central Colorado: U.S. Geological Survey Water-Resources Investigations Report 83–4103, 232 p.

Stephens, J.C., and Stewart, E.H., 1963, A comparison of procedures for computing evaporation and evapotranspiration: International Association of Scientific Hydrology, Publication 62, Berkley, California, International Union of Geodesy and Geophysics, p. 123–133.

Stewart, R.B., and Rouse, W.R., 1976, A simple equation for determining the evaporation from shallow lakes and ponds: Water Resources Research, v. 12, p. 623–628.

Sturrock, A.M., Winter, T.C., and Rosenberry, D.O., 1992, Energy budget evaporation from Williams Lake—A closed lake in north central Minnesota: Water Resources Research, v. 28, no. 6, p. 1605–1617.

Swancar, Amy, Lee, T.M., and O'Hare, T.M., 2000, Hydrogeologic setting, water budget, and preliminary analysis of ground-water exchange at Lake Starr, a seepage lake in Polk County, Florida: U.S. Geological Survey Water-Resources Investigations Report 00–4030, 61 p.

Texas Water Development Board, 1998, Monthly pan coefficients used in ThEvap: Texas Water Development Board, accessed February 15, 2012, at http://midgewater.twdb.state.tx.us/Evaporation/pancoef.txt.

Texas Water Development Board, 2012, Precipitation and lake evaporation data for Texas: Texas Water Development Board, accessed February 15, 2012, at http://midgewater.twdb.state.tx.us/Evaporation/evap.html.

Tschirhart, W., and Rodriguez, D.A., 1998, Program documentation and user's manual, ThEvap 1.0, monthly reservoir evaporation rates for Texas using GIS: Texas Water Development Board.

Tulsa District, U.S. Army Corps of Engineers, 2012, Calculated evaporation for Tulsa District lakes: Public Affairs Office, Tulsa District U.S. Army Corps of Engineers, accessed February 15, 2012, at http://www.swt-wc.usace.army.mil/evap/calcevap.shtml.

U.S. Geological Survey, 2012, Northern Prairie Wildlife Research Center—Cottonwood Lake Study Area (available at http://www.npwrc.usgs.gov/cottonwood.html).

Westenburg, C.L., DeMeo, G.A., and Tanko, D.J., 2006, Evaporation from Lake Mead, Arizona and Nevada, 1997–99: U.S. Geological Survey Scientific Investigations Report 2006–5252, 24 p.

Wiche, G.J., 1992, Evaporation computed by energy-budget and mass-transfer methods and water-balance estimates for Devils Lake, North Dakota, 1986–88: North Dakota State Water Commission Water-Resources Investigations Report 11, 52 p.

Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: Water Resources Bulletin, v. 17, no. 1, p. 82–115.

Winter, T.C., Buso, D.C., Rosenberry, D.O., Likens, G.E., Sturrock Jr., A.M., and Mau, D.P., 2003, Evaporation determined by the energy-budget method for Mirror Lake, New Hampshire: Limnology and Oceanography, v. 48, no. 3, p. 995–1009.

Winter, T.C., Rosenberry, D.O., and Sturrock, A.M., 1995, Evaluation of 11 equations for determining evaporation for a small lake in north central United States: Water Resources Research, v. 31, no. 4, p. 983–993.

Appendix 1—Summary of Selected Studies Pertinent to Open-Water Evaporation Estimation

The energy-budget method is often considered the most accurate method for open-water evaporation estimation (Harbeck and others, 1958; Gunaji, 1968; Winter, 1981; Brutsaert, 1982; Sturrock and others, 1992; Winter and others, 2003; Rosenberry and others, 2004; Dalton and others, 2004; Westenburg and others, 2006). Estimates of evaporation using the energy-budget method are recognized as a standard by which other estimates are compared. The energy-budget method requires large amounts of data to account for all energy fluxes into and out of the water body. An energy budget would not be necessary if a complete water budget were available. However, accurate water budgets based on volume are difficult to acquire to estimate evaporation. The inaccuracies of a water budget based on volume could be of the same order of magnitude as the amount of evaporation (Anderson, 1954).

An energy budget is expressed as the change in stored energy in the water body that is equal to the energy fluxes into and out of the water body. The amount of energy added to the water body that does not cause an increase in the energy stored in the water body is attributed to evaporation, which can be expressed as a subsequent energy loss. The energy budget in equation form is as follows (Sturrock and others, 1992):

$$\begin{aligned} &Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} \\ &+ Q_v - Q_e - Q_h - Q_w + Q_b = Q_x \end{aligned} \tag{1.1}$$

where

- Q_s is incoming short-wave solar radiation;
- Q_r is outgoing (reflected) short-wave solar radiation;
- Q_a is incoming long-wave atmospheric radiation;
- Q_{ar} is outgoing (reflected) long-wave radiation;
- Q_{bs} is emitted long-wave radiation from the water body;
- Q_v is net advected energy to the water body by precipitation, surface water, and groundwater;
- Q_e is energy used for evaporation;
- Q_h is energy conducted from the water body to the atmosphere as sensible heat;
- Q_w is energy advected from the water body by the evaporated water;
- Q_b is energy transfer from the bottom sediments; and
- Q_x is change in the stored energy of the water body.

There are various equations for estimation of evaporation from open water. Some investigators have reported as many as 30 different equations (Winter and others, 1995). Some equations are simple and require only air temperature, whereas, others are complex and require an extensive suite of meteorological data along with some of the energy flux terms such as net radiation (Q_n) and the change in the stored energy of the water body. Net radiation is the algebraic sum of the first five terms of the energy budget equation (Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}). Some investigators have included estimates of evaporation from many different simple and complex equations and have compared such estimates to those from comprehensive energy-budget method estimates (Winter and others, 1995; Dalton and others, 2004; Rosenberry and others, 2004; Rosenberry and others, 2007). It is beyond the scope of this report to discuss in detail the theory behind the many different simple and complex equations and to describe in detail the conditions under which the equations (and empirically derived coefficients) were developed. The objective is to relate how well different equations have performed under different hydrologic conditions when compared to comprehensive energy-budget method estimates.

Two methods that appear somewhat frequently in the literature, the mass transfer method (Winter, 1981) and the eddy correlation method (Shuttleworth, 1993), are not discussed. The mass transfer method is not discussed because of the need to determine a mass transfer coefficient for a particular water body in order to use the method. Because the goal of many end users is to economically estimate evaporation with minimal data requirements, the development of the mass transfer coefficient for a particular water body is generally not considered practical. The eddy correlation method has shown great promise in its ability to actually measure evaporation (Winter, 1981). However, the eddy correlation method is relatively expensive to implement, requires careful site selection and maintenance, and requires appreciable data analyses and interpretation by highly trained staff.

The remainder of this appendix summarizes selected energy-budget studies. Included in the summaries of these studies are findings that contribute to an understanding of the relations between energy-budget method estimates, equation estimates, and Class A pan estimates.

Williams Lake, Minnesota

Williams Lake is a natural lake in north-central Minnesota (fig. 1.1). It is a closed lake, meaning it has no surface water inflow or outflow. The lake is relatively small with a surface area of 89 acres, a drainage area of 561 acres, an average depth of 17 feet (ft), and a volume of 1,540 acre-ft. (Sturrock and others, 1992).

Williams Lake was one of four experimental water bodies selected as part of the USGS Hydrology of Lakes Project (HLP). The purpose of HLP was to evaluate the energy-budget method with respect to its ability to determine hydrologic fluxes in and out of small lakes. Prior to the HLP, most research on energy-budget method estimates of evaporation losses from lakes was done in arid and semiarid regions of the United States on large reservoirs because of the need for accurate accounting of water resources. The HLP focused on small lakes and included humid regions to improve the knowledge base of understanding the energy budget in a wider

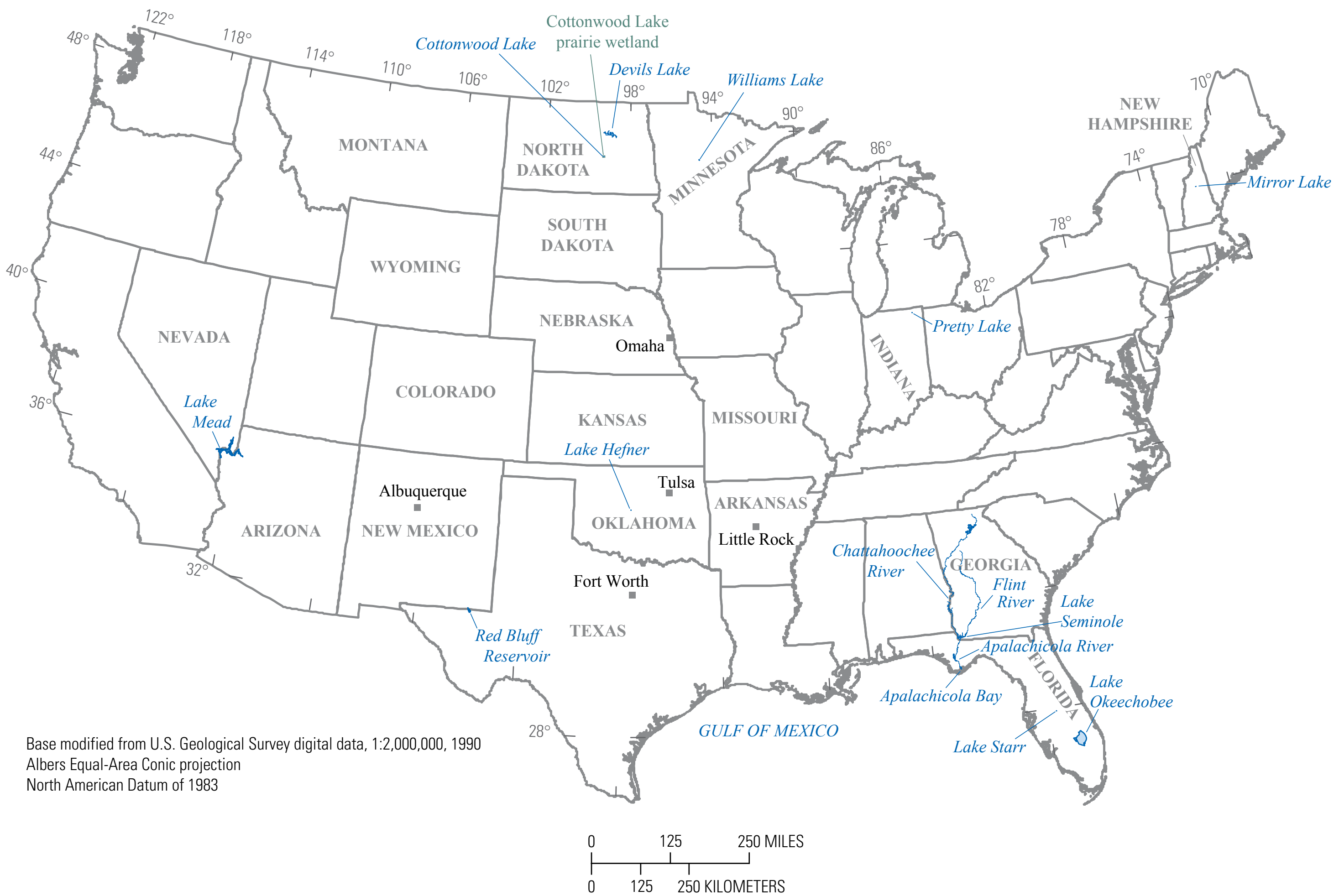


Figure 1.1. Location of selected studies pertinent to open-water evaporation estimation discussed in appendix 1 of this report.

range of climatic and physical settings (Sturrock and others, 1992). An improved understanding of the energy budget in different settings also would provide data to compare to evaporation estimates using different equations.

Evaporation estimates for Williams Lake were made during the open-water periods from about May to October during 1982–86. The data collection stations during 1982–86 included a raft station and a land station. The raft station was located in the center of the lake, and the land station was located in the center of an open field approximately 328 ft northwest of the lake. The raft station included anemometers at different heights to collect vertical wind speed profile data, a thermistor at the surface to measure water-surface temperature, and a thermistor psychrometer located 6.56 ft above the water surface to measure air temperature and vapor pressure. The land station included a spectral pyranometer to measure incoming short-wave solar radiation, an infrared radiometer to measure incoming long-wave atmospheric radiation, an anemometer to collect wind-speed data, a thermistor psychrometer to measure air temperature and vapor pressure, and a tipping bucket rain gage to measure precipitation. These data were collected hourly with a sampling frequency of 1 minute and daily averages were computed. Evaporation pan data were not collected during this study.

Incoming short-wave solar radiation was directly measured at the land station (Sturrock and others, 1992). The amount of outgoing short-wave solar radiation was calculated from incoming short-wave solar-radiation data using a published method (Anderson, 1954; Koberg, 1964). Incoming long-wave atmospheric radiation was directly measured at the land station. Outgoing long-wave radiation was calculated (not directly measured) using a published method as 3 percent of the incoming atmospheric radiation (Anderson, 1954). The amount of long-wave radiation emitted from the water surface of the lake was calculated using the Stefan-Boltzmann law for black-body radiation using an emissivity of the surface as 0.97 and water-surface temperature measured as close to the surface as practically possible.

The net advected energy to Williams Lake was calculated from the volume and temperature of precipitation to the lake as well as the volume and temperature of groundwater flow to and from the lake. Precipitation volume was measured at the land station and its temperature was determined at the time of the rain event. Groundwater inflow and lake seepage outflow volumes were determined from Darcy's law with data obtained from nearby groundwater wells. The temperature of groundwater inflow was determined from well data and the temperature of the lake water measured from the raft was assumed to equal the temperature of lake seepage outflow (Sturrock and others, 1992).

The next three terms (Q_e, Q_h, and Q_w) in the energy budget (eq. 1.1) were not directly measured but were calculated as functions of the evaporation rate and the Bowen ratio (Bowen, 1926). The theory behind all of the calculations to solve for the three terms, along with the inherent assumptions of the methodology, and the substitution of terms required to make the calculations are explained by Bowen (1926), Harbeck and others (1958), and Sturrock and others, (1992).

The energy transfer from lake bottom sediments was included in the energy budget at Williams Lake. Most energy-budget studies do not address this transfer of energy and assume the amount of energy is not appreciable with respect to the entire energy budget. Energy transfer from the bottom sediments was computed following methods described by Pearce and Gold (1959).

The change in the stored energy of Williams Lake was determined from temperature profiles made approximately every 2 weeks at 16 stations in the lake. This corresponds to a station density of one station per 5.7 acres. Collection of these data was termed thermal surveys. The approximate 2-week periods between thermal surveys were termed energy-budget periods, meaning these were the periods in which the energy-budget equation was applied and evaporation rates were determined. All other data that were measured or calculated as daily averages were input into the energy-budget equation as averages over the energy-budget period of approximately 2 weeks. Therefore, the average of about 14 daily averages was used in the energy-budget equation for measured and calculated data.

During each of the thermal surveys, Sturrock and others (1992) divided Williams Lake into horizontal layers, and the average temperature at the midpoint of each layer was determined from the thermal survey data at the 16 stations. The quantity of stored energy in each layer was calculated by multiplying the area of each layer by the layer thickness, the specific heat of the water, and the density of the water. The total amount of stored energy in the lake was calculated as the sum of the energy content of each layer. Lastly, the change in the stored energy of Williams Lake between energy-budget periods was then calculated as the difference between the total amount of stored energy at the end of the energy-budget period minus the total amount of stored energy at the beginning of the energy-budget period.

Results of the Williams Lake energy-budget study were first presented by Sturrock and others (1992). Other publications soon followed in which investigators presented results evaluating the energy-budget method at Williams Lake using different instrumentation and study approaches (Rosenberry and others, 1993) as well as comparing the energy-budget method estimates with estimates from 11 different equations (Winter and others, 1995).

The results from Sturrock and others (1992) showed that the greatest energy flux term into Williams Lake was incoming long-wave atmospheric radiation, followed by incoming short-wave solar radiation. These two energy flux terms into the lake averaged 63.6 and 36.0 percent, respectively, of the total energy input to the lake during all of the energy-budget periods. The net advected energy (related to precipitation and groundwater) was only about 0.4 percent of the total energy input to the lake and only reached a maximum of 1.4 percent of the total energy input. The net advected energy was the smallest component in the Williams Lake energy budget for at least two reasons. First, Williams Lake was equally balanced between groundwater inflow and seepage outflow. Secondly, the relatively low temperatures of groundwater inflow added little energy to the lake and the temperature of the lake seepage outflow was higher than the surrounding groundwater for short periods of time.

The results also showed that the greatest energy flux term out of the lake was the emitted long-wave radiation, accounting for an average of 77.2 percent of the total energy output from the lake during all of the energy-budget periods and only reached a minimum of 70.5 percent. The energy used for evaporation followed and accounted for an average of 13.6 percent of the total energy output from the lake during all of the energy periods. All other energy outputs (Q_r, Q_{ar}, Q_h, Q_w, and Q_b) in the energy budget (eq. 1.1) from the lake each averaged less than 3.1 percent of the total energy output. The energy transfer from the bottom sediments was found to be negative for all energy-budget periods, meaning the bed sediment acted as a sink and resulted in the movement of energy out of the lake. The investigators of the Williams Lake energy budget concluded that the energy transfer from bottom sediments was appreciable because evaporation estimates during midsummer decreased by as much as 7.0 percent when it was included in the energy budget (Sturrock and others, 1992).

Rosenberry and others (1993) evaluated the energy-budget method estimates of evaporation from Williams Lake reported by Sturrock and others (1992). Rosenberry and others (1993) used alternative instrumentation and data substitutions to evaluate the effects of different types of data on energy-budget estimates of evaporation. One important result of the research pertained to using land-based air temperature and atmospheric vapor pressure data instead of data collected from a raft station in the lake. When air temperature and atmospheric vapor pressure data collected at the land station adjacent to the lake were used in Bowen ratio calculations, resulting evaporation estimates between energy-budget periods were within 10 percent of best estimates 97 percent of the time and within 5 percent 81 percent of the time. Rosenberry and others (1993) concluded that substituting air temperature and atmospheric vapor pressure data from a nearshore land station had little effect on evaporation estimates. This result does not mean that raft-based data could be abandoned completely because accurate surface-water temperature data and the resulting saturated vapor pressure were still required from the raft station to calculate the Bowen ratio and the emitted long-wave radiation.

Rosenberry and others (1993) substituted air temperature, atmospheric vapor pressure, and incoming short-wave solar-radiation data from a station about 68 miles (mi) south of Williams Lake for data collected at the nearshore land station to evaluate the effect of using remotely collected data on evaporation estimates. When only incoming short-wave solar-radiation data were substituted, evaporation estimates between energy-budget periods were within 10 percent of best estimates 92 percent of the time and within 5 percent only 58 percent of the time. However, if all three of the remotely collected data were substituted, the evaporation estimates were within 10 percent only 61 percent of the time and within 5 percent only 39 percent of the time. These results indicate that incoming short-wave solar-radiation data from a remote station could be used instead of data collected nearshore but air temperature and atmospheric vapor pressure data need to be collected much closer to the lake. Although the remotely collected incoming short-wave solar-radiation data performed well, the incoming long-wave atmospheric radiation data were still collected nearshore because remotely collected data were not available for this parameter to make comparisons.

Rosenberry and others (1993) also determined that estimating the change in the stored energy of Williams Lake by using the daily change in surface-water temperature instead of the thermal-survey data resulted in large differences between evaporation estimates during energy-budget periods. When the change in the stored energy was determined from thermal survey data at one station (instead of 16), the evaporation estimates between energy-budget periods were within 10 and 5 percent 96 percent of the time. This corresponds to a thermal survey station density of one station per 89 acres. Contrasted to Williams Lake, research by others at Lake Hefner in Oklahoma showed the optimum number of stations to be one station per 519 acres (Crow and Hottman, 1973).

Rosenberry and others (1993) reported that ignoring the net advected energy had little effect on evaporation estimates for Williams Lake because the lake does not have surface-water inflow or outflow and because groundwater inflow and seepage outflow amounts and temperatures are similar. The investigators acknowledge that the omission of net advected energy could be substantial for lakes and reservoirs that have substantial surface-water inflow and outflow and imbalances between groundwater inflow and seepage outflows. Estimates of evaporation at water-supply reservoirs in Colorado changed by more than 100 percent when net advected energy was ignored (Ficke and others, 1976; Spahr and Ruddy, 1983). Conversely, at Lake Mead, Nevada, a 5-percent increase in surface-water inflow and a 1-degree Celsius increase in the temperature of the inflow changed evaporation estimates by only 2 to 4 percent (Koberg, 1958).

In the third of three reports summarizing evaporation research at Williams Lake, Winter and others (1995) evaluated the performance of 11 different equations for estimating monthly evaporation. Evaporation equation estimates were compared with energy-budget method estimates and average differences and standard deviations between the two estimates were reported.

Winter and others (1995) concluded that the Penman, DeBruin-Keijman, and Priestley-Taylor equations performed the best with respect to the following criteria: (1) lower average monthly differences between equation and energy-budget method estimates; (2) lower standard deviations of the differences; and (3) equation estimates did not indicate a seasonal bias and, therefore, did not tend to overestimate or underestimate evaporation at certain times of the year (Brutsaert, 1982; DeBruin and Keijman, 1979; Stewart and Rouse, 1976). These three equation estimates had average monthly differences from the energy-budget method estimates of less than 0.39 inch (in.), standard deviations of less than 0.39 in., and little to no indication of seasonal bias. The energy-budget method monthly estimates of evaporation for Williams Lake for the 22 months considered averaged 3.35 in. and ranged from 1.97 to 4.72 in. Therefore, average differences of less than 0.39 in. between evaporation equation estimates and energy-budget method estimates indicate average percent errors less than about 12 percent.

Winter and others (1995) also concluded that the Penman, DeBruin-Keijman, and Priestley-Taylor equations calculated monthly evaporation relatively accurately when using data collected from a raft station in the middle of the lake or from a land station about 328 ft northwest of the lake. The investigators were able to substitute wind speed, air temperature, and vapor pressure data collected from the raft station with data collected from the land station. All three equations require net radiation, which is the algebraic sum of the first five terms of the energy-budget equation. Net radiation was determined by measuring incoming short-wave solar radiation at the land station, measuring incoming long-wave atmospheric radiation at the land station, calculating outgoing short-wave solar radiation from incoming short-wave solar radiation, calculating outgoing long-wave radiation as 3 percent of incoming long-wave atmospheric radiation, and calculating emitted long-wave radiation from water temperature. Water-temperature data collected from the raft station were still required to calculate emitted long-wave radiation to determine net radiation for the three equations. Therefore, if land stations near a lake are used to collect data for these equations, water-temperature data are required when using the same methodology as the Williams Lake study. However, the development of net radiometers enables investigators of today (2012) to quantify the net radiation term directly. The Penman, DeBruin-Keijman, and Priestley-Taylor equations also require the change in the stored energy from temperature surveys for the period in which the evaporation calculations are being made, and collecting these data is labor intensive.

Winter and others (1995) noted two equations with less intensive data requirements that performed reasonably well for Williams Lake were the Jensen-Haise and Makkink equations (McGuinness and Bordne, 1972). Both equations require only incoming short-wave solar-radiation and air-temperature data. The average monthly differences from the energy-budget method estimates when using data collected from the raft station, the land station, and the remote station were less than 0.39 in. The standard deviations were large for both equations and for all data sources. Therefore, these equations would not be appropriate for estimating evaporation for short periods of time, such as less than 1 month.

The Papadakis equation estimates had average monthly differences from the energy-budget method estimates of less than 0.39 in. when raft-based data for saturated vapor pressure at the temperature of the air were used (McGuinness and Bordne, 1972). However, standard deviations were large for all data sources making the estimates inappropriate for short periods of time, such as less than 1 month.

The Hamon equation also compared reasonably well with energy-budget method estimates when using raft-based data or data from a remote station (Hamon, 1961). Average monthly differences were also less than 0.39 in., and standard deviations were similar to those from the Jensen-Haise, Makkink, and Papadakis equations. For the Hamon equation, air-temperature data need to be collected. The maximum number of daylight hours is also included in the equation as a surrogate for solar radiation but this value is calculated from the latitude of Williams Lake.

Mirror Lake, New Hampshire

Mirror Lake is a small reservoir in New Hampshire (fig. 1.1). The surface area of the lake is about 37 acres and the average depth is about 18.9 ft. Unlike Williams Lake, surface-water inflow and outflow occurs at Mirror Lake. Two streams drain about 70 percent of the drainage basin to the lake. A third stream drains less than 30 percent of the basin. Much of the flow in this third stream is diverted before reaching the lake by a berm placed upstream during construction of a roadway. Surface-water outflow occurs through a spillway on the dam impounding Mirror Lake (Winter and others, 2003).

Similar to the Williams Lake study, research on Mirror Lake was done as part of the USGS Hydrology of Lakes Project. During 1982–87, a comprehensive energy-budget study was done on Mirror Lake to evaluate the terms of the energy-budget equation for a small lake in New England and to evaluate equation estimates of evaporation. The results of the research on Mirror Lake discussed here were presented in two publications. The first publication presented the results of the energy-budget method estimates of evaporation (Winter and others, 2003), and the second focused on comparing the energy-budget method estimates to estimates from 14 different equations (Rosenberry and others, 2007).

The instrumentation, data collection methods, and field methods used for the study on Mirror Lake were almost identical to those used in the Williams Lake study. Parameters for the energy budget equation were collected at a raft station in the middle of the lake (wind speed, surface-water temperature, air temperature, and vapor pressure) and at a land station about 1,476 ft west of the lake (incoming short-wave solar radiation, incoming long-wave atmospheric radiation, air temperature, relative humidity, and precipitation). The Mirror Lake land station did not collect wind-speed data.

The individual terms of the energy-budget equation were also determined using the same methods as those in the Williams Lake study (Sturrock and others, 1992). However, for the Mirror Lake study, surface-water inflow and outflow and the temperature of each were measured to quantify the net advected energy (Winter and others, 2003). Similar to the Williams Lake study, evaporation pan data were not collected during the Mirror Lake study.

The energy-budget periods, or the time between thermal surveys, ranged from 5 to 22 days in the Mirror Lake study. During 1982–87, 152 thermal surveys of Mirror Lake were done that resulted in 146 different energy-budget periods to estimate losses attributed to evaporation and to compare against equation estimates of evaporation. By varying the times between energy-budget periods, Winter and others (2003) were able to evaluate the effect of the length of the energy-budget period on calculated evaporation. Temperature measurements for each thermal survey were made at 10 locations in the lake, corresponding to a thermal survey station density of one station per 3.7 acres.

Similar to results at Williams Lake, three of the energy flux terms were much greater than the others. The greatest energy flux term into the lake was incoming long-wave atmospheric radiation, followed by incoming short-wave solar radiation. The greatest energy flux term out of the lake was emitted long-wave radiation. Winter and others (2003) did not present tabulated values of each of the individual energy flux terms for each of the energy-budget periods as did Sturrock and others (1992) for the Williams Lake study so statements pertaining to percent contributions of each of the energy-budget terms are not possible. Instead, Winter and others (2003) summarized the information in a graph so only general statements about the relative magnitude of each of the energy-budget terms can be made.

The net advected energy was a small part of the energy budget for Mirror Lake even though there are surface inflows and outflows to the lake. Precipitation-related advected energy was minimal. Advected energy resulting from the exchange of surface water to and from the lake was reported as minimal because most of the peak flows occurred during the spring when cold water and snowmelt flowed into the lake, which was already at relatively low temperatures, resulting in little change in net energy. Similarly, large outflows usually coincided with large inflows and therefore negligible changes in net energy. Energy inputs and outputs from groundwater were also small despite seepage from groundwater being one of the largest losses of water from the lake (Winter and others, 2003).

Some of the more noteworthy conclusions of the study on Mirror Lake pertained to the effect of varying the length of the energy-budget period (time between thermal surveys) on evaporation estimates (Winter and others, 2003). By reducing the energy-budget period from about 2 weeks to 1 week, the variability in evaporation estimates increased, but the total amount of calculated evaporation for an entire open-water period when ice was absent was the same using either approach and seasonal patterns of evaporation were similar.

Of the 14 different equations that were evaluated against energy-budget method estimates at Mirror Lake, the Priestley-Taylor, DeBruin-Keijman, and Penman equations performed the best (Rosenberry and others, 2007). Estimates of evaporation with these three equations were within 20 percent of energy-budget method estimates during more than 90 percent of the energy-budget periods analyzed. The three equations also had the lowest standard deviations of monthly differences between equation estimates and energy-budget method estimates. The average monthly differences for all three equations were within the amount of uncertainty associated with the energy-budget method estimates. The three equations all had positive seasonal bias, indicating a tendency to overestimate evaporation during midsummer. Smaller overestimates or underestimates occurred during the spring and the fall. The investigators were able to reduce the amount of positive bias with the three equations when net advected energy and energy transfer from bottom sediments were included in the available energy term of the three equations.

Equations with minimal data requirements when compared to the Priestley-Taylor, DeBruin-Keijman, and Penman that also performed well for Mirror Lake include the Papadakis, Thornthwaite, Makkink, and Hamon. The Papadakis and Thornthwaite equations (requiring only air-temperature data) indicated positive and zero bias, respectively, and both had intermediate amounts of variance relative to energy-budget method estimates. Of these two, only the Thornthwaite had average monthly differences within the amount of uncertainty associated with the energy-budget method estimates. The Papadakis and Thornthwaite equation results were within 20 percent of the energy-budget method estimates for 60 and 59 percent, respectively, of the energy-budget periods analyzed. The Makkink and Hamon equations are all part of a group of equations that require air-temperature and solar-radiation data or a surrogate for solar radiation such as maximum number of daylight hours. Estimates were within 20 percent of energy-budget method estimates for 54 percent of the energy-budget periods for the Makkink equation and for 46 percent of the energy-budget periods for the Hamon equation. The Makkink and Hamon equations had average monthly differences within the amount of uncertainty associated with the energy-budget method estimates.

When the Hamon equation was modified with a coefficient to reduce a small amount of bias, the modified Hamon estimates were within 20 percent of energy-budget method estimates for 54 percent of the energy-budget periods. Similarly, the Papadakis equation was modified to reduce bias, and energy-budget method estimates and modified estimates were within 20 percent of energy-budget method estimates for 81 percent of the energy-budget periods.

Cottonwood Lake Prairie Wetland, North Dakota

The Cottonwood Lake prairie wetland (referred to hereinafter as wetland P1) near Cottonwood Lake in north-central North Dakota is a semi-permanent prairie pothole wetland (U.S. Geological Survey, 2012) (fig. 1.1). Wetland P1 is small and shallow, with depths rarely exceeding 3.28 ft in the center and has a surface area of 4.94 acres at that depth. The wetland is surrounded by hills that rise as much as 32.8 ft above the bottom of the wetland, and vegetation around the wetland is mostly prairie grassland and herbs (Parkhurst and others, 1998).

During 1982–85 and 1987, a comprehensive energy budget (also part of the USGS Hydrology of Lakes Project) was done for wetland P1. The results of the energy-budget assessment were first presented by Parkhurst and others (1998), and the same general approach with respect to instrumentation, data collection methods, and field methods described by Sturrock and others (1992) at Williams Lake and Winter and others (2003) at Mirror Lake was also applied to the study at wetland P1. Rosenberry and others (2004) present the results of the energy-budget method estimates of evaporation from wetland P1 that were compared with 13 equation estimates. The comparisons made with equation estimates from wetland P1 are included in this summary for three main reasons: (1) the methodologies used at wetland P1 and those used in other studies referenced in this report were identical and therefore make comparisons possible; (2) the comparisons of comprehensive energy-budget method estimates with equation estimates indicate the applicability (or lack thereof) of the different equations under different hydrologic conditions; and (3) in the publication presenting the energy-budget method results, the magnitudes of each of the terms of the energy budget are given and similarities and differences between the most important components in a wetland environment and a lake environment are worth noting. Evaporation pan data were not collected as part of the wetland P1 study.

The thermal surveys of the wetland, which define the energy-budget period for which evaporation estimates were made, were done about two times per month during the period of open water. During the thermal surveys, temperature measurements were made at the surface, at the bottom, and at depths of about 7.87 and 19.69 in. at seven locations, which correspond to a thermal survey station density of about one station per 0.74 acres (Parkhurst and others, 1998).

The results from Parkhurst and others (1998) showed the greatest energy flux term into the wetland was incoming long-wave atmospheric radiation followed by incoming short-wave solar radiation. These two energy flux terms into the wetland averaged 58.9 and 40.4 percent, respectively, of the total energy input to the wetland during all of energy-budget periods. The net energy advected from precipitation and groundwater was only about 0.2 percent of the total energy input to the wetland and only reached a maximum of 1.0 percent of the total energy input.

The results from Parkhurst and others (1998) also showed that the greatest energy flux term out of the wetland was emitted long-wave radiation, accounting for an average of 73.9 percent of the total energy output from the wetland during all of the energy-budget periods and reached a minimum of only 62.7 percent. The energy used for evaporation followed and accounted for an average of 17.1 percent of the total energy output from the wetland during all of the energy periods. Other energy outputs (Q_r, Q_{ar}, Q_h, and Q_w) averaged less than 3.3 percent of the total energy output.

The energy transfer from bottom sediments was generally negative, meaning the bed sediment acted as a sink and resulted in the movement of energy out of the wetland during energy-budget periods at the beginning of the open-water period (April, May, and June) and remained negative through June and into July (Parkhurst and others, 1998). The bed-sediment term averaged about 1 percent of the total energy output from the wetland during all of the energy-budget periods. At some time in July, the bed-sediment term became positive, meaning the flux of energy changed to input energy into the wetland, and averaged about 1 percent of the total energy input to the wetland during all of the energy-budget periods. Parkhurst and others (1998) concluded that the energy transfer from bed sediments affects evaporation rates by less than 5 percent at wetland P1.

With respect to the change in the stored energy, Parkhurst and others (1998) concluded that for small shallow lakes the change in the stored energy is affected more by changes in volume than changes in water temperature. Therefore, accurate elevation-capacity curves are more important for shallow lakes than deep lakes when determining the change in stored energy from one thermal survey to the next, and temperature data are more important for larger lakes.

The net advected energy was affected by precipitation. Parkhurst and others (1998) concluded that although cloudy conditions and precipitation can cool the lake considerably, the effect does not last long because increased radiation following a precipitation event quickly warms the water and results in little influence on average advected energy for the energy-budget period. The advected energy related to groundwater flow was minimal because of small relative magnitudes of groundwater flow and low temperatures.

Parkhurst and others (1998) compared the results from the study of wetland P1 with results from a similar study done at about the same time at Devils Lake (Sether and Wiche, 1990; Wiche 1992), a large natural lake about 37 mi north of the Cottonwood Lake Study Area and wetland P1 (fig. 1.1). The surface area of Devils Lake averaged 56,834 acres and had an average depth of 29.5 ft in 1987. The study at Devils Lake was similar to the study at wetland P1 with respect to design and instrumentation. Solar-radiation data were similar for wetland P1 and Devils Lake because of only a 37-mi separation, but the responses of water temperature at the two lakes were different. The much greater heat storage capacity (a function of volume) of Devils Lake resulted in warmer water temperatures and greater evaporation rates in the later parts of summer and fall. Conversely, wetlands P1 with its smaller heat storage capacity cooled more quickly and resulted in lower evaporation rates in the fall.

Rosenberry and others (2004) evaluated the performance of 13 different equations for estimating monthly evaporation from wetland P1. The investigators concluded that the

Priestley-Taylor and DeBruin-Keijman equations performed the best with respect to the following criteria: (1) lower average differences between equation and energy-budget method estimates; (2) lower standard deviations of the differences; and (3) equation estimates did not indicate an appreciable seasonal bias and therefore did not tend to overestimate or underestimate evaporation at certain times of the year. Estimates from these two equations were within 20 percent of energy-budget method estimates for 100 percent of the energy-budget periods and within 10 percent for at least 90 percent of the energy-budget periods. The Penman equation also performed well with respect to the same criteria. The Penman equation estimates were within 20 percent of the energy-budget method estimates for 85 percent of the energy-budget periods and within 10 percent for 65 percent of the energy-budget periods. All three equations had average differences from energy-budget method estimates that were positive, indicating a tendency to overestimate evaporation.

Equations with minimal data requirements when compared to the Priestley-Taylor, DeBruin-Keijman, and Penman equations that also performed well at wetland P1 include the Mather (also known as Thornthwaite in other publications), Jensen-Haise, Makkink, and Hamon. The Mather equation requires only air temperature data. Estimates were within 20 percent of energy-budget method estimates for 75 percent of the energy-budget periods, and average differences and standard deviations were relatively low. Average differences were negative for the Mather equation, indicating a tendency to underpredict evaporation. The Jensen-Haise, Makkink, and Hamon equations require incoming short-wave solar radiation (or a surrogate such as maximum number of daylight hours) and air temperature data. Estimates were within 20 percent of energy-budget method estimates for 70 percent of the energy-budget periods for the Jensen-Haise and Makkink equations and for 55 percent of the energy-budget periods for the Hamon equation. The Jensen-Haise equation tended to overpredict and the Makkink and Hamon equations tended to underpredict evaporation.

Lake Seminole, Florida

Lake Seminole is a reservoir impounded at the confluence of the Flint and Chattahoochee Rivers in southwestern Georgia and northwestern Florida and is designed to be operated at full capacity and pass virtually all inflows with little or no additional storage, an impoundment referred to as a run-of-the river reservoir (fig.1.1). Outflow from the lake forms the Apalachicola River, which empties into the Gulf of Mexico at Apalachicola Bay. The lake has a surface area of about 37,600 acres (Dalton and others, 2004).

As part of a comprehensive study (Dalton and others, 2004) to account for groundwater and surface-water flow from Lake Seminole, evaporation rates were determined using the energy-budget method and compared against long-term average annual Class A pan-evaporation estimates and estimates from five equations over a period of 18 months from April 2000 through September 2001. The equations included the Priestley-Taylor, Penman, DeBruin-Keijman, Papadakis, and a form of the Priestley-Taylor equation used by the Georgia Automated Environmental Monitoring Network, 2012 (GAEMN; http://www.georgiaweather.net/).

Unlike the other lakes for which energy budgets have been done and reported on, Lake Seminole serves as a water-supply reservoir with appreciable surface-water and groundwater components. Dalton and others (2004) reported that about 81 percent of the inflow is from surface water, 18 percent is from groundwater, and 1 percent is from precipitation. Outflows from Lake Seminole are about 89 percent surface water, 4 percent groundwater, and 2 percent lake evaporation. The investigators acknowledged that because of measurement error and uncertainty in flux calculations, inflow and outflow components remained unbalanced by about 4 percent, probably because of errors in estimating the groundwater components.

Data collection methods for the Lake Seminole study were different from those used for Williams Lake, Mirror Lake, and the Cottonwood Lake Prairie Wetland studies. These three studies collected incoming short-wave solar-radiation and incoming long-wave atmospheric-radiation data and calculated the reflected components and the emitted long-wave radiation to determine net radiation. The Lake Seminole study measured these variables directly with net radiometers deployed at two overwater stations. The net radiometers measure the algebraic sum of the incoming and outgoing components (short-wave and long-wave radiation). Net radiometers were not available when the other three studies were done. The methods used in the previous studies were accurate methods to determine net radiation even though three of the components were calculated and not directly measured.

The two overwater stations on Lake Seminole also collected precipitation, wind speed, wind direction, air temperature, relative humidity, vapor pressure, barometric pressure, and water temperature data every 15 minutes and summarized values on a daily basis. The stations were selected to represent two different ecological conditions. Lake Seminole has submerged vegetation below about half of its surface area. One of the stations was installed over the open-water part of the lake and the other was installed over submerged vegetation. Data from the two stations were averaged to estimate average conditions for the entire lake for each of the measured parameters. These average values from the two stations were used in calculations of daily evaporation using the energy-budget method and the five equations.

The hydrologic conditions of Lake Seminole with respect to surface-water and groundwater inflows and outflows make the contributions of advected energy different than previous studies at Williams Lake, Mirror Lake, and the Cottonwood Lake Prairie Wetland. The amount of advected energy by surface water and groundwater was an appreciable part of the total energy flux into and out of the lake. During water year 2001, about 51 percent of the total amount of energy input to the lake was from surface water, about 16 percent was from groundwater, and about 1 percent was from precipitation. The remaining 32 percent of energy input to the lake was from net radiation and change in heat storage. Similarly, about 60 percent of the total amount of energy output from the lake was from surface water and 7 percent was from groundwater. The remaining 33 percent of energy output from the lake was from lake evaporation (Brent Aulenbach, U.S. Geological Survey, written commun., 2011). The investigators of the Lake Seminole study did not include an evaluation of the relative magnitudes of the individual terms of the energy-budget equation because the report did not focus primarily on evaporation. Dalton and others (2004) used evaporation estimates to address the main purpose of their study, which was to quantify the individual components of the water budget. These percentage contributions have been included to highlight the potential magnitude of advected energy for a large run-of-the-river reservoir compared to the other studies mentioned in this report where advected energy was minimal. For computations of energy-budget method estimates, the advected energy was calculated on a daily time step from daily average surface-water inflow, surface-water outflow, groundwater inflow, groundwater outflow, precipitation amounts, and temperature data for each of the components.

For the Lake Seminole study, the change in the stored energy was also calculated on a daily time step from a network of 100 temperature probes collecting continuous data at 11 locations on the main body of the lake, 7 locations on arms of the lake (formed by impounding Fishpond Drain and Spring Creek), and 8 locations on two major rivers (Flint and Chattahoochee Rivers). The average depth of water at the 26 temperature measurement locations was 13.3 ft and ranged from 6.2 to 21.5 ft. The depths at which the water temperature measurements were made varied from one location to another but typically three to five probes were distributed uniformly throughout the water column at each location. The thermal survey station density for this study was about one station per 1,446 acres, not as dense a network as for the other studies. The energy-budget studies of Williams Lake, Mirror Lake, and the Cottonwood Lake Prairie Wetland made calculations of evaporation by the energy-budget method and with equations on time steps that coincided with the length of time between thermal surveys, which were about 14 days, 5–22 days, and 14 days, respectively, for the three studies. Daily thermal survey data make it possible to calculate daily evaporation rates with the energy-budget method and the equations. However, daily estimates of evaporation from Lake Seminole were not reported by Dalton and others (2004). The daily estimates were summed to report total monthly evaporation.

The difference between the Priestley-Taylor equation and the GAEMN equation is associated with the way in which the change in the stored energy is calculated. The Priestley-Taylor equation estimates were calculated using data from the entire network of temperature probes at the 26 locations throughout the lake to estimate the change in the stored energy on a daily basis. The GAEMN equation is the same as the Priestley-Taylor equation, but the change in the stored energy is estimated from water temperature profile data at only the two overwater stations. This was done to evaluate the performance of the less costly GAEMN equation when compared to Priestley-Taylor equation estimates with detailed temperature data to estimate the change in the stored energy.

Of the five equations evaluated, the DeBruin-Keijman equation performed the best with respect to the lowest average monthly percentage difference (8 percent) from energy-budget method estimates, and it overestimated annual evaporation by about 5.1 in. from April 2000 through March 2001. The equation with the highest average monthly percent difference (26 percent) was the Penman equation, and it underestimated annual evaporation by 17.2 in. during the same period. The Priestley-Taylor equation and the GAEMN equation had average monthly percentage differences from the energy-budget method estimates of 14 and 25 percent, respectively. Both of these equations underestimated annual evaporation by 9.7 and 17.1 in., respectively.

The Papadakis equation, which requires less data, performed better than either the GAEMN or Penman equations. Average monthly percentage difference for the Papadakis equation estimates was 17 percent, and it underestimated annual evaporation by 11.7 in. The Papadakis equation does not require the measurement of net radiation or the change in the stored energy, only the difference between the saturated vapor pressures at maximum and minimum air temperatures above the water. An interesting comparison not evaluated in the Lake Seminole report would be to evaluate the performance of the Papadakis equation when air temperature and vapor pressure data from an adjacent land station and a land station some distance away from the lake are used instead of data collected from overwater stations. Results from the study on Williams Lake found little difference when land-based air temperature and vapor pressure data were substituted for data collected from overwater stations when using the Papadakis equation (Rosenberry and others, 1993).

Although much effort was spent to quantify the net advected energy for Lake Seminole, the investigators did not include the net advected energy in the DeBriun-Keijman, Penman, Priestley-Taylor, and GAEMN equation estimates. Traditionally, only the net radiation and the change in the stored energy term are included. However, if the net advected energy or the energy transfer from bed sediments are appreciable components of the total energy budget, then including them in these equations has shown to improve estimates of evaporation when compared to energy-budget method estimates at Mirror Lake (Rosenberry and others, 2007). The performance of the DeBriun-Keijman, Penman, Priestley-Taylor, and GAEMN equation estimates for Lake Seminole may improve if the net advected energy was included because the amount of advected energy by surface water and groundwater was an appreciable part of the total energy flux into and out of the lake. However, an interesting result of the omission of the net advected energy is that, on average, monthly equation estimates of evaporation from

Lake Seminole differed by 26 percent at the most (Penman equation) and 8 percent at the least (DeBruin-Keijman equation) from energy-budget method estimates when net advected energy was omitted. However, the variability in the individual monthly percentage differences between equation estimates and energy-budget method estimates was appreciable. For example, the Penman equation estimates during December 2000 were about 64 percent lower than energy-budget method estimates but during July 2001 there was no difference. Similarly, the DeBruin-Keijman equation estimates during May 2000 were about 58 percent more than energy-budget method estimates but during January 2001 there was no difference.

Evaporation estimates from the different equations were not compared to evaporation estimates determined from the energy-budget method on a daily time step for Lake Seminole (Dalton and others, 2004). Comparing the estimates on a daily time step would be valuable information, as many entities, such as the USACE, manage water resources and balance reservoirs on a daily basis. This is a contributing reason to the historical use of a daily amount of evaporation from a Class A pan. The performance of the DeBriun-Keijman, Penman, Priestley-Taylor, and GAEMN equation estimates would also be interesting if the change in stored energy of Lake Seminole was not included in the calculations, because this term is difficult to measure and frequently omitted from equations used to estimate evaporation.

Evaporation estimates from long-term average monthly Class A pan data collected from 1959–78 (not the Class A pan data collected during the period of study, from April 2000 through September 2001) were compared with energy-budget method estimates for Lake Seminole (Dalton and others, 2004). Long-term average monthly pan evaporation was calculated by summing the amount of pan evaporation for each month from 1959–78 and dividing the total by the number of months. The long-term average monthly pan data were collected at Woodruff Dam at Lake Seminole from 1959–1978 and published (Farnsworth and Thompson, 1982). The long-term average monthly pan data, when adjusted with a 0.77-pan coefficient for the Lake Seminole area (Kohler and others, 1959), were within 20 percent of energy-budget method estimates for the entire 18-month study period from April 2000 through September 2001 and within 26 percent annually. For both the entire study period and annually, evaporation pan estimates were lower than energy-budget method estimates. Monthly evaporation pan estimates differed by an average of about 21 percent from energy-budget method estimates.

Dalton and others (2004) acknowledged that although the energy-budget method is generally the preferred method of obtaining accurate estimates of evaporation, its application to Lake Seminole is difficult because of the large contribution of advected energy to the total energy budget. Inaccuracies in the estimates of surface water and groundwater inflows and outflows, which are substantial at Lake Seminole when compared to other energy-budget studies, could mean appreciable errors in the estimates of energy flux into and out of the lake. The inability to quantify net advected energy accurately may explain the relatively large differences between energy-budget method estimates and estimates from equations and evaporation pan data. Anderson (1954) noted the inability to adequately evaluate the net advected energy for run-of-the-river reservoirs (such as Lake Seminole) may make the energy-budget method inappropriate for the determination of evaporation from these types of impoundments.

Brief Summaries of Results from Selected Studies Related to the U.S. Weather Bureau and Class A Evaporation Pan Methods for Estimating Evaporation from Open Water

A method, based on the Penman equation, to estimate average daily lake evaporation was published as equation 10 in a U.S. Weather Bureau (USWB) research paper (Kohler and others, 1955, p. 14). The Penman approach was applied to daily Class A evaporation pan data from stations throughout the United States to empirically derive coefficients to estimate the amount of daily evaporation from a Class A pan and ultimately the amount of average daily lake evaporation from air temperature, relative humidity, wind speed, and solar radiation data. Average daily lake evaporation is estimated as the product of the Penman estimated evaporation from a Class A pan and a 0.70 coefficient. The USWB method assumes that the change in the amount of stored energy and the amount of advected energy are negligible. Therefore, the USWB method is intended to estimate average daily lake evaporation such that the sum of the daily estimates should approximate annual evaporation if the annual change in the amount of stored energy and advected energy is negligible.

Kohler and others (1955) compared lake evaporation estimates from the USWB method with lake evaporation as determined from water budgets for Lake Hefner, Oklahoma, Lake Okeechobee, Florida, and Red Bluff Reservoir, Texas (fig. 1.1). Percentage errors between the USWB method and water-budget estimates at the three locations ranged from about 4.4 percent at Lake Hefner to about 14.4 percent at Lake Okeechobee. The time periods compared were 1 year for Lake Hefner, 1 year for Lake Okeechobee, and 8 years for Red Bluff Reservoir. Similarly, Kohler and others (1955) compared lake evaporation as determined from Class A pan data and application of a 0.70-pan coefficient to lake evaporation as determined from water budgets and found percentage errors ranged from about 2.4 percent at Lake Hefner to about 6.5 percent at Lake Okeechobee. Percentage errors between lake evaporation determined from Class A pan data and application of a 0.70-pan coefficient and the USWB method averaged about 12.0 percent and ranged from about 6.6 to 22.0 percent with three of the four percentage errors less than 10 percent.

A comprehensive energy budget was done on Lake Mead by Harbeck and others (1958) for the period from March 1952 to September 1953. Lake Mead is a large reservoir on the Colorado River between Nevada and Arizona formed by Hoover Dam (fig. 1.1). The surface area of Lake Mead at total capacity during flood-control operation was 158,000 acres. Although investigators did not specifically compare the energy-budget method estimates with estimates from the same version of the USWB method discussed in this report, table 23 of the report by Harbeck and others (1958) contains all of the required information to make such comparisons. Harbeck and others (1958) compared energy-budget method estimates with estimates of evaporation calculated from the USWB method discussed in this report but with adjustments made for the change in the amount of stored energy and the amount of advected energy. Table 23 (Harbeck and others, 1958) contains the sum of the stored energy and the advected energy terms. To evaluate the USWB method as discussed in this report, the stored energy and advected energy terms were removed and the resulting estimates of evaporation from the USWB method were compared with the energy-budget method estimates. The results of this comparison showed that USWB method estimates of annual evaporation were within about 10.4 percent of energy-budget method estimates for the period from March 12, 1952, to March 2, 1953. Similarly, USWB method estimates of annual evaporation were within about 6.0 percent of energy-budget method estimates for the period from October 3, 1952, to September 28, 1953. Monthly USWB method estimates of evaporation for Lake Mead were more variable with respect to energy-budget method estimates and average differences were about 23.3 percent. However, monthly USWB estimates of evaporation were within 20 percent of energy-budget method estimates for 10 of the 19 months (about 53 percent) compared. The USWB estimates were usually greater than energy-budget method estimates in the spring and less than energy-budget method estimates in the fall. Harbeck and others (1958) computed an average annual pan coefficient of 0.70 for Lake Mead for Class A pan data collected in Boulder City, Nevada. From 1941 to 1953, Harbeck and others (1958) were able to back-calculate estimates of annual evaporation from Lake Mead using the USWB method from meteorological data. The USWB method estimates that were adjusted for the change in the amount of stored energy and the amount of advected energy were compared with the historical annual Class A pan data collected in Boulder City and adjusted with the 0.70-pan coefficient. Differences between these two estimates averaged about 6.1 percent and were less than 10 percent for all 13 years. The evaporation pan estimate was lower than the adjusted USWB method estimate for 12 of the 13 years. If a published pan coefficient of 0.60 from Kohler and others (1959) was used instead of the energy-budget determined pan coefficient of 0.70, the differences between the two estimates averaged about 19.1 percent and ranged from about 11.3 percent to about 22.2 percent, with evaporation pan estimates lower than adjusted USWB estimates for all 13 years. The differences between the two methods were less than 20 percent for 7 of the 13 years or 54 percent.

Stephens and Stewart (1963) compared nine different methods of estimating Class A pan evaporation and determined that the USWB method ranked the best for stations in Florida. The authors did not compare method estimates in terms of percentage errors, but evaluated the nine methods by comparing the coefficients of determination and the slope and intercept terms of linear regression equations in which the estimates from the nine different methods were the independent variables and the measured pan data were the dependent variables.

Pretty Lake is a 184-acre natural lake in Indiana of glacial origin with a maximum depth of about 82 ft and an average depth of about 25.6 ft (fig. 1.1). Results of a comprehensive energy budget on Pretty Lake showed that during open-water periods, energy-budget method estimates compared well with estimates of evaporation from Class A pan data and application of a 0.76-pan coefficient appropriate for the region and with computed pan evaporation estimates from the USWB method (Ficke, 1972). During 1963, 1964, and 1965, evaporation estimates from Class A pan data were within 16.7, 7.5, and 3.2 percent, respectively, of energy-budget method estimates for open-water periods of 106–211 days. Similarly, USWB method estimates were within 7.0, 6.1, and 1.1 percent, respectively, of energy-budget method estimates for the same open-water periods. For time periods less than 1 month, errors between energy-budget method estimates and evaporation estimates from Class A pan data and the USWB method were greater than time periods of 106–211 days. Evaporation pan and USWB method estimates were usually greater than energy-budget method estimates in the spring and were less than energy-budget method estimates in the fall.

Lake Starr is a 134-acre seepage lake in central Florida with a maximum depth of about 32 ft (fig. 1.1). Results of a comprehensive energy budget on Lake Starr showed that from December 1996 through November 1997 energy-budget method estimates compared well with estimates of evaporation from Class A pan data collected at Lake Alfred, a nearby National Weather Service site (Swancar and others, 2000). During the study period, energy-budget method estimates were 56.47 in., and pan estimates were 59.44 in. after application of the published annual pan coefficient for the area of 0.74 (Swancar and others, 2000). Therefore, Class A pan estimates of annual evaporation were within 5.3 percent of energy-budget method estimates. Monthly Class A pan estimates of evaporation for the year averaged about 9.4 percent of monthly energy-budget method estimates and were within 10 percent of monthly energy-budget method estimates for 9 of the 12 months and within 20 percent of energy-budget method estimates for 11 of the 12 months.

Appendix 2—Summary of Equations and Computational Steps of the Hamon and U.S. Weather Bureau Methods of Estimating Reservoir Evaporation

Hamon Method

The Hamon method for estimation of evaporation from open water is thoroughly discussed by Hamon (1961). A summary of the method as envisioned for the general application for estimating evaporation from five Texas reservoirs is provided to document the computation of evaporation and comparison to pan evaporation discussed in this report.

The computation of reservoir evaporation from the unmodified (steps 1–7) and modified (steps 1–8) Hamon methods are dependent in part on the maximum number of daylight hours for a given latitude and Julian day, which are based on equations summarized by Shuttleworth (1993). The enumerated computation steps are as follows:

(1) Calculate the solar declination with the equation:

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.405\right) \quad (2.1)$$

where

- δ is the solar declination, in radians;
- *sin* is the sine function;
- π is the dimensionless constant pi (equal to 3.14); and
- J is the Julian day.

(2) Calculate the sunset hour angle. The latitude is positive for the northern hemisphere.

$$\omega = \arccos\left(-\tan\phi \tan\delta\right) \quad (2.2)$$

where

- ω is the sunset hour angle, in radians;
- *arccos* is the arc cosine function;
- *tan* is the tangent function;
- ϕ is the latitude of the reservoir, in decimal degrees; and
- δ is the solar declination, in radians.

(3) Calculate the maximum possible daylight hours. As a reference to verify computer code and formulas in spreadsheets, the maximum number of daylight hours for April 15 (J=105) at latitude 30 degrees in the northern hemisphere is 12.7 hours.

$$D = \frac{24}{\pi}\omega \quad (2.3)$$

where

- D is the maximum possible daylight hours,
- π is the dimensionless constant pi; and
- ω is the sunset hour angle, in radians.

(4) Calculate the saturation vapor pressure with the equation:

$$e_s = 0.6108 \exp\left(\frac{17.27 T_a}{237.3 + T_a}\right) \quad (2.4)$$

where

- e_s is the saturation vapor pressure, in kilopascals;
- *exp* is the exponential function; and
- T_a is the average daily air temperature, in degrees Celsius.

(5) Convert average daily air temperature from degrees Celsius to degrees Kelvin with the equation:

$$T_a\left[Kelvin\right] = T_a\left[Celsius\right] + 273.15 \quad (2.5)$$

where

- T_a is the average daily air temperature, in degrees Kelvin or Celsius.

(6) Calculate the saturation vapor density from the ideal gas law with the equation:

$$SVD = 2{,}166.74 \frac{(e_s)}{(T_a)} \quad (2.6)$$

where

- *SVD* is the saturation vapor density, in grams per cubic meter;
- e_s is the saturation vapor pressure, in kilopascals; and
- T_a is the average daily air temperature, in degrees Kelvin.

(7) For the unmodified version of the Hamon method, compute the amount of reservoir evaporation from the equation:

$$E = 0.55\left(\frac{D}{12}\right)^2\left(\frac{SVD}{100}\right) \quad (2.7)$$

where

- E is the amount of reservoir evaporation, in inches per day,
- D is the maximum possible daylight hours, and
- *SVD* is the saturation vapor density, in grams per cubic meter.

Do not apply the monthly Texas Water Development Board pan coefficient (Tschirhart and Rodriguez, 1998) for a particular reservoir listed in appendix tables 3.1–3.5 to the result of equation 2.7.

(8) For the modified version of the Hamon method, compute the amount of reservoir evaporation from the equation:

$$E = (HM_c)(P_c)(0.55)\left(\frac{D}{12}\right)^2\left(\frac{SVD}{100}\right) \qquad (2.8)$$

where

- E is the amount of reservoir evaporation, in inches per day;
- HM_c is the monthly Hamon coefficient for a reservoir in appendix table 2.1; and
- P_c is the monthly Texas Water Development Board pan coefficient (Tschirhart and Rodriguez, 1998) for a reservoir listed in appendix tables 3.1–3.5;
- D is the maximum possible daylight hours, and
- SVD is the saturation vapor density, in grams per cubic meter.

Multiplying the result of step 7 (equation 2.7) by HM_c predicts the amount of evaporation from the Class A pan. Further multiplication by P_c calculates the amount of reservoir evaporation from the predicted amount of Class A pan evaporation.

U.S. Weather Bureau Method

A method to estimate average daily lake evaporation was published as equation 10 in a U.S. Weather Bureau (USWB) research paper (Kohler and others, 1955, p. 14) and is based directly on the Penman equation. The Penman approach was applied to daily Class A evaporation pan data from stations throughout the United States to empirically derive coefficients and to estimate the amount of average daily lake evaporation from air temperature, relative humidity, wind speed, and solar radiation data. The USWB method assumes that the change in the amount of stored energy and the amount of advected energy are negligible.

The computations of reservoir evaporation from the unmodified (steps 1–8) and modified (steps 1–9) USWB method shown in this section are adapted from Linsley and others (1982). Other references are needed and given as appropriate.

(1) Calculate the complement of relative humidity with the equation:

$$X = 1.00 - \left(\frac{f}{100}\right) \qquad (2.9)$$

where

- X is the complement of relative humidity, dimensionless; and
- f is the average daily relative humidity, in percent.

Appendix 2.1. Summary of monthly coefficients for modified Hamon and U.S. Weather Bureau methods to estimate Class A pan evaporation at five Texas reservoirs.

[USWB, U.S. Weather Bureau; p-values less than 0.05 except for the December USWB coefficient for Hords Creek Lake, which had a p-value less than 0.10]

Reservoir	Monthly coefficients[1]	January	February	March	April	May	June	July	August	September	October	November	December
Benbrook Lake	Hamon	3.56	3.15	2.75	2.18	1.55	1.47	1.45	1.62	1.80	2.24	2.78	3.51
	USWB	1.70	1.57	1.61	1.44	1.27	1.26	1.30	1.39	1.60	1.60	1.60	1.64
Canyon Lake	Hamon	2.82	2.58	2.20	2.13	1.69	1.78	1.60	1.80	1.80	2.20	2.40	2.75
	USWB	1.74	1.70	1.61	1.61	1.49	1.60	1.53	1.63	1.63	1.79	1.60	1.59
Granger Lake	Hamon	3.09	3.09	2.58	2.40	1.76	1.62	1.51	1.73	1.80	1.93	2.29	3.09
	USWB	1.53	1.67	1.60	1.49	1.40	1.37	1.31	1.34	1.44	1.29	1.37	1.51
Hords Creek Lake	Hamon	5.20	4.00	3.47	2.93	2.09	1.95	1.78	1.96	2.24	2.73	3.71	4.65
	USWB	1.77	1.49	1.61	1.49	1.51	1.50	1.43	1.47	1.57	1.49	1.69	1.54
Sam Rayburn Lake	Hamon	2.16	2.13	2.11	1.84	1.56	1.33	1.25	1.40	1.45	1.71	1.80	2.16
	USWB	1.47	1.41	1.43	1.46	1.37	1.37	1.39	1.43	1.46	1.37	1.36	1.63

[1]Hamon and USWB coefficients are the values for the variables HM_c and $USWB_c$ to compute the amount of evaporation with the modified forms of the respective methods.

(2) Calculate the dewpoint temperature with the equation:

$$T_d = T_a - \begin{bmatrix} (14.55 + 0.114T_a)X + \left[(2.5 + 0.007T_a)X\right]^3 \\ +(15.9 + 0.117T_a)X^{14} \end{bmatrix} \quad (2.10)$$

where

- T_d is the dewpoint temperature, in degrees Celsius;
- T_a is the average daily air temperature, in degrees Celsius; and
- X is the complement of relative humidity, dimensionless.

(3) Calculate the following dimensionless ratio:

$$\frac{\Delta}{\Delta+\gamma} = \left[1 + \frac{0.66}{(0.00815T_a + 0.8912)^7}\right]^{-1} \quad (2.11)$$

where

- Δ is the gradient of saturated vapor pressure; and
- γ is the psychrometric constant; and
- T_a is the average daily air temperature, in degrees Celsius.

(4) Calculate the following dimensionless ratio by subtracting the result of step 3 from unity with the equation:

$$\frac{\gamma}{\Delta+\gamma} = 1 - \frac{\Delta}{\Delta+\gamma} \quad (2.12)$$

(5) Calculate effective net radiation with the equation:

$$Q_n = 0.00714Q_s + 0.00000526Q_s(T_a + 17.8)^{1.87} + 0.00000394Q_s^2 - 0.00000000239Q_s^2(T_a - 7.2)^2 - 1.02 \quad (2.13)$$

where

- Q_n is the effective net radiation, in millimeters of evaporation per day; and
- Q_s daily solar radiation, in calories per square centimeter; and
- T_a is the average daily air temperature, in degrees Celsius.

Remote Automatic Weather Stations (RAWS) in Texas report Q_s in kilowatt-hours per square meter per day. To convert to Q_s in calories per square centimeter to use in the equation 2.13 multiply the Q_s reported by the RAWS station by 86.011.

(6) Calculate the vapor pressure difference with the equation (Lamoreau, 1962):

$$e_s - e_a = 33.86\left[(0.00738T_a + 0.8072)^8 - (0.00738T_d + 0.8072)^8\right] \quad (2.14)$$

where

- e_s is the saturation vapor pressure, in millibars; and
- e_a is the vapor pressure at the temperature of the air, in millibars;
- T_a is the average daily air temperature, in degrees Celsius; and
- T_d is the dewpoint temperature, in degrees Celsius.

(7) Compute the amount of evaporation from a Class A pan with the equation (Kohler and others, 1955):

$$E_a = (e_s - e_a)^{0.88}(0.42 + 0.0029v_p) \quad (2.15)$$

where

- E_a is the amount of evaporation from a Class A pan, in millimeters per day;
- e_s is the saturation vapor pressure, in millibars;
- e_a is the vapor pressure at the temperature of the air, in millibars; and
- v_p is the average wind speed, in kilometers per day.

(8) For the unmodified version of the USWB method, compute the amount of reservoir evaporation from the equation (Kohler and others, 1955):

$$E = 0.7\left[\frac{\Delta}{\Delta+\gamma}Q_n + \frac{\gamma}{\Delta+\gamma}E_a\right] \quad (2.16)$$

where

- E is the amount of reservoir evaporation, in millimeters per day;
- Δ is the gradient of saturated vapor pressure;
- γ is the psychrometric constant;
- Q_n is the effective net radiation, in millimeters of evaporation per day; and
- E_a is the amount of evaporation from a Class A pan, in millimeters per day.

To convert from millimeters per day to inches per day divide the result from step 8 (equation 2.16) by 25.4. Do not apply the monthly Texas Water Development Board pan coefficient (Tschirhart and Rodriguez, 1998) for a particular reservoir listed in appendix tables 3.1–3.5 to the result of equation 2.16.

(9) For the modified version of the USWB method, compute the amount of reservoir evaporation from the equation:

$$E = (USWB_c)(P_c)(0.7)\left[\frac{\Delta}{\Delta+\gamma}Q_n + \frac{\gamma}{\Delta+\gamma}E_a\right] \qquad (2.17)$$

where

- E is the amount of reservoir evaporation, in millimeters per day;
- $USWB_c$ is the monthly USWB coefficient for a reservoir in appendix table 2.1; and
- P_c is the monthly Texas Water Development Board pan coefficient (Tschirhart and Rodriguez, 1998) for a reservoir listed in appendix tables 3.1–3.5;
- Δ is the gradient of saturated vapor pressure;
- γ is the psychrometric constant;
- Q_n is the effective net radiation, in millimeters of evaporation per day; and
- E_a is the amount of evaporation from a Class A pan, in millimeters per day.

To convert from millimeters per day to inches per day divide the result from step 9 (equation 2.17) by 25.4. Multiplying the result of step 8 (equation 2.16) by $USWB_c$ predicts the amount of evaporation from the Class A pan. Further multiplication by P_c calculates the amount of reservoir evaporation from the predicted amount of Class A pan evaporation.

Appendix 3—Published Monthly Class A Pan Evaporation Tables for Five U.S. Army Corps of Engineers Reservoirs in Texas

The published monthly Class A pan data for the five Texas reservoirs discussed in this report are included in appendix tables 3.1–3.5 for reference. The data are the monthly Class A pan data (not adjusted with pan coefficients) reported by the U.S. Army Corps of Engineers (USACE) at the five reservoirs to the National Oceanic and Atmospheric Administration and published in annual summaries (National Oceanic and Atmospheric Administration, 1953–2010).

The Texas Water Development Board (TWDB) monthly pan coefficients (P_c) for the five Texas reservoirs (Tschirhart and Rodriguez, 1998) also are included for reference at the bottom of appendix tables 3.1–3.5. The monthly and spatially distributed pan coefficients are available from the TWDB website for different regions (or quadrants) of Texas (http://midgewater.twdb.state.tx.us/Evaporation/pancoef.txt). The quadrants are displayed at another TWDB website (http://midgewater.twdb.state.tx.us/Evaporation/evap.html).

Appendix 3.1. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1953–2010 for Benbrook Lake, Texas.

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1953	--	--	--	--	--	--	12.03	11.67	10.96	7.55	3.81	3.65
1954	--	6.51	8.05	9.21	8.16	14.92	16.71	16.29	12.84	7.82	4.91	4.14
1955	2.78	3.78	6.83	9.27	11.01	11.23	13.88	12.30	10.46	8.82	6.51	3.70
1956	--	4.12	8.27	9.25	12.21	14.28	17.30	17.49	13.31	9.00	5.04	4.10
1957	2.82	2.71	4.65	4.70	6.46	9.53	14.11	14.23	8.35	5.19	2.75	3.98
1958	2.75	2.99	3.83	6.27	8.39	11.91	14.02	12.35	7.69	4.93	4.47	2.91
1959	2.67	3.04	8.75	8.06	8.90	9.95	10.37	12.57	9.37	6.06	3.92	3.29
1960	2.52	3.70	5.64	8.11	10.76	11.70	11.68	10.76	9.51	6.15	4.45	2.24
1961	2.13	3.87	7.01	8.47	9.80	9.42	10.13	10.84	10.36	6.18	3.41	2.65
1962	2.29	5.22	7.31	6.41	11.98	8.71	11.32	11.55	7.00	5.83	3.44	2.33
1963	--	3.99	7.25	8.52	8.40	11.12	13.40	13.02	8.44	8.49	4.72	2.49
1964	3.19	3.32	6.50	7.18	7.87	11.25	14.85	11.74	8.44	5.77	3.73	3.00
1965	3.19	3.30	4.31	7.32	5.90	9.24	13.11	11.34	10.18	5.57	3.36	2.22
1966	2.18	2.75	6.57	7.19	7.02	9.54	11.04	8.97	5.69	5.86	4.90	2.70
1967	3.91	4.44	7.64	7.36	9.58	10.00	10.94	11.87	6.44	6.70	3.30	2.70
1968	1.34	2.81	4.66	6.14	7.06	8.60	10.35	11.15	7.61	6.38	3.86	3.23
1969	2.91	3.26	4.61	6.66	7.33	11.20	13.27	9.92	6.45	5.68	3.37	2.44
1970	1.87	3.45	4.35	6.06	7.99	9.46	11.43	11.75	7.64	5.59	4.62	4.09
1971	3.48	4.51	7.64	8.39	9.15	11.92	13.11	7.64	7.56	5.44	4.26	3.09
1972	3.11	4.13	7.93	9.36	8.58	11.09	11.67	10.73	7.35	5.78	3.18	2.23
1973	--	2.80	6.69	5.53	9.06	8.81	10.53	10.29	6.99	5.25	3.70	3.65
1974	--	4.75	6.45	8.36	9.04	11.18	12.87	8.65	5.19	5.10	2.97	2.38
1975	3.19	3.29	5.14	6.42	6.59	9.53	9.76	9.29	9.03	7.27	5.19	--
1976	--	5.95	6.86	6.37	7.74	8.97	8.61	11.12	6.61	4.51	3.80	--
1977	--	5.16	7.55	7.74	7.70	11.75	14.34	11.39	11.10	7.89	4.50	--
1978	--	--	7.74	8.77	9.55	13.22	16.68	12.85	8.30	8.92	3.57	--
1979	--	--	5.94	6.55	7.88	10.13	11.21	9.67	8.27	8.81	3.85	--
1980	--	--	--	8.21	7.94	14.24	17.22	14.53	10.89	7.70	4.50	--
1981	--	--	6.02	7.40	8.40	8.66	12.26	11.83	8.14	5.20	4.17	3.51
1982	--	--	5.68	6.58	7.72	9.12	10.78	11.30	9.85	6.90	4.37	3.63
1983	2.77	3.42	6.03	7.81	8.80	9.17	10.96	10.58	9.35	6.34	4.72	
1984	--	--	6.50	8.60	10.73	12.84	13.63	12.41	10.07	5.33	4.21	3.21
1985	--	--	5.24	7.34	8.95	10.97	12.00	13.98	10.03	5.23	3.28	--
1986	--	--	7.45	7.14	8.06	8.95	14.21	10.93	7.85	5.40	3.41	--
1987	--	3.27	5.58	9.00	--	8.40	11.39	13.51	--	7.70	4.03	--
1988	--	--	8.95	9.09	10.62	10.13	12.30	12.11	8.97	5.69	5.18	3.15
1989	--	--	--	8.61	9.41	9.46	10.23	10.00	8.27	8.13	5.09	--
1990	--	--	4.64	6.53	9.47	12.49	11.78	10.29	7.34	6.59	4.30	--
1991	--	--	7.04	6.71	6.00	7.26	12.58	9.17	6.09	7.14	--	--
1992	--	3.49	5.66	6.77	6.98	8.97	12.14	9.14	8.34	6.57	4.01	2.75
1993	--	--	5.43	7.07	7.56	9.39	15.28	12.84	9.31	5.42	--	3.55

Appendix 3.1. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1953–2010 for Benbrook Lake, Texas.—Continued

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1994	--	--	5.44	7.86	6.58	10.78	12.25	11.83	7.18	5.81	3.63	2.36
1995	--	4.21	4.89	6.18	7.53	9.73	11.89	10.17	7.01	7.79	5.04	--
1996	--	--	7.06	8.86	12.54	10.93	12.55	8.83	6.27	5.91	4.00	--
1997	--	3.51	5.04	6.17	7.63	8.80	10.89	10.23	8.93	5.87	3.14	3.73
1998	2.82	2.45		8.37	10.57	13.50	15.27	10.74	8.29	6.01	4.05	2.85
1999	--	4.41	4.39	--	7.59	--	11.15	13.26	9.30	6.75	4.83	--
2000	--	4.96	5.94	--	--	8.01	11.75	--	10.62	--	--	--
2001	--	4.07	--	--	9.33	10.28	12.34	10.52	6.25	5.95	4.38	2.90
2002	3.23	4.10	5.60	6.33	7.61	8.09	9.05	9.87	7.96	4.01	3.76	2.68
2003	2.85	--	4.87	7.70	7.55	7.61	11.00	9.90	6.00	5.00	4.38	4.52
2004	3.18	2.69	6.24	5.60	7.45	7.86	8.25	8.97	7.32	5.47	3.40	3.61
2005	--	3.81	5.68	7.20	6.74	8.53	9.30	8.60	9.67	7.50	6.34	5.02
2006	6.07	5.19	7.57	7.96	9.12	10.45	10.38	12.07	8.07	5.82	3.89	--
2007	--	3.43	5.14	5.72	5.39	7.28	7.64	8.93	6.79	6.03	4.47	3.08
2008	3.40	4.60	6.38	7.03	7.89	10.56	12.28	9.48	6.22	6.12	4.99	3.81
2009	--	5.12	6.72	7.10	6.62	8.77	9.84	10.44	5.73	4.04	3.72	--
2010	--	--	6.17	7.11	7.81	9.60	8.95	10.35	7.32	--	4.35	--
Monthly average	2.94	3.91	6.22	7.40	8.41	10.17	12.07	11.20	8.33	6.32	4.17	3.20
Number of samples	24	40	53	54	55	56	58	57	57	56	55	38
TWDB monthly pan coefficients (P_c)	0.73	0.70	0.69	0.67	0.60	0.67	0.69	0.70	0.73	0.77	0.80	0.77

Appendix 3.2. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1961–2010 for Canyon Lake, Texas.

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1961	--	--	--	--	--	--	9.05	9.25	--	5.06	3.20	2.48
1962	2.16	4.69	5.31	6.08	10.25	8.13	12.25	12.91	6.91	6.18	4.34	2.35
1963	2.63	4.20	6.23	8.08	8.53	10.28	12.07	11.76	8.87	7.67	4.08	2.45
1964	3.67	4.09	5.91	6.54	7.96	10.80	12.26	11.60	8.05	6.99	4.23	2.95
1965	3.99	3.15	4.66	5.97	6.14	9.66	12.60	11.25	10.08	5.48	3.42	2.46
1966	2.38	2.90	5.17	6.85	6.77	9.34	11.55	9.08	7.29	6.43	5.67	3.35
1967	3.51	4.28	7.31	7.48	9.67	11.65	12.54	11.13	6.58	6.48	3.82	2.97
1968	2.19	3.19	5.21	5.19	6.92	8.00	10.02	11.35	6.70	6.22	6.00	3.18
1969	2.85	3.81	5.74	6.40	7.15	10.22	12.42	10.96	7.11	5.77	3.84	3.32
1970	2.72	3.62	4.72	5.91	7.34	8.80	10.63	10.45	7.57	5.47	5.56	4.09
1971	4.05	5.66	8.32	8.16	9.36	10.24	12.35	7.54	6.80	5.25	4.69	3.12
1972	3.00	4.45	6.93	8.29	8.34	8.60	9.55	8.61	7.46	6.23	3.60	2.59
1973	--	3.21	5.80	5.19	8.27	7.82	9.64	9.32	6.34	4.81	3.90	4.24
1974	2.85	4.96	5.68	7.90	8.24	9.68	11.89	8.30	5.75	5.15	3.11	2.51
1975	3.36	4.40	5.56	5.94	6.21	8.42	8.53	8.36	6.92	6.99	4.78	3.19
1976	--	5.14	5.57	5.64	7.68	8.19	7.95	9.49	6.54	5.29	2.98	--
1977	--	4.88	5.71	6.71	5.11	9.12	11.08	10.40	8.76	7.05	4.64	3.93
1978	--	--	6.59	6.33	8.35	9.92	12.16	9.58	5.43	5.77	3.01	2.68
1979	--	--	5.37	5.58	6.74	8.26	9.32	8.30	7.17	7.35	4.34	3.00
1980	2.90	3.93	6.26	7.93	6.84	10.69	12.64	10.19	6.76	5.27	4.08	2.73
1981	3.37	2.76	5.58	5.59	7.56	7.23	9.63	9.88	7.76	5.25	3.87	3.62
1982	--	--	4.32	5.73	6.73	9.02	12.63	10.81	9.08	5.77	3.73	3.37
1983	2.68	3.56	5.16	7.84	7.56	7.45	8.93	9.15	7.31	4.60	4.53	--
1984	--	4.56	6.85	9.88	10.01	10.40	--	--	--	5.07	4.39	2.75
1985	2.81	2.79	--	6.24	7.87	9.00	9.52	11.81	8.03	4.80	2.68	--
1986	3.50	4.32	6.85	--	6.33	7.40	11.85	10.25	6.23	4.64	--	--
1987	--	--	5.49	8.20	--	--	--	--	--	--	--	--
1988	--	--	--	7.74	8.16	8.88	9.54	10.06	8.63	6.72	5.58	3.32
1989	3.21	--	5.43	7.05	8.70	10.14	11.36	10.86	9.77	6.92	3.81	--
1990	3.20	4.41	4.60	5.19	--	11.59	9.98	9.63	6.98	6.25	3.80	--
1991	2.44	3.59	6.75	5.51	7.31	7.77	8.48	10.20	5.84	6.73	3.52	2.16
1992	2.24	4.00	6.09	5.62	6.40	9.13	10.22	9.15	8.87	7.34	4.29	2.31
1993	2.79	3.27	5.47	6.96	7.69	--	11.09	12.35	9.22	6.78	3.49	3.28
1994	2.81	--	5.25	5.97	6.52	8.91	12.26	10.17	7.83	5.35	3.68	2.33
1995	3.36	3.25	4.48	6.43	7.29	8.49	11.20	9.68	6.93	7.36	4.19	2.97
1996	4.13	--	6.64	8.14	8.82	11.23	11.76	11.16	5.82	5.64	4.30	4.02
1997	--	3.16	4.60	5.11	7.11	7.68	10.86	10.55	8.58	5.94	4.37	3.49
1998	2.65	4.02	5.79	7.44	9.45	11.48	12.14	--	6.90	4.76	3.19	2.98
1999	--	4.24	5.53	6.97	8.48	9.46	9.81	11.78	9.96	7.51	4.86	3.57
2000	3.88	4.63	5.50	6.85	7.80	8.76	11.97	11.17	9.18	5.38	2.85	3.78
2001	3.21	2.63	3.92	5.25	7.80	9.56	11.30	11.69	5.96	5.50	3.31	2.01

Appendix 3.2. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1961–2010 for Canyon Lake, Texas.—Continued

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
2002	2.77	3.99	4.88	5.70	8.04	9.29	5.67	8.51	6.24	--	3.65	3.11
2003	3.10	3.17	4.62	6.87	8.26	9.28	7.78	9.04	6.89	5.17	3.86	4.50
2004	3.81	3.26	3.65	4.13	6.69	8.71	8.84	8.76	6.66	4.44	3.84	--
2005	3.30	2.57	5.47	7.03	6.74	10.00	9.41	10.00	7.73	5.69	5.06	3.44
2006	4.81	4.68	5.52	9.63	10.14	11.62	10.05	10.99	8.13	6.01	3.97	2.32
2007	--	3.00	4.20	5.57	5.97	7.79	6.00	8.31	5.90	6.56	3.43	3.41
2008	2.89	4.41	5.71	6.78	9.50	12.29	10.45	8.03	8.12	7.24	4.99	4.04
2009	3.79	5.01	6.19	8.37	8.45	11.22	12.55	12.32	--	--	3.51	2.82
2010	--	--	6.33	5.91	8.01	9.82	8.77	11.69	6.85	7.33	4.29	3.24
Monthly average	3.14	3.90	5.59	6.66	7.77	9.39	10.51	10.17	7.45	5.99	4.05	3.11
Number of samples	36	40	47	48	47	47	48	47	46	47	48	42
TWDB monthly pan coefficients (P_c)	0.72	0.70	0.70	0.69	0.64	0.69	0.70	0.70	0.72	0.75	0.76	0.75

Appendix 3.3. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1980–2010 for Granger Lake, Texas.

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1980	--	--	--	--	--	9.70	12.45	10.51	7.49	5.44	3.77	--
1981	2.92	3.19	4.83	4.67	7.20	--	8.51	8.31	6.71	4.40	3.38	--
1982	--	--	4.71	4.90	5.95	7.50	9.97	11.55	8.33	5.06	2.83	3.21
1983	2.30	3.11	5.20	7.22	7.40	7.25	9.27	8.82	6.85	5.20	3.95	--
1984	--	5.16	6.78	8.78	9.89	10.31	11.22	--	8.70	3.92	3.73	2.82
1985	--	--	4.07	6.04	8.34	9.49	10.21	11.91	8.68	4.53	2.76	--
1986	3.43	4.56	6.77	6.70	6.24	7.59	11.76	9.68	6.05	4.48	3.31	2.03
1987	--	3.46	5.43	8.19	6.00	7.79	9.21	10.41	7.50	6.83	4.39	--
1988	--	4.69	6.36	7.26	8.65	9.42	9.68	10.68	9.06	6.96	5.60	3.21
1989	2.68	--	5.79	7.02	8.06	8.16	9.76	8.89	8.52	7.18	4.48	--
1990	3.75	4.04	4.07	6.20	8.92	11.67	9.26	10.03	6.84	5.98	4.04	--
1991	--	3.88	6.69	5.08	6.55	7.92	9.09	7.57	5.37	5.79	--	2.31
1992	--	3.63	5.11	5.45	6.23	8.22	9.47	7.87	7.63	6.73	4.17	2.12
1993	--	3.43	5.36	6.10	6.75	7.60	10.35	8.86	7.14	5.34	--	--
1994	--	--	5.14	5.68	6.06	8.99	11.74	8.09	6.88	4.68	3.40	2.45
1995	--	--	4.14	6.19	7.15	8.60	10.19	8.09	6.95	7.48	4.31	3.58
1996	--	7.62	--	9.94	10.91	9.30	11.69	9.40	6.53	5.37	3.51	--
1997	--	3.05	4.74	6.14	6.98	7.70	10.27	9.83	8.80	5.49	3.50	--
1998	2.91	4.47	6.75	7.83	8.85	11.21	12.29	9.88	7.58	4.20	2.85	4.21
1999	--	4.34	5.30	7.00	6.75	7.84	8.67	11.43	10.29	6.67	4.04	3.60
2000	4.64	4.48	5.97	8.09	7.84	8.04	12.56	12.80	10.42	5.21	3.15	2.84
2001	2.72	3.21	3.84	5.82	8.82	8.69	10.41	10.97	6.09	5.16	3.56	2.78
2002	3.58	4.40	5.87	6.57	8.73	9.84	8.30	9.67	8.19	4.29	3.70	3.19
2003	3.00	3.10	4.45	7.41	7.48	9.21	9.29	10.21	6.58	5.65	3.90	3.80
2004	2.25	--	4.93	--	7.42	7.74	9.24	9.13	7.01	4.42	3.15	--
2005	--	2.34	5.90	8.03	7.49	10.00	9.90	9.20	9.05	5.88	4.91	4.40
2006	5.49	3.82	6.37	8.79	11.18	10.43	10.51	11.78	8.73	5.26	4.06	3.09
2007	--	5.51	5.29	6.12	6.74	6.96	6.16	8.92	6.23	5.65	4.04	3.24
2008	3.38	5.53	6.00	7.97	8.36	11.80	11.01	10.34	8.58	6.20	4.33	3.90
2009	4.45	5.63	6.33	8.73	8.66	11.32	--	--	6.13	4.19	2.76	3.27
2010	--	3.25	7.92	6.26	8.24	8.25	8.28	11.05	6.58	6.03	4.29	4.07
Monthly average	3.39	4.16	5.52	6.90	7.79	8.95	10.02	9.86	7.60	5.47	3.79	3.21
Number of samples	14	24	29	29	30	30	30	29	31	31	29	20
TWDB monthly pan coefficients (P_c)	0.73	0.70	0.69	0.67	0.60	0.67	0.69	0.70	0.73	0.77	0.80	0.77

Appendix 3.4. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1953–2010 for Hords Creek Lake, Texas.

[--, indicates data not available; P_e, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1953	--	--	--	--	--	--	13.22	11.45	11.22	7.00	4.32	--
1954	--	7.82	9.19	9.65	9.38	13.28	16.85	16.64	14.02	9.26	6.91	--
1955	--	4.87	9.01	12.91	13.74	13.15	13.51	12.58	9.87	8.09	6.17	4.88
1956	--	--	9.47	10.92	13.11	15.42	17.79	16.30	12.84	9.41	5.78	4.94
1957	--	3.13	7.26	8.21	7.51	10.67	13.71	14.19	9.92	6.27	3.53	4.57
1958	3.10	--	3.61	7.66	9.75	12.94	15.36	13.32	7.04	4.68	4.67	3.56
1959	3.45	3.11	10.04	10.30	9.57	10.96	9.83	11.76	10.56	6.60	3.68	3.68
1960	3.29	4.90	7.00	9.70	10.47	14.99	13.51	10.81	10.67	7.09	5.42	1.91
1961	--	4.41	8.11	11.31	11.76	10.14	11.12	11.53	9.62	7.14	3.20	3.00
1962	3.44	6.27	7.82	9.02	13.17	11.45	12.47	13.75	9.05	7.88	4.53	3.24
1963	3.18	5.43	9.16	10.93	10.56	11.40	15.86	13.71	9.76	8.61	5.97	2.98
1964	5.53	4.69	8.84	10.73	11.18	13.47	15.98	14.44	8.13	6.75	4.25	4.04
1965	4.18	3.81	6.01	8.61	7.77	11.25	14.85	12.40	11.09	6.52	4.21	2.73
1966	--	3.40	7.88	9.37	8.65	12.33	13.79	10.87	6.56	6.98	5.83	4.25
1967	5.20	5.90	9.64	10.59	12.37	14.23	12.48	12.19	7.22	7.91	4.13	3.13
1968	1.87	3.01	5.36	7.75	7.94	9.07	11.30	12.11	8.96	7.73	5.26	4.09
1969	4.04	4.26	5.86	8.65	8.95	11.41	14.29	11.87	6.59	6.35	4.70	3.47
1970	--	4.01	5.26	7.63	9.76	11.89	14.69	13.41	9.96	6.09	6.62	5.27
1971	5.28	5.94	10.54	10.96	13.27	12.79	13.91	8.09	7.89	6.03	4.41	3.15
1972	3.79	5.14	9.57	10.53	9.73	12.63	12.00	9.90	8.41	7.16	3.95	4.06
1973	2.60	3.52	8.47	8.12	11.09	10.66	10.88	11.74	8.22	6.24	4.94	5.46
1974	--	6.75	7.60	12.37	11.11	14.20	14.66	10.35	6.43	5.93	3.74	3.34
1975	3.79	4.19	7.06	8.11	8.54	10.27	10.62	11.87	8.66	7.99	5.74	--
1976	--	8.01	9.71	8.28	9.39	12.31	9.60	11.38	7.17	--	--	--
1977	--	5.85	9.46	7.92	7.05	12.53	14.30	12.45	12.13	7.99	4.96	--
1978	--	--	8.80	10.82	11.74	13.02	15.82	10.52	6.70	7.27	3.69	--
1979	--	--	8.27	8.03	8.78	10.48	12.17	11.31	10.21	10.56	--	--
1980	--	--	--	11.34	9.30	12.12	16.12	13.62	9.18	6.86	--	--
1981	--	--	7.05	8.22	9.33	9.97	14.04	12.06	10.00	6.36	5.11	--
1982	--	--	7.42	9.15	9.13	10.52	11.84	12.59	9.29	7.91	6.73	--
1983	--	3.92	7.01	10.51	10.60	9.31	12.61	11.71	11.19	7.43	5.20	--
1984	--	--	7.40	12.78	13.96	14.60	13.74	12.96	10.84	5.47	5.01	--
1985	--	--	5.47	9.26	10.50	11.44	11.71	13.37	9.22	5.77	3.48	--
1986	--	--	9.10	9.02	8.71	8.57	12.74	10.52	7.35	4.99	--	--
1987	--	3.55	5.95	9.77	8.03	7.93	10.81	12.31	8.04	6.80	--	--
1988	--	--	--	10.49	11.17	10.59	10.62	10.76	8.76	7.18	--	--
1989	--	--	--	9.29	10.59	10.01	11.69	11.25	9.01	7.41	6.68	--
1990	--	5.47	6.53	6.82	9.72	14.07	10.17	9.52	6.35	6.30	4.64	--
1991	--	4.61	8.73	8.35	9.27	10.99	11.73	8.85	5.93	7.32	3.85	--
1992	--	--	7.35	7.76	6.96	10.82	11.41	9.78	8.96	7.41	--	--
1993	--	4.19	--	9.16	9.79	9.83	14.09	12.29	8.55	6.44	--	3.86

Appendix 3.4. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1953–2010 for Hords Creek Lake, Texas.—Continued

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1994	--	--	6.43	8.03	7.65	12.13	13.44	11.73	7.73	5.76	4.13	2.47
1995	--	4.20	6.20	8.21	12.75	12.56	13.50	11.16	7.44	8.71	7.73	--
1996	--	--	--	11.41	15.56	10.64	10.51	9.67	7.07	6.24	4.42	--
1997	--	--	6.98	8.76	9.98	11.20	12.20	10.62	9.69	7.44	4.81	--
1998	--	3.68	--	10.37	12.34	12.33	13.46	9.36	9.23	8.03	3.82	--
1999	--	6.06	6.03	10.16	7.95	9.77	12.29	13.26	10.49	7.77	5.31	5.57
2000	--	6.37	8.37	9.43	13.05	12.25	13.64	13.42	10.01	6.05	3.88	--
2001	--	4.71	3.81	6.70	9.76	10.83	13.27	11.27	7.62	6.80	4.62	--
2002	5.39	--	7.63	7.67	11.73	11.35	9.36	13.02	9.37	5.52	5.06	--
2003	--	--	6.86	9.55	9.37	10.64	11.73	11.74	7.42	7.64	4.50	--
2004	--	--	6.02	6.71	9.06	9.51	11.72	9.14	7.79	4.43	4.45	--
2005	--	3.28	7.32	9.24	8.00	9.38	10.53	8.14	9.47	7.12	6.74	--
2006	8.31	--	10.30	11.50	12.42	12.87	11.85	12.04	8.87	7.74	6.12	--
2007	3.24	5.40	6.55	8.11	7.83	9.77	8.03	10.96	7.59	8.31	5.52	5.12
2008	4.46	6.31	7.92	9.03	12.16	16.21	14.56	--	10.58	7.67	7.75	5.26
2009	6.38	7.24	9.59	11.04	10.24	--	11.39	13.20	--	6.12	4.98	--
2010	--	--	7.70	9.32	11.04	11.66	9.74	13.19	9.15	7.78	6.60	--
Monthly average	4.24	4.93	7.62	9.41	10.25	11.62	12.74	11.83	8.97	7.06	5.03	3.92
Number of samples	19	36	51	57	57	56	58	57	57	57	50	25
TWDB monthly pan coefficients (P_c)	0.72	0.69	0.68	0.67	0.61	0.67	0.68	0.69	0.72	0.75	0.77	0.75

Appendix 3.5. Monthly Class A pan evaporation, in inches, from National Oceanic and Atmospheric Administration, Climatological Data, Annual Summary, Texas, 1968–2010 for Sam Rayburn Lake, Texas.

[--, indicates data not available; P_c, Texas Water Development Board (TWDB) monthly pan coefficients in computation steps of appendix 2 are included in the table for reference and are available at http://midgewater.twdb.state.tx.us/Evaporation/evap2.html]

Year	January	February	March	April	May	June	July	August	September	October	November	December
1968	2.12	2.75	4.42	5.45	7.50	6.72	7.86	7.64	6.12	5.38	4.07	3.14
1969	2.75	3.08	5.50	5.91	6.75	8.40	8.55	8.17	6.73	5.87	3.53	2.47
1970	2.50	3.38	4.24	5.78	7.19	7.95	8.40	8.08	5.95	4.98	3.63	3.04
1971	2.56	4.20	5.15	6.71	7.15	8.26	8.91	7.05	5.54	5.16	4.71	3.43
1972	3.76	3.70	5.85	6.67	7.84	8.18	8.16	7.32	6.10	5.34	3.71	2.53
1973	2.65	3.52	4.90	5.74	8.09	8.02	8.82	7.25	5.67	5.67	4.91	4.03
1974	2.97	4.71	6.94	7.66	7.23	8.94	8.17	7.48	5.57	5.09	4.10	3.32
1975	3.46	3.23	5.21	5.93	6.47	7.73	7.43	8.11	5.88	5.25	4.41	3.32
1976	--	--	4.65	6.71	7.24	7.81	7.53	8.12	6.73	4.77	3.20	2.67
1977	--	3.87	5.16	6.51	7.96	8.08	9.47	7.54	6.24	5.46	3.53	--
1978	--	--	5.10	6.80	7.19	9.02	9.14	9.23	6.02	5.44	3.36	--
1979	--	--	5.33	5.27	7.00	7.92	7.46	7.31	6.23	5.58	3.72	--
1980	2.48	--	5.44	5.86	6.64	9.02	9.66	9.11	6.80	5.33	2.72	2.52
1981	--	2.88	4.72	5.74	7.19	--	7.76	8.03	6.12	4.80	2.99	2.85
1982	--	3.00	4.79	4.58	6.71	7.30	7.76	7.29	6.86	4.94	2.80	3.74
1983	2.33	2.93	5.12	5.88	7.20	6.79	7.61	6.98	5.69	4.43	3.39	--
1984	--	4.17	4.64	6.50	7.72	7.00	8.02	7.36	6.25	3.83	3.06	2.44
1985	--	--	4.59	6.11	7.64	7.97	7.77	7.95	7.03	4.78	2.85	--
1986	--	3.13	5.52	6.38	5.95	6.69	8.50	7.79	5.15	4.11	2.26	1.83
1987	--	2.82	4.73	7.01	6.47	7.41	7.22	8.10	5.96	5.75	3.34	--
1988	--	2.81	4.98	6.28	7.52	8.08	7.48	7.20	6.64	4.85	3.56	2.57
1989	--	--	4.91	5.87	7.28	7.39	7.15	7.23	6.73	4.95	3.26	--
1990	--	3.57	4.73	6.14	6.75	8.20	7.61	8.30	6.07	5.06	3.38	2.66
1991	2.36	2.42	4.17	4.81	5.48	7.42	7.76	--	5.20	4.24	2.70	2.50
1992	--	2.62	4.40	5.36	6.49	7.89	7.44	7.23	5.88	4.89	3.16	1.95
1993	2.36	2.77	4.65	5.20	5.99	6.62	8.43	8.07	6.20	4.12	2.29	3.06
1994	2.03	2.69	4.50	5.25	5.35	6.13	7.57	6.12	5.73	3.66	2.59	2.11
1995	--	2.62	4.11	5.11	6.44	7.29	7.56	5.97	5.83	4.77	2.88	1.95
1996	2.49	4.27	4.59	6.38	7.92	7.01	7.29	7.24	5.50	4.68	2.98	3.34
1997	--	2.83	4.11	5.08	6.15	6.77	8.39	7.41	6.50	4.10	2.52	--
1998	2.10	2.76	4.98	5.41	7.41	9.45	10.01	7.94	5.74	4.22	2.57	1.98
1999	--	3.39	4.23	6.15	6.94	7.25	6.99	8.82	6.54	4.92	3.23	3.33
2000	3.02	3.73	5.01	5.74	7.89	7.31	9.71	9.74	--	4.93	2.82	2.21
2001	2.50	2.56	4.04	5.51	7.80	6.12	7.47	7.13	5.36	4.59	2.93	2.76
2002	2.67	3.47	4.92	6.00	7.81	6.73	7.59	8.22	5.35	3.79	3.33	3.05
2003	--	2.89	4.40	5.77	7.25	8.30	7.51	7.67	6.08	4.59	3.50	3.38
2004	2.62	3.29	5.10	6.25	8.69	6.70	7.50	8.37	6.44	5.12	3.54	3.17
2005	2.69	2.52	5.79	6.18	7.26	8.48	7.64	7.41	7.34	4.84	3.38	2.90
2006	3.53	2.84	4.99	6.49	6.99	7.98	6.58	7.32	6.41	5.05	2.92	2.31
2007	2.49	2.92	4.76	5.43	6.44	7.08	6.49	7.78	5.40	4.87	2.90	2.28
2008	2.87	3.28	4.86	6.16	7.00	7.74	9.01	7.59	5.12	4.46	2.71	2.41
2009	2.73	3.62	4.54	6.21	7.37	8.43	8.28	6.95	4.09	4.19	2.71	--
2010	--	2.58	4.85	6.62	7.79	7.45	7.26	8.23	6.42	--	--	--
Monthly average	2.67	3.18	4.87	5.97	7.10	7.64	7.97	7.71	6.03	4.83	3.24	2.77
Number of samples	24	37	43	43	43	42	43	42	42	42	42	33
TWDB monthly pan coefficients (P_c)	0.75	0.73	0.73	0.72	0.67	0.72	0.73	0.73	0.75	0.78	0.79	0.78

Appendix 4—Regression Equations to Estimate Air Temperature, Relative Humidity, Wind Speed, and Solar Radiation at Remote Automatic Weather Stations

The Remote Automatic Weather Station (RAWS) network is a national network consisting of about 2,200 stations. About 70 stations are in Texas (http://www.raws.dri.edu/wraws/txF.html).

For each of the five reservoirs in Texas discussed in detail in this report (Benbrook Lake, Canyon Lake, Granger Lake, Hords Creek Lake, and Sam Rayburn Lake), a RAWS "base station" was selected to provide the necessary meteorological data for the Hamon and U.S. Weather Bureau (USWB) methods with missing data filled in as described in the section of the report entitled "Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas" (appendix tables 4.1–4.4).

Linear regression equations for air temperature, relative humidity, wind speed, and solar radiation were developed to estimate missing average daily values at base stations from satellite stations when estimating evaporation with unmodified and modified forms of the Hamon and USWB methods discussed in this report. For example, to estimate average daily air temperature at the Cedar Hill State Park RAWS base station for a day with missing record, input the average daily air temperature value from the Granberry satellite station into the Granberry satellite station regression equation and compute the average daily air temperature at Cedar Hill State Park. Similarly, if data were not available from the Granberry satellite station, input the average daily air temperature value from the LBJ Road satellite station into the LBJ Road satellite station regression equation and compute the average daily air temperature at Cedar Hill State Park.

Appendix 4.1. Regression equations for satellite stations to estimate average daily air temperature in degrees Celsius at base stations.

[avg_air_temp, average daily air temperature; RAWS; Remote Automatic Weather Stations; p-values for all the equations are less than 0.05]

RAWS base station[1]	RAWS satellite station[1]	Linear regression equation	Adjusted R-squared	Residual standard error (degrees Celsius)	Number of daily values used to generate regression	Percentage of days when air temperature at base station was estimated from equations
Cedar Hill State Park	Granbury	1.22 + 0.95 (avg_air_temp Granbury)	0.988	0.9	2,138	0.5
	LBJ Road	1.70 + 0.96 (avg_air_temp LBJ Road)	0.987	1.0	2,378	
Guadalupe River State Park	Balcones	1.40 + 0.94 (avg_air_temp Balcones)	0.987	0.8	2,239	2.2
Temple	Balcones	0.51 + 0.99 (avg_air_temp Balcones)	0.982	1.1	2,387	0.2
	Bastrop	-0.39 + 1.00 (avg_air_temp Bastrop)	0.976	1.2	2,431	
Coleman	Mason	-0.83 + 1.05 (avg_air_temp Mason)	0.977	1.2	2,484	5.6
	Hamby	2.91 + 0.90 (avg_air_temp Hamby)	0.976	1.2	2,088	
Woodville	Lufkin	1.76 + 0.94 (avg_air_temp Lufkin)	0.984	0.9	3,407	3.0
	Sabine South	2.30 + 0.94 (avg_air_temp Sabine South)	0.982	1.0	2,906	
	Southern Rough	1.19 + 0. 98 (avg_air_temp Southern Rough)	0.976	1.1	3,071	
						Average = 2.3

[1]RAWS stations report daily average meteorological data required for the Hamon and U.S. Weather Bureau methods discussed in this report. The RAWS base stations are intended to provide the average daily air temperature for the two methods. If the base station data are not available, the regression equations are intended to estimate average daily air temperature from RAWS satellite stations.

Appendix 4.2. Regression equations for satellite stations to estimate average daily relative humidity at base stations.

[RAWS, Remote Automatic Weather Stations; avg_humidity, average daily relative humidity; p-values for the equations are less than 0.05 except the intercept terms for Lufkin when wind direction is from the east and the west and the intercept terms for Sabine South when wind direction is from the north and east; wnd_dir, stands for wind direction and north, east, south, and west directions are defined as 315–45, 45–135, 135–225, and 225–315 degrees, respectively]

RAWS base station[1]	RAWS satellite station[1]	Linear regression equation	Adjusted R-squared	Residual standard error (percent humidity)	Number of daily values used to generate regression	Percentage of days when relative humidity at base station was estimated from equations
Cedar Hill State Park	Granbury	8.34 + 0.88 (avg_humidity Granbury)	0.773	7.4	2,105	1.8
	LBJ Road	9.61 + 0.88 (avg_humidity LBJ Road)	0.831	6.4	2,346	
Guadalupe River State Park	Balcones	1.37 + 0.99 (avg_humidity Balcones)	0.878	5.7	2,211	2.4
Temple	Balcones	2.66 + 0.95 (avg_humidity Balcones)	0.865	5.8	2,387	0.2
	Bastrop	-10.9 + 1.08 (avg_humidity Bastrop)	0.813	6.9	2,426	
Coleman	Mason	2.21 + 0.90 (avg_humidity Mason)	0.849	6.2	2,451	7.2
	Hamby	8.12 + 0.87 (avg_humidity Hamby)	0.861	5.9	2,071	
Woodville	Lufkin	-5.77 + 1.05 (avg_humidity Lufkin) when wnd_dir is from the north	0.708	8.5	940	3.8
		-0.51 + 1.00 (avg_humidity Lufkin) when wnd_dir is from the east	0.700	7.8	750	
		18.3 + 0.79 (avg_humidity Lufkin) when wnd_dir is from the south	0.513	7.0	1,323	
		-3.91 + 1.02 (avg_humidity Lufkin) when wnd_dir is from the west	0.670	8.1	373	
	Sabine South	-3.78 + 0.96 (avg_humidity Sabine South) when wnd_dir is from the north	0.603	10.1	816	0.1
		0.66 + 0.95 (avg_humidity Sabine South) when wnd_dir is from the east	0.611	8.8	636	
		27.3 + 0.65 (avg_humidity Sabine South) when wnd_dir is from the south	0.408	7.6	1,122	
		-14.9 + 1.11 (avg_humidity Sabine South) when wnd_dir is from the west	0.696	7.7	302	
						Average = 2.6

[1]RAWS stations report daily average meteorological data required for the Hamon and U.S. Weather Bureau methods discussed in this report. The RAWS base stations are intended to provide the average daily relative humidity for the two methods. If the base station data are not available, the regression equations are intended to estimate average daily relative humidity from RAWS satellite stations.

Appendix 4.3. Regression equations for satellite stations to estimate average daily wind speed in meters per second at base stations.

[RAWS, Remote Automatic Weather Stations; avg_wnd_spd, average daily wind speed; p-values for all the equations are less than 0.05]

RAWS base station[1]	RAWS satellite station[1]	Linear regression equation	Adjusted R-squared	Residual standard error (meters per second)	Number of daily values used to generate regression	Percentage of days when wind speed at base station was estimated from equations
Cedar Hill State Park	Granbury	0.15 + 0.79 (avg_wnd_spd Granbury)	0.766	0.59	2,139	0.5
	LBJ Road	0.12 + 0.97 (avg_wnd_spd LBJ Road)	0.764	0.59	2,380	
Guadalupe River State Park	Balcones	0.42 + 0.96 (avg_wnd_spd Balcones)	0.728	0.43	2,269	2.1
Temple	Balcones	1.11 + 1.13 (avg_wnd_spd Balcones)	0.383	1.05	2,397	0.2
	Bastrop	0.51 + 1.60 (avg_wnd_spd Bastrop)	0.551	0.90	2,434	
Coleman	Mason	0.50 + 0.92 (avg_wnd_spd Mason)	0.750	0.55	2,488	6.3
	Hamby	1.45 + 0.51 (avg_wnd_spd Hamby)	0.492	0.79	2,090	
Woodville	Lufkin	1.23 + 0.96 (avg_wnd_spd Lufkin)	0.490	0.81	3,339	4.9
	Sabine South	0.89 + 0.75 (avg_wnd_spd Sabine South)	0.372	0.89	2,839	
						Average = 2.8

[1]RAWS stations report daily average meteorological data required for the Hamon and U.S. Weather Bureau methods discussed in this report. The RAWS base stations are intended to provide the average daily wind speed for the two methods. If the base station data are not available, the regression equations are intended to estimate average daily wind speed from RAWS satellite stations.

Appendix 4.4. Regression equations for satellite stations to estimate average daily solar radiation in calories per square centimeter at base stations.

[RAWS, Remote Automatic Weather Stations; avg_srad, average daily solar radiation; p-values for all the equations are less than 0.05 except the intercept term for Bastrop]

RAWS base station[1]	RAWS satellite station[1]	Linear regression equation	Adjusted R-squared	Residual standard error (calories per square centimeter)	Number of daily values used to generate regression	Percentage of days when solar radiation at base station was estimated from equations
Cedar Hill State Park	Granbury	20.8 + 0.94 (avg_srad Granbury)	0.878	63.7	2,133	0.5
	LBJ Road	22.6 + 0.88 (avg_srad LBJ Road)	0.819	77.1	2,300	
Guadalupe River State Park	Balcones	40.7 + 0.83 (avg_srad Balcones)	0.759	83.8	2,067	2.2
Temple	Balcones	22.5 + 0.92 (avg_srad Balcones)	0.746	98.1	1,792	22.4
	Bastrop	-1.36 + 0.99 (avg_srad Bastrop)	0.787	88.6	1,729	
Coleman	Mason	40.4 + 0.94 (avg_srad Mason)	0.810	78.2	1,836	18.2
	Hamby	119 + 0.79 (avg_srad Hamby)	0.741	90.7	1,840	
Woodville	Lufkin	33.5 + 0.91 (avg_srad Lufkin)	0.834	72.1	2,229	1.0
	Sabine South	47.1 + 0.90 (avg_srad Sabine South)	0.839	69.4	1,986	
						Average = 8.9

[1]RAWS stations report daily average meteorological data required for the Hamon and U.S. Weather Bureau methods discussed in this report. The RAWS base stations are intended to provide the average daily solar radiation for the two methods. If the base station data are not available, the regression equations are intended to estimate average daily solar radiation from RAWS satellite stations.

Appendix 5—Percentage Error between Unmodified and Modified Hamon and U.S. Weather Bureau Method Estimates of Monthly Reservoir Evaporation with Monthly Reservoir Evaporation from Class A Pan Data

Appendix tables 5.1–5.5 summarize the results of comparisons between unmodified and modified Hamon and U.S. Weather Bureau (USWB) method estimates of monthly reservoir evaporation with monthly reservoir from pan data described in the section of the report entitled "Evaluation of Two Methods for Estimation of Evaporation from Five Reservoirs in Texas." The percentage error was calculated as the difference between the method estimate and the reservoir evaporation from pan data divided by the reservoir evaporation from pan data and multiplied by 100.

Appendix 5.1. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Benbrook Lake, Texas.

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
1	2004	2.32	1.18	-49.2	3.07	32.1	1.81	-22.1	2.24	-3.4
2	2004	1.88	1.13	-40.1	2.49	32.0	1.87	-0.6	2.06	9.3
3	2004	4.31	2.44	-43.2	4.63	7.6	3.79	-11.9	4.22	-1.9
4	2004	3.75	3.13	-16.5	4.58	22.0	3.75	-0.0	3.63	-3.4
5	2004	4.47	4.76	6.6	4.42	-1.2	5.74	28.5	4.38	-2.0
6	2004	5.27	5.53	5.0	5.45	3.6	4.83	-8.3	4.07	-22.8
7	2004	5.69	6.27	10.1	6.29	10.5	6.84	20.2	6.14	7.8
8	2004	6.28	5.34	-14.9	6.05	-3.6	5.81	-7.4	5.64	-10.2
9	2004	5.34	3.98	-25.6	5.23	-2.2	4.35	-18.6	5.08	-4.9
10	2004	4.21	2.84	-32.6	4.89	16.1	2.78	-33.9	3.43	-18.6
11	2004	2.72	1.48	-45.6	3.29	21.0	1.26	-53.7	1.61	-40.8
12	2004	2.78	1.14	-59.0	3.08	10.8	2.32	-16.6	2.93	5.5
1	2005	--	1.24	--	3.22	--	1.63	--	2.02	--
2	2005	2.67	1.38	-48.1	3.05	14.2	1.92	-28.1	2.11	-20.9
3	2005	3.92	2.07	-47.3	3.92	-0.1	3.69	-5.8	4.11	4.9
4	2005	4.82	3.02	-37.4	4.41	-8.5	4.61	-4.5	4.45	-7.7
5	2005	4.04	4.57	13.0	4.24	4.8	4.80	18.7	3.66	-9.4
6	2005	5.72	6.42	12.4	6.34	10.9	7.29	27.6	6.14	7.5
7	2005	6.42	6.40	-0.2	6.43	0.2	6.50	1.3	5.83	-9.1
8	2005	6.02	6.00	-0.3	6.80	13.0	6.14	2.0	5.96	-1.1
9	2005	7.06	4.77	-32.4	6.27	-11.1	5.39	-23.6	6.30	-10.8
10	2005	5.78	2.71	-53.2	4.66	-19.3	4.12	-28.6	5.08	-12.0
11	2005	5.07	1.77	-65.2	3.93	-22.5	3.47	-31.5	4.45	-12.3
12	2005	3.87	1.08	-71.9	2.93	-24.2	2.66	-31.2	3.36	-13.0
1	2006	4.43	1.41	-68.1	3.67	-17.1	3.52	-20.6	4.37	-1.5
2	2006	3.63	1.23	-66.3	2.70	-25.7	2.52	-30.6	2.77	-23.7
3	2006	5.22	2.42	-53.6	4.59	-12.1	4.22	-19.2	4.70	-10.0
4	2006	5.33	3.72	-30.2	5.44	2.0	5.76	7.9	5.56	4.3
5	2006	5.47	5.06	-7.6	4.69	-14.3	7.32	33.9	5.59	2.1
6	2006	7.00	6.29	-10.1	6.21	-11.3	8.17	16.7	6.88	-1.7
7	2006	7.16	7.08	-1.1	7.11	-0.8	8.30	15.9	7.44	3.9
8	2006	8.45	6.78	-19.8	7.68	-9.1	8.18	-3.2	7.93	-6.1
9	2006	5.89	3.97	-32.5	5.22	-11.3	4.84	-17.8	5.65	-4.0
10	2006	4.48	2.64	-41.1	4.54	1.4	4.09	-8.7	5.04	12.5
11	2006	3.11	1.55	-50.1	3.46	11.1	2.64	-15.1	3.38	8.7
12	2006	--	1.17	--	3.15	--	2.14	--	2.71	--

Appendix 5.1. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Benbrook Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
1	2007	--	0.89	--	2.31	--	1.38	--	1.71	--
2	2007	2.40	1.28	-46.8	2.81	17.1	2.63	9.4	2.89	20.3
3	2007	3.55	2.52	-29.0	4.77	34.4	3.51	-1.0	3.91	10.3
4	2007	3.83	2.84	-25.8	4.16	8.5	3.89	1.4	3.76	-2.0
5	2007	3.23	4.38	35.4	4.06	25.6	3.77	16.7	2.88	-11.0
6	2007	4.88	5.48	12.3	5.40	10.8	5.00	2.6	4.21	-13.6
7	2007	5.27	5.82	10.3	5.84	10.7	5.32	0.9	4.77	-9.5
8	2007	6.25	5.93	-5.1	6.72	7.5	5.96	-4.7	5.78	-7.5
9	2007	4.96	4.12	-17.0	5.41	9.1	3.88	-21.6	4.54	-8.5
10	2007	4.64	2.79	-40.0	4.80	3.3	3.68	-20.8	4.53	-2.4
11	2007	3.58	1.68	-53.0	3.74	4.7	2.53	-29.3	3.24	-9.5
12	2007	2.37	1.10	-53.6	2.97	25.4	1.87	-21.2	2.36	-0.3
1	2008	2.48	1.03	-58.5	2.68	7.9	2.16	-12.8	2.69	8.2
2	2008	3.22	1.40	-56.4	3.09	-4.0	3.06	-5.1	3.36	4.4
3	2008	4.40	2.21	-49.7	4.20	-4.7	3.84	-12.7	4.28	-2.8
4	2008	4.71	3.03	-35.6	4.43	-5.9	4.66	-1.0	4.51	-4.3
5	2008	4.73	4.78	1.0	4.44	-6.3	5.95	25.7	4.54	-4.1
6	2008	7.08	6.33	-10.5	6.25	-11.7	7.84	10.9	6.61	-6.6
7	2008	8.47	7.03	-17.1	7.05	-16.8	9.19	8.5	8.25	-2.7
8	2008	6.64	5.81	-12.4	6.59	-0.7	6.61	-0.5	6.41	-3.4
9	2008	4.54	3.76	-17.3	4.93	8.7	4.55	0.2	5.32	17.1
10	2008	4.71	2.55	-45.9	4.39	-6.9	4.37	-7.2	5.39	14.3
11	2008	3.99	1.56	-60.9	3.47	-13.0	3.05	-23.6	3.90	-2.2
12	2008	2.93	1.10	-62.5	2.97	1.2	2.60	-11.5	3.28	12.0
1	2009	--	1.13	--	2.94	--	2.95	--	3.66	--
2	2009	3.58	1.51	-57.9	3.33	-7.2	3.57	-0.3	3.93	9.7
3	2009	4.64	2.26	-51.3	4.28	-7.8	4.07	-12.1	4.54	-2.1
4	2009	4.76	3.01	-36.7	4.40	-7.5	5.05	6.2	4.88	2.6
5	2009	3.97	4.56	14.7	4.23	6.4	5.48	37.9	4.18	5.2
6	2009	5.88	6.49	10.5	6.41	9.0	8.37	42.5	7.05	20.0
7	2009	6.79	6.94	2.2	6.97	2.6	7.96	17.3	7.14	5.2
8	2009	7.31	5.99	-18.1	6.78	-7.2	7.91	8.3	7.68	5.0
9	2009	4.18	3.80	-9.1	5.00	19.4	3.89	-6.9	4.55	8.7
10	2009	3.11	2.21	-29.0	3.80	22.2	2.47	-20.7	3.04	-2.3
11	2009	2.98	1.62	-45.5	3.61	21.2	2.51	-15.7	3.21	7.9
12	2009	--	0.88	--	2.37	--	1.46	--	1.85	--

Appendix 5.1. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Benbrook Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
1	2010	--	1.01	--	2.63	--	1.81	--	2.25	--
2	2010	--	0.91	--	2.01	--	1.56	--	1.72	--
3	2010	4.26	1.93	-54.6	3.66	-14.0	4.21	-1.0	4.69	10.3
4	2010	4.76	3.15	-34.0	4.60	-3.5	5.13	7.6	4.96	4.1
5	2010	4.69	4.98	6.3	4.62	-1.5	6.70	43.0	5.11	9.1
6	2010	6.43	6.59	2.4	6.50	1.1	7.67	19.3	6.46	0.5
7	2010	6.18	6.64	7.5	6.66	7.9	7.22	17.0	6.48	4.9
8	2010	7.25	6.81	-6.1	7.71	6.4	8.51	17.4	8.25	13.9
9	2010	5.34	4.20	-21.4	5.52	3.2	5.23	-2.1	6.11	14.4
10	2010	--	2.66	--	4.58	--	5.26	--	6.48	--
11	2010	3.48	1.58	-54.5	3.52	1.2	3.45	-1.0	4.41	26.7
12	2010	--	1.14	--	3.09	--	3.13	--	3.96	--
--	--	Average[1]	--	31.0	--	10.7	--	15.2	--	8.6
--	--	25th percentile[1]	--	11.4	--	4.3	--	5.5	--	3.7
--	--	Median[1]	--	32.4	--	8.7	--	15.1	--	7.7
--	--	75th percentile[1]	--	49.5	--	14.3	--	21.4	--	10.9

[1]Summary statistics of percentage error are calculated from the absolute value of the difference between the method estimate and the reservoir evaporation from pan data divided by the reservoir evaporation from pan data and multiplied by 100. Reporting the absolute value of the errors reduces the cancelling effects of positive and negative numbers.

Appendix 5.2. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Canyon Lake, Texas.

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percentage error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
12	2003	3.38	1.26	-62.6	2.60	-23.1	2.50	-25.9	2.98	-11.8
1	2004	2.74	1.29	-52.9	2.62	-4.4	1.40	-48.9	1.76	-35.9
2	2004	2.28	1.27	-44.3	2.30	0.7	1.55	-32.1	1.84	-19.2
3	2004	2.56	2.50	-2.1	3.85	50.8	2.40	-5.9	2.72	6.3
4	2004	2.85	2.99	4.9	4.39	54.0	2.65	-7.1	2.95	3.5
5	2004	4.28	4.54	6.0	4.91	14.7	4.43	3.5	4.21	-1.6
6	2004	6.01	5.23	-12.9	6.44	7.1	4.23	-29.5	4.67	-22.2
7	2004	6.19	5.78	-6.7	6.47	4.5	6.04	-2.5	6.46	4.4
8	2004	6.13	5.20	-15.2	6.55	6.9	5.24	-14.5	5.98	-2.5
9	2004	4.80	3.85	-19.7	4.99	4.1	3.66	-23.7	4.29	-10.5
10	2004	3.33	3.07	-7.8	5.07	52.1	2.29	-31.1	3.07	-7.8
11	2004	2.92	1.60	-45.3	2.91	-0.2	1.58	-45.8	1.92	-34.1
12	2004	--	1.20	--	2.48	--	1.96	--	2.33	--
1	2005	2.38	1.38	-42.1	2.79	17.5	1.32	-44.3	1.66	-30.1
2	2005	1.80	1.43	-20.7	2.58	43.4	1.15	-36.0	1.37	-23.8
3	2005	3.83	2.25	-41.2	3.47	-9.4	3.48	-9.1	3.93	2.7
4	2005	4.85	3.14	-35.3	4.60	-5.1	4.77	-1.6	5.32	9.6
5	2005	4.31	4.48	3.9	4.85	12.4	4.53	5.1	4.31	-0.1
6	2005	6.90	5.83	-15.4	7.17	4.0	5.87	-14.9	6.48	-6.1
7	2005	6.59	6.21	-5.7	6.96	5.6	5.89	-10.5	6.31	-4.2
8	2005	7.00	5.54	-20.8	6.98	-0.2	5.48	-21.7	6.25	-10.7
9	2005	5.57	4.54	-18.4	5.88	5.7	4.83	-13.2	5.67	1.8
10	2005	4.27	2.71	-36.5	4.47	4.8	2.66	-37.6	3.57	-16.4
11	2005	3.85	1.88	-51.2	3.42	-10.9	2.65	-31.2	3.22	-16.3
12	2005	2.58	1.23	-52.2	2.54	-1.6	2.24	-13.3	2.66	3.1
1	2006	3.46	1.50	-56.8	3.04	-12.3	2.85	-17.8	3.57	3.2
2	2006	3.28	1.39	-57.4	2.52	-23.1	2.29	-30.2	2.72	-17.0
3	2006	3.86	2.58	-33.3	3.97	2.6	3.08	-20.2	3.48	-9.9
4	2006	6.64	3.82	-42.4	5.61	-15.5	5.09	-23.4	5.67	-14.6
5	2006	6.49	4.85	-25.3	5.25	-19.1	6.81	4.9	6.47	-0.3
6	2006	8.02	5.75	-28.3	7.07	-11.8	7.11	-11.3	7.85	-2.1
7	2006	7.04	6.03	-14.2	6.76	-3.9	6.50	-7.6	6.96	-1.1
8	2006	7.69	5.85	-24.0	7.37	-4.2	6.98	-9.2	7.96	3.5
9	2006	5.85	3.87	-33.9	5.01	-14.4	4.46	-23.8	5.23	-10.6
10	2006	4.51	2.82	-37.5	4.64	3.0	3.16	-29.9	4.23	-6.1
11	2006	3.02	1.79	-40.7	3.27	8.2	2.70	-10.5	3.28	8.8
12	2006	1.74	1.26	-27.4	2.60	49.5	1.77	1.5	2.10	20.8

Appendix 5.2. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Canyon Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percentage error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
1	2007	--	1.03	--	2.08	--	1.16	--	1.46	--
2	2007	2.10	1.39	-33.9	2.51	19.5	2.17	3.3	2.58	22.9
3	2007	2.94	2.45	-16.6	3.78	28.4	2.48	-15.5	2.81	-4.6
4	2007	3.84	2.87	-25.2	4.22	9.8	3.33	-13.4	3.71	-3.5
5	2007	3.82	4.35	13.9	4.71	23.3	3.82	0.0	3.63	-4.9
6	2007	5.38	5.33	-0.9	6.55	21.8	5.08	-5.5	5.61	4.3
7	2007	4.20	5.23	24.5	5.85	39.4	3.92	-6.7	4.19	-0.2
8	2007	5.82	5.26	-9.6	6.63	14.0	5.19	-10.8	5.92	1.7
9	2007	4.25	3.95	-7.1	5.12	20.5	3.65	-14.0	4.28	0.8
10	2007	4.92	2.87	-41.6	4.74	-3.7	3.37	-31.5	4.51	-8.3
11	2007	2.61	1.75	-32.9	3.19	22.3	2.00	-23.4	2.43	-6.9
12	2007	2.56	1.32	-48.2	2.73	6.7	1.90	-25.6	2.26	-11.5
1	2008	2.08	1.18	-43.3	2.40	15.1	1.83	-12.3	2.29	10.1
2	2008	3.09	1.70	-44.8	3.08	-0.2	2.72	-11.9	3.24	4.8
3	2008	4.00	2.36	-41.1	3.63	-9.2	3.35	-16.3	3.78	-5.4
4	2008	4.68	3.28	-29.8	4.82	3.0	4.66	-0.3	5.19	11.0
5	2008	6.08	5.06	-16.8	5.47	-10.0	6.28	3.2	5.97	-1.8
6	2008	8.48	6.15	-27.5	7.56	-10.9	7.55	-11.0	8.34	-1.7
7	2008	7.31	5.74	-21.5	6.43	-12.1	7.11	-2.8	7.61	4.0
8	2008	5.62	5.24	-6.7	6.61	17.5	5.88	4.7	6.71	19.3
9	2008	5.85	3.88	-33.6	5.03	-14.0	5.62	-3.8	6.60	12.8
10	2008	5.43	2.67	-50.9	4.40	-19.0	3.93	-27.5	5.27	-3.0
11	2008	3.79	1.74	-54.1	3.17	-16.4	2.92	-23.1	3.55	-6.4
12	2008	3.03	1.28	-57.8	2.63	-13.2	2.38	-21.6	2.83	-6.7
1	2009	2.73	1.27	-53.6	2.57	-5.8	2.68	-1.7	3.37	23.3
2	2009	3.51	1.71	-51.2	3.10	-11.7	3.22	-8.1	3.83	9.4
3	2009	4.33	2.40	-44.6	3.70	-14.7	3.98	-8.3	4.49	3.7
4	2009	5.78	3.22	-44.2	4.73	-18.1	5.49	-4.9	6.12	5.9
5	2009	5.41	4.84	-10.6	5.23	-3.2	6.31	16.7	6.00	11.0
6	2009	7.74	6.18	-20.2	7.59	-1.9	8.26	6.7	9.12	17.8
7	2009	8.79	6.66	-24.2	7.46	-15.1	8.39	-4.5	8.98	2.2
8	2009	8.62	5.92	-31.3	7.46	-13.5	8.24	-4.5	9.39	8.9
9	2009	--	3.67	--	4.75	--	3.51	--	4.12	--
10	2009	--	2.60	--	4.29	--	2.91	--	3.90	--
11	2009	2.67	1.62	-39.4	2.95	10.5	2.19	-17.8	2.67	-0.0
12	2009	2.12	1.01	-52.3	2.08	-1.7	1.40	-34.0	1.66	-21.5

Appendix 5.2. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Canyon Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percentage error (A and B)	Modified Hamon (C) (inches)	Percentage error (A and C)	Unmodified USWB (D) (inches)	Percentage error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
1	2010	--	1.13	--	2.30	--	1.74	--	2.19	--
2	2010	--	1.08	--	1.95	--	1.62	--	1.93	--
3	2010	4.43	2.08	-53.0	3.20	-27.7	4.11	-7.3	4.64	4.8
4	2010	4.08	3.11	-23.7	4.57	12.0	3.41	-16.3	3.80	-6.8
5	2010	5.13	4.79	-6.5	5.19	1.2	4.78	-6.8	4.54	-11.4
6	2010	6.78	5.85	-13.6	7.20	6.2	5.90	-12.9	6.52	-3.8
7	2010	6.14	5.94	-3.3	6.65	8.3	5.36	-12.7	5.74	-6.6
8	2010	8.18	6.08	-25.7	7.66	-6.4	5.61	-31.5	6.39	-21.9
9	2010	4.93	3.96	-19.8	5.13	4.0	4.08	-17.3	4.78	-3.1
10	2010	5.50	2.68	-51.2	4.42	-19.5	4.87	-11.4	6.52	18.7
11	2010	3.26	1.74	-46.7	3.17	-2.8	3.48	6.6	4.23	29.6
12	2010	2.43	1.26	-48.3	2.58	6.4	2.60	7.1	3.10	27.4
--	--	Average[1]	--	30.3	--	13.3	--	15.5	--	9.8
--	--	25th percentile[1]	--	16.0	--	4.4	--	6.6	--	3.5
--	--	Median[1]	--	29.8	--	10.9	--	12.7	--	6.7
--	--	75th percentile[1]	--	44.5	--	17.5	--	23.4	--	13.7

[1]Summary statistics of percentage error are calculated from the absolute value of the difference between the method estimate and the reservoir estimate from pan data divided by the reservoir estimate from pan data and multiplied by 100. Reporting the absolute value of the errors reduces the cancelling effects of positive and negative numbers.

Appendix 5.3. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Granger Lake, Texas.

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
1	2004	1.64	1.28	-22.3	2.88	75.4	1.73	5.2	1.93	17.4
2	2004	--	1.22	--	2.65	--	1.80	--	2.10	--
3	2004	3.40	2.53	-25.6	4.51	32.6	3.30	-3.1	3.64	7.0
4	2004	--	3.10	--	4.99	--	3.72	--	3.70	--
5	2004	4.45	4.61	3.6	4.88	9.7	5.26	18.1	4.42	-0.8
6	2004	5.19	5.32	2.6	5.77	11.2	4.80	-7.4	4.41	-14.9
7	2004	6.38	5.99	-6.1	6.23	-2.2	6.75	5.9	6.12	-4.0
8	2004	6.39	5.40	-15.6	6.53	2.1	6.46	1.1	6.08	-4.9
9	2004	5.12	4.09	-20.1	5.37	5.0	4.65	-9.1	4.90	-4.2
10	2004	3.40	3.08	-9.4	4.57	34.4	2.65	-22.1	2.63	-22.9
11	2004	2.52	1.59	-36.8	2.92	15.9	1.42	-43.5	1.56	-38.0
12	2004	--	1.20	--	2.85	--	1.90	--	2.21	--
1	2005	--	1.32	--	2.98	--	1.59	--	1.77	--
2	2005	1.64	1.42	-13.2	3.08	87.8	1.56	-5.0	1.82	11.1
3	2005	4.07	2.17	-46.8	3.86	-5.2	3.44	-15.5	3.80	-6.7
4	2005	5.38	3.10	-42.4	4.98	-7.4	5.08	-5.5	5.06	-6.0
5	2005	4.49	4.53	0.8	4.79	6.7	5.19	15.4	4.36	-3.1
6	2005	6.70	5.98	-10.7	6.49	-3.2	6.74	0.6	6.19	-7.5
7	2005	6.83	6.31	-7.6	6.57	-3.8	6.53	-4.4	5.93	-13.3
8	2005	6.44	5.54	-14.0	6.70	4.0	5.43	-15.7	5.10	-20.8
9	2005	6.61	4.71	-28.7	6.19	-6.3	4.81	-27.1	5.07	-23.2
10	2005	4.53	2.76	-39.0	4.10	-9.5	3.06	-32.5	3.02	-33.2
11	2005	3.93	1.88	-52.1	3.45	-12.2	3.15	-19.8	3.46	-12.0
12	2005	3.39	1.19	-64.7	2.84	-16.1	2.22	-34.4	2.59	-23.5
1	2006	4.01	1.52	-62.1	3.43	-14.5	3.30	-17.7	3.68	-8.2
2	2006	2.67	1.32	-50.5	2.86	7.1	2.34	-12.6	2.73	2.2
3	2006	4.40	2.48	-43.5	4.42	0.6	3.82	-13.1	4.22	-4.1
4	2006	5.89	3.71	-37.1	5.96	1.2	5.63	-4.3	5.61	-4.8
5	2006	6.71	4.76	-29.0	5.04	-24.8	5.96	-11.1	5.01	-25.3
6	2006	6.99	5.78	-17.2	6.27	-10.3	7.18	2.8	6.60	-5.5
7	2006	7.25	6.28	-13.3	6.54	-9.8	8.16	12.6	7.40	2.1
8	2006	8.25	6.24	-24.3	7.55	-8.5	9.04	9.7	8.50	3.1
9	2006	6.37	4.09	-35.8	5.38	-15.6	6.04	-5.2	6.36	-0.2
10	2006	4.05	2.79	-31.1	4.14	2.2	3.92	-3.2	3.88	-4.1
11	2006	3.25	1.70	-47.6	3.12	-4.0	3.06	-5.6	3.36	3.5
12	2006	2.38	1.27	-46.6	3.02	27.1	2.23	-6.3	2.60	9.3

Appendix 5.3. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Granger Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
1	2007	--	1.01	--	2.27	--	1.54	--	1.72	--
2	2007	3.86	1.37	-64.5	2.96	-23.2	2.74	-28.9	3.21	-16.8
3	2007	3.65	2.53	-30.6	4.52	23.7	3.55	-2.7	3.92	7.4
4	2007	4.10	2.87	-29.9	4.62	12.6	4.46	8.8	4.44	8.3
5	2007	4.04	4.47	10.5	4.73	16.9	5.05	24.8	4.24	4.8
6	2007	4.66	5.38	15.4	5.83	25.1	5.45	16.9	5.01	7.4
7	2007	4.25	5.54	30.2	5.76	35.6	5.14	21.0	4.66	9.7
8	2007	6.24	5.71	-8.6	6.90	10.5	6.91	10.7	6.50	4.1
9	2007	4.55	4.19	-7.9	5.51	21.0	4.79	5.4	5.05	11.0
10	2007	4.35	2.94	-32.4	4.36	0.3	4.27	-1.9	4.23	-2.9
11	2007	3.23	1.76	-45.6	3.22	-0.4	2.56	-20.7	2.81	-13.0
12	2007	2.49	1.27	-48.9	3.03	21.5	2.07	-16.9	2.42	-3.1
1	2008	2.47	1.14	-53.7	2.58	4.5	2.15	-13.0	2.40	-2.9
2	2008	3.87	1.56	-59.6	3.38	-12.6	3.28	-15.3	3.84	-0.9
3	2008	4.14	2.29	-44.8	4.07	-1.6	3.80	-8.3	4.19	1.2
4	2008	5.34	3.18	-40.4	5.12	-4.1	5.39	0.8	5.36	0.4
5	2008	5.02	4.76	-5.1	5.04	0.4	6.22	24.1	5.23	4.2
6	2008	7.91	6.23	-21.2	6.75	-14.6	7.98	1.0	7.34	-7.2
7	2008	7.60	6.35	-16.4	6.61	-13.0	7.98	5.0	7.23	-4.8
8	2008	7.24	5.76	-20.4	6.97	-3.7	6.71	-7.3	6.31	-12.9
9	2008	6.26	3.94	-37.1	5.17	-17.4	5.77	-7.8	6.08	-2.9
10	2008	4.77	2.67	-44.0	3.97	-16.9	4.78	0.2	4.73	-0.8
11	2008	3.46	1.70	-50.8	3.12	-9.9	3.33	-4.0	3.65	5.4
12	2008	3.00	1.23	-59.1	2.92	-2.7	2.88	-4.0	3.36	11.9
1	2009	3.25	1.22	-62.4	2.76	-15.1	3.12	-3.9	3.48	7.2
2	2009	3.94	1.64	-58.5	3.54	-10.2	3.79	-3.9	4.43	12.5
3	2009	4.37	2.32	-46.9	4.13	-5.4	4.04	-7.4	4.47	2.2
4	2009	5.85	3.13	-46.5	5.03	-14.0	5.04	-13.8	5.02	-14.2
5	2009	5.20	4.74	-8.8	5.02	-3.5	5.74	10.4	4.82	-7.2
6	2009	7.58	6.47	-14.6	7.02	-7.4	7.94	4.7	7.29	-3.8
7	2009	--	7.09	--	7.38	--	7.85	--	7.12	--
8	2009	--	6.18	--	7.48	--	7.68	--	7.22	--
9	2009	4.47	3.87	-13.5	5.08	13.6	3.53	-21.1	3.72	-16.9
10	2009	3.23	2.47	-23.4	3.67	13.7	2.75	-14.9	2.72	-15.7
11	2009	2.21	1.69	-23.5	3.10	40.2	2.44	10.6	2.68	21.4
12	2009	2.52	0.97	-61.5	2.30	-8.6	1.43	-43.3	1.66	-33.9

Appendix 5.3. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Granger Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
1	2010	--	1.09	--	2.47	--	1.80	--	2.01	--
2	2010	2.28	1.00	-55.9	2.17	-4.5	1.82	-19.9	2.13	-6.3
3	2010	5.46	2.03	-62.9	3.61	-33.9	4.84	-11.5	5.34	-2.3
4	2010	4.19	3.18	-24.1	5.12	22.0	5.31	26.6	5.29	26.1
5	2010	4.94	5.11	3.3	5.41	9.4	7.63	54.4	6.41	29.7
6	2010	5.53	6.12	10.8	6.64	20.1	8.05	45.6	7.40	33.8
7	2010	5.71	6.24	9.3	6.50	13.8	7.58	32.7	6.87	20.3
8	2010	7.74	6.44	-16.7	7.79	0.7	9.63	24.4	9.05	17.0
9	2010	4.80	4.22	-12.2	5.54	15.4	5.97	24.3	6.29	30.9
10	2010	4.64	2.83	-39.0	4.20	-9.5	6.24	34.4	6.18	33.1
11	2010	3.43	1.70	-50.5	3.11	-9.3	3.60	4.8	3.94	14.9
12	2010	3.13	1.24	-60.5	2.95	-6.0	3.15	0.6	3.68	17.3
--	--	Average[1]	--	31.3	--	13.7	--	13.9	--	11.3
--	--	25th percentile[1]	--	13.9	--	4.5	--	4.9	--	4.0
--	--	Median[1]	--	30.1	--	10.0	--	10.7	--	7.4
--	--	75th percentile[1]	--	46.8	--	16.3	--	20.1	--	16.8

[1]Summary statistics of percentage error are calculated from the absolute value of the difference between the method estimate and the reservoir estimate from pan data divided by the reservoir estimate from pan data and multiplied by 100. Reporting the absolute value of the errors reduces the cancelling effects of positive and negative numbers.

Appendix 5.4. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Hords Creek Lake, Texas.

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
4	2003	6.40	3.50	-45.3	6.86	7.3	--	--	--	--
5	2003	5.72	5.31	-7.1	6.77	18.5	--	--	--	--
6	2003	7.13	5.56	-22.1	7.24	1.6	--	--	--	--
7	2003	7.98	6.52	-18.3	7.90	-1.0	--	--	--	--
8	2003	8.10	5.95	-26.5	8.06	-0.5	--	--	--	--
9	2003	5.34	3.66	-31.5	5.89	10.3	--	--	--	--
10	2003	5.73	2.56	-55.2	5.25	-8.5	--	--	--	--
11	2003	3.47	1.60	-53.9	4.56	31.7	--	--	--	--
12	2003	--	1.15	--	4.01	--	--	--	--	--
1	2004	--	1.19	--	4.47	--	--	--	--	--
2	2004	--	1.18	--	3.25	--	--	--	--	--
3	2004	4.09	2.44	-40.3	5.77	40.9	--	--	--	--
4	2004	4.50	2.98	-33.6	5.85	30.2	--	--	--	--
5	2004	5.53	4.78	-13.5	6.09	10.3	--	--	--	--
6	2004	6.37	5.55	-13.0	7.23	13.5	--	--	--	--
7	2004	7.97	6.12	-23.2	7.42	-6.9	7.63	-4.2	7.41	-7.0
8	2004	6.31	5.05	-19.8	6.85	8.6	6.12	-3.0	6.21	-1.5
9	2004	5.61	3.78	-32.6	6.09	8.5	5.07	-9.6	5.74	2.3
10	2004	3.32	2.68	-19.5	5.47	64.7	3.37	1.5	3.76	13.1
11	2004	3.43	1.43	-58.3	4.08	19.0	2.33	-32.1	3.02	-11.9
12	2004	--	1.07	--	3.72	--	2.86	--	3.31	--
1	2005	--	1.24	--	4.64	--	2.43	--	3.10	--
2	2005	2.26	1.29	-43.0	3.56	57.4	2.16	-4.6	2.21	-2.2
3	2005	4.98	2.04	-59.1	4.81	-3.4	4.42	-11.3	4.85	-2.6
4	2005	6.19	3.08	-50.3	6.03	-2.6	6.48	4.7	6.45	4.2
5	2005	4.88	4.41	-9.6	5.63	15.3	5.58	14.3	5.15	5.5
6	2005	6.28	5.91	-5.9	7.71	22.6	7.42	18.1	7.46	18.7
7	2005	7.16	6.39	-10.8	7.74	8.1	7.76	8.4	7.54	5.3
8	2005	5.62	5.22	-7.0	7.08	26.0	6.16	9.6	6.25	11.3
9	2005	6.82	4.34	-36.3	6.99	2.6	6.34	-7.0	7.17	5.2
10	2005	5.34	2.55	-52.2	5.22	-2.3	4.21	-21.1	4.69	-12.1
11	2005	5.19	1.65	-68.2	4.71	-9.3	4.06	-21.8	5.27	1.5
12	2005	--	1.08	--	3.76	--	3.21	--	3.71	--
1	2006	5.98	1.35	-77.5	5.04	-15.8	4.15	-30.7	5.29	-11.6
2	2006	--	1.29	--	3.56	--	3.55	--	3.64	--
3	2006	7.00	2.40	-65.8	5.66	-19.2	5.36	-23.5	5.88	-16.1

Appendix 5.4. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Hords Creek Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
4	2006	7.71	3.65	-52.6	7.16	-7.0	6.62	-14.1	6.59	-14.5
5	2006	7.58	5.09	-32.9	6.49	-14.4	7.82	3.2	7.22	-4.7
6	2006	8.62	6.22	-27.9	8.10	-6.0	8.88	3.0	8.92	3.5
7	2006	8.06	6.83	-15.2	8.28	2.7	8.93	10.8	8.67	7.6
8	2006	8.31	6.36	-23.5	8.61	3.6	8.12	-2.3	8.24	-0.8
9	2006	6.39	3.79	-40.6	6.11	-4.4	5.69	-10.8	6.44	0.9
10	2006	5.81	2.62	-54.8	5.36	-7.6	4.53	-22.0	5.05	-13.1
11	2006	4.71	1.62	-65.6	4.63	-1.9	3.33	-29.3	4.33	-8.2
12	2006	--	1.10	--	3.84	--	2.60	--	3.01	--
1	2007	2.33	0.88	-62.3	3.31	41.7	1.62	-30.7	2.06	-11.6
2	2007	3.73	1.31	-64.8	3.62	-2.8	3.38	-9.4	3.46	-7.1
3	2007	4.45	2.38	-46.6	5.62	26.2	3.90	-12.5	4.28	-4.0
4	2007	5.43	2.86	-47.4	5.61	3.2	5.37	-1.1	5.35	-1.6
5	2007	4.78	4.22	-11.8	5.38	12.6	5.00	4.7	4.62	-3.3
6	2007	6.55	5.35	-18.2	6.98	6.6	6.38	-2.5	6.42	-2.0
7	2007	5.46	5.33	-2.3	6.46	18.4	5.66	3.6	5.50	0.7
8	2007	7.56	5.44	-28.1	7.37	-2.6	7.43	-1.8	7.54	-0.3
9	2007	5.46	3.96	-27.6	6.37	16.6	5.40	-1.1	6.11	11.9
10	2007	6.23	2.84	-54.4	5.82	-6.7	5.93	-4.8	6.61	6.1
11	2007	4.25	1.64	-61.4	4.69	10.3	3.45	-18.8	4.48	5.4
12	2007	3.84	1.10	-71.3	3.84	0.1	2.84	-26.1	3.28	-14.5
1	2008	3.21	1.05	-67.4	3.92	22.2	3.00	-6.5	3.83	19.2
2	2008	4.35	1.48	-66.0	4.09	-6.1	4.50	3.3	4.61	5.9
3	2008	5.39	2.25	-58.2	5.32	-1.2	5.35	-0.7	5.87	9.0
4	2008	6.05	3.23	-46.6	6.33	4.6	7.32	21.0	7.29	20.5
5	2008	7.42	5.05	-32.0	6.44	-13.2	8.61	16.0	7.95	7.2
6	2008	10.86	6.57	-39.5	8.56	-21.2	10.10	-7.0	10.15	-6.5
7	2008	9.90	6.41	-35.3	7.77	-21.6	9.32	-5.8	9.06	-8.5
8	2008	--	5.40	--	7.31	--	7.07	--	7.18	--
9	2008	7.62	3.61	-52.6	5.82	-23.6	6.17	-19.0	6.99	-8.3
10	2008	5.75	2.52	-56.1	5.16	-10.3	5.36	-6.9	5.97	3.7
11	2008	5.97	1.56	-73.8	4.46	-25.2	4.07	-31.7	5.29	-11.4
12	2008	3.95	1.13	-71.4	3.93	-0.3	3.75	-4.9	4.34	10.1
1	2009	4.59	1.14	-75.2	4.27	-7.2	3.92	-14.7	5.00	8.8
2	2009	5.00	1.54	-69.2	4.24	-15.1	4.88	-2.3	5.00	0.1
3	2009	6.52	2.38	-63.5	5.62	-13.9	5.96	-8.5	6.55	0.4

Appendix 5.4. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Hords Creek Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percentage error (A and B)	Modified Hamon (C) (inches)	Percentage error (A and C)	Unmodified USWB (D) (inches)	Percentage error (A and D)	Modified USWB (E) (inches)	Percentage error (A and E)
4	2009	7.40	3.21	-56.6	6.30	-14.8	7.35	-0.6	7.32	-1.1
5	2009	6.25	4.67	-25.2	5.96	-4.6	7.17	14.8	6.62	6.1
6	2009	--	6.47	--	8.43	--	8.93	--	8.98	--
7	2009	7.75	6.60	-14.8	8.00	3.3	8.58	10.8	8.33	7.6
8	2009	9.11	5.97	-34.5	8.08	-11.2	9.48	4.1	9.62	5.7
9	2009	--	3.62	--	5.83	--	5.21	--	5.90	--
10	2009	4.59	2.35	-48.8	4.81	4.8	4.11	-10.4	4.58	-0.2
11	2009	3.83	1.54	-59.8	4.40	14.8	3.51	-8.4	4.56	18.9
12	2009	--	0.89	--	3.11	--	2.16	--	2.50	--
1	2010	--	1.00	--	3.74	--	2.40	--	3.06	--
2	2010	--	0.98	--	2.71	--	2.38	--	2.44	--
3	2010	5.24	1.98	-62.2	4.68	-10.7	5.47	4.4	6.00	14.6
4	2010	6.24	3.07	-50.8	6.02	-3.6	5.99	-4.0	5.97	-4.4
5	2010	6.73	4.84	-28.2	6.17	-8.4	6.39	-5.1	5.90	-12.4
6	2010	7.81	6.25	-20.0	8.14	4.3	7.35	-5.9	7.39	-5.4
7	2010	6.62	6.14	-7.3	7.44	12.4	6.43	-2.9	6.25	-5.6
8	2010	9.10	6.28	-31.0	8.50	-6.6	8.11	-10.9	8.23	-9.5
9	2010	6.59	4.08	-38.1	6.56	-0.4	5.18	-21.4	5.86	-11.1
10	2010	5.84	2.67	-54.3	5.46	-6.5	5.44	-6.7	6.06	3.9
11	2010	5.08	1.57	-69.1	4.48	-11.8	4.15	-18.3	5.39	6.0
12	2010	--	1.15	--	4.01	--	3.29	--	3.81	--
--	--	Average[1]	--	41.2	--	12.4	--	10.8	--	7.4
--	--	25th percentile[1]	--	23.9	--	4.3	--	4.1	--	3.5
--	--	Median[1]	--	41.8	--	8.6	--	8.4	--	6.1
--	--	75th percentile[1]	--	58.3	--	15.6	--	15.7	--	11.4

[1]Summary statistics of percentage error are calculated from the absolute value of the difference between the method estimate and the reservoir estimate from pan data divided by the reservoir estimate from pan data and multiplied by 100. Reporting the absolute value of the errors reduces the cancelling effects of positive and negative numbers.

Appendix 5.5. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Sam Rayburn Lake, Texas.

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
12	2000	1.72	0.95	-44.9	1.60	-7.0	--	--	--	--
1	2001	1.88	1.10	-41.3	1.78	-4.8	--	--	--	--
2	2001	1.87	1.62	-13.4	2.51	34.5	--	--	--	--
3	2001	2.95	1.90	-35.6	2.92	-0.9	--	--	--	--
4	2001	3.97	3.59	-9.6	4.74	19.6	--	--	--	--
5	2001	5.23	4.69	-10.2	4.91	-6.0	--	--	--	--
6	2001	4.41	5.34	21.3	5.11	15.9	--	--	--	--
7	2001	5.45	6.16	12.9	5.64	3.4	--	--	--	--
8	2001	5.20	5.49	5.4	5.61	7.8	--	--	--	--
9	2001	4.02	3.73	-7.3	4.07	1.1	--	--	--	--
10	2001	3.58	2.41	-32.6	3.22	-10.1	--	--	--	--
11	2001	2.31	1.82	-21.3	2.59	11.9	--	--	--	--
12	2001	2.15	1.36	-37.0	2.29	6.3	--	--	--	--
1	2002	2.00	1.37	-31.5	2.23	11.2	--	--	--	--
2	2002	2.53	1.22	-52.0	1.89	-25.5	--	--	--	--
3	2002	3.59	2.32	-35.4	3.57	-0.5	--	--	--	--
4	2002	4.32	3.60	-16.6	4.76	10.3	--	--	--	--
5	2002	5.23	4.69	-10.3	4.92	-6.1	--	--	--	--
6	2002	4.85	5.60	15.6	5.35	10.4	--	--	--	--
7	2002	5.54	5.90	6.6	5.41	-2.4	--	--	--	--
8	2002	6.00	5.38	-10.4	5.50	-8.4	--	--	--	--
9	2002	4.01	4.03	0.5	4.40	9.6	--	--	--	--
10	2002	2.96	2.65	-10.3	3.54	19.6	--	--	--	--
11	2002	2.63	1.49	-43.4	2.12	-19.6	--	--	--	--
12	2002	2.38	1.22	-48.6	2.06	-13.3	--	--	--	--
1	2003	--	1.10	--	1.78	--	--	--	--	--
2	2003	2.11	1.28	-39.5	1.98	-6.1	1.12	-46.9	1.16	-45.2
3	2003	3.21	2.10	-34.5	3.24	0.8	2.09	-34.8	2.18	-32.0
4	2003	4.15	3.26	-21.5	4.31	3.8	3.33	-19.9	3.49	-15.9
5	2003	4.86	4.99	2.7	5.22	7.5	4.46	-8.1	4.10	-15.5
6	2003	5.98	5.52	-7.7	5.27	-11.8	4.54	-24.1	4.48	-25.0
7	2003	5.48	5.77	5.2	5.28	-3.7	4.39	-19.8	4.45	-18.9
8	2003	5.60	5.41	-3.4	5.53	-1.3	4.48	-20.0	4.67	-16.5
9	2003	4.56	3.68	-19.2	4.02	-11.9	2.98	-34.7	3.26	-28.6
10	2003	3.58	2.66	-25.8	3.54	-1.1	2.32	-35.3	2.48	-30.8
11	2003	2.77	1.85	-33.2	2.63	-5.0	1.53	-44.6	1.64	-40.6
12	2003	2.64	1.18	-55.3	1.99	-24.5	1.49	-43.5	1.89	-28.2

Appendix 5.5. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Sam Rayburn Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
1	2004	1.97	1.28	-34.7	2.08	6.0	1.02	-48.3	1.12	-43.0
2	2004	2.40	1.26	-47.3	1.96	-18.2	1.32	-45.1	1.36	-43.3
3	2004	3.72	2.53	-32.1	3.89	4.5	2.59	-30.3	2.71	-27.3
4	2004	4.50	3.15	-29.9	4.17	-7.3	2.90	-35.5	3.04	-32.3
5	2004	5.82	4.59	-21.1	4.81	-17.4	3.93	-32.4	3.62	-37.9
6	2004	4.82	5.29	9.7	5.05	4.8	3.37	-30.2	3.32	-31.1
7	2004	5.48	5.83	6.5	5.34	-2.4	4.60	-16.0	4.65	-15.1
8	2004	6.11	5.16	-15.5	5.27	-13.7	4.48	-26.7	4.67	-23.5
9	2004	4.83	4.05	-16.0	4.42	-8.4	3.53	-26.9	3.86	-20.1
10	2004	3.99	3.14	-21.5	4.18	4.7	2.37	-40.7	2.53	-36.6
11	2004	2.80	1.67	-40.3	2.37	-15.2	.95	-66.0	1.02	-63.5
12	2004	2.47	1.23	-50.2	2.08	-16.0	1.18	-52.1	1.50	-39.2
1	2005	2.02	1.39	-31.2	2.25	11.6	0.97	-51.8	1.07	-46.8
2	2005	1.84	1.49	-18.8	2.32	26.1	1.13	-38.4	1.17	-36.4
3	2005	4.23	2.21	-47.7	3.40	-19.5	2.59	-38.8	2.70	-36.1
4	2005	4.45	3.03	-31.9	4.01	-10.0	3.46	-22.1	3.64	-18.3
5	2005	4.86	4.56	-6.3	4.78	-1.8	4.78	-1.7	4.39	-9.7
6	2005	6.11	5.93	-2.8	5.67	-7.1	5.39	-11.8	5.32	-12.9
7	2005	5.58	6.05	8.5	5.54	-0.6	5.23	-6.3	5.29	-5.2
8	2005	5.41	5.45	0.7	5.57	2.9	4.59	-15.2	4.79	-11.5
9	2005	5.51	4.52	-17.9	4.93	-10.4	4.51	-18.0	4.93	-10.4
10	2005	3.78	2.73	-27.7	3.64	-3.6	4.29	13.8	4.59	21.7
11	2005	2.67	1.83	-31.4	2.61	-2.4	2.65	-0.7	2.84	6.4
12	2005	2.26	1.23	-45.7	2.07	-8.4	2.14	-5.5	2.71	20.0
1	2006	2.65	1.49	-43.6	2.42	-8.6	2.73	3.1	3.01	13.8
2	2006	2.07	1.34	-35.5	2.08	0.2	2.16	4.2	2.23	7.6
3	2006	3.64	2.49	-31.6	3.84	5.3	3.69	1.4	3.85	5.7
4	2006	4.67	3.63	-22.4	4.80	2.7	4.43	-5.2	4.65	-0.6
5	2006	4.68	4.67	-0.2	4.89	4.5	5.35	14.3	4.92	5.0
6	2006	5.75	5.59	-2.7	5.34	-7.1	5.97	3.9	5.90	2.6
7	2006	4.80	5.80	20.8	5.31	10.6	4.73	-1.5	4.78	-0.4
8	2006	5.34	5.50	2.9	5.62	5.2	5.56	4.1	5.80	8.5
9	2006	4.81	3.88	-19.4	4.23	-12.1	4.21	-12.5	4.60	-4.4
10	2006	3.94	2.68	-32.0	3.57	-9.3	3.12	-20.9	3.33	-15.4
11	2006	2.31	1.65	-28.3	2.35	1.9	2.43	5.5	2.61	13.1
12	2006	1.80	1.29	-28.2	2.18	21.2	1.58	-12.2	2.01	11.5

Appendix 5.5. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Sam Rayburn Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
1	2007	1.87	1.16	-38.1	1.88	0.5	1.40	-24.9	1.55	-17.1
2	2007	2.13	1.37	-35.6	2.13	0.0	2.03	-4.6	2.10	-1.6
3	2007	3.47	2.59	-25.3	3.99	15.0	3.68	5.9	3.84	10.4
4	2007	3.91	3.00	-23.3	3.97	1.4	3.85	-1.6	4.04	3.2
5	2007	4.31	4.56	5.7	4.78	10.8	4.68	8.5	4.30	-0.3
6	2007	5.10	5.61	10.1	5.36	5.2	4.88	-4.3	4.82	-5.5
7	2007	4.74	5.65	19.4	5.18	9.3	4.51	-4.9	4.56	-3.8
8	2007	5.68	5.65	-0.6	5.77	1.6	5.38	-5.2	5.61	-1.1
9	2007	4.05	4.13	1.9	4.50	11.2	3.71	-8.4	4.05	0.1
10	2007	3.80	2.85	-25.0	3.80	-0.0	3.78	-0.5	4.04	6.4
11	2007	2.29	1.77	-22.8	2.52	9.8	2.12	-7.4	2.28	-0.7
12	2007	1.78	1.43	-19.4	2.42	36.1	1.67	-6.3	2.12	19.0
1	2008	2.15	1.19	-44.5	1.94	-10.0	1.79	-16.8	1.98	-8.2
2	2008	2.39	1.63	-31.9	2.53	5.7	2.78	16.0	2.87	19.8
3	2008	3.55	2.41	-32.0	3.72	4.7	4.07	14.9	4.25	19.8
4	2008	4.44	3.24	-26.9	4.29	-3.3	4.80	8.2	5.04	13.5
5	2008	4.69	4.86	3.6	5.09	8.6	6.08	29.7	5.59	19.1
6	2008	5.57	5.83	4.5	5.57	-0.1	6.46	16.0	6.38	14.5
7	2008	6.58	6.15	-6.4	5.64	-14.3	7.18	9.1	7.26	10.4
8	2008	5.54	5.31	-4.2	5.42	-2.1	5.11	-7.7	5.33	-3.7
9	2008	3.84	3.73	-2.8	4.07	6.1	4.71	22.7	5.15	34.1
10	2008	3.48	2.56	-26.5	3.41	-2.0	4.17	19.7	4.46	28.1
11	2008	2.14	1.64	-23.5	2.33	8.7	2.52	17.7	2.70	26.2
12	2008	1.88	1.29	-31.4	2.18	15.7	1.63	-13.4	2.07	10.0
1	2009	2.05	1.27	-38.1	2.06	0.4	2.44	19.0	2.69	31.3
2	2009	2.64	1.61	-38.9	2.51	-5.1	2.88	9.1	2.98	12.7
3	2009	3.31	2.27	-31.5	3.49	5.4	3.37	1.8	3.52	6.2
4	2009	4.47	3.08	-31.1	4.07	-8.9	4.79	7.1	5.02	12.3
5	2009	4.94	4.65	-5.8	4.87	-1.3	5.60	13.4	5.15	4.2
6	2009	6.07	6.04	-0.4	5.78	-4.8	7.24	19.3	7.15	17.8
7	2009	6.04	6.31	4.3	5.78	-4.5	6.41	6.1	6.49	7.3
8	2009	5.07	5.53	8.9	5.65	11.3	5.93	16.9	6.19	21.9
9	2009	3.07	3.76	22.7	4.11	33.9	3.40	10.8	3.71	21.1
10	2009	3.27	2.68	-18.0	3.57	9.4	2.86	-12.6	3.06	-6.5
11	2009	2.14	1.68	-21.4	2.39	11.8	2.38	11.0	2.55	19.0
12	2009	--	1.06	--	1.78	--	1.50	--	1.90	--

Appendix 5.5. Percentage error between unmodified and modified Hamon and U.S. Weather Bureau method estimates of monthly reservoir evaporation with monthly reservoir evaporation from published monthly Class A pan data and application of Texas Water Development Board monthly pan coefficients for Sam Rayburn Lake, Texas.—Continued

[USWB, U.S. Weather Bureau; --, indicates not applicable or data not available]

Month	Year	Monthly reservoir evaporation from pan data (A) (inches)	Unmodified Hamon (B) (inches)	Percent-age error (A and B)	Modified Hamon (C) (inches)	Percent-age error (A and C)	Unmodified USWB (D) (inches)	Percent-age error (A and D)	Modified USWB (E) (inches)	Percent-age error (A and E)
1	2010	--	1.13	--	1.83	--	2.12	--	2.34	--
2	2010	1.88	1.05	-44.1	1.63	-13.2	2.10	11.6	2.17	15.2
3	2010	3.54	2.00	-43.4	3.08	-12.9	4.14	16.8	4.31	21.8
4	2010	4.77	3.30	-30.8	4.36	-8.5	5.16	8.2	5.41	13.5
5	2010	5.22	5.23	0.2	5.48	5.0	6.82	30.6	6.26	20.0
6	2010	5.36	6.15	14.6	5.88	9.5	5.94	10.7	5.87	9.3
7	2010	5.30	6.12	15.6	5.61	5.8	5.80	9.4	5.87	10.7
8	2010	6.01	5.99	-0.2	6.13	2.0	6.63	10.4	6.91	15.1
9	2010	4.82	4.23	-12.1	4.62	-4.1	4.88	1.4	5.34	10.8
10	2010	--	2.88	--	3.84	--	5.58	--	5.97	--
11	2010	--	1.68	--	2.38	--	2.40	--	2.58	--
12	2010	--	1.25	--	2.10	--	2.24	--	2.84	--
--	--	Average[1]	--	22.0	--	8.7	--	17.7	--	17.6
--	--	25th percentile[1]	--	8.7	--	3.6	--	6.5	--	7.7
--	--	Median[1]	--	21.4	--	7.1	--	13.6	--	15.2
--	--	75th percentile[1]	--	32.0	--	11.4	--	24.7	--	24.7

[1]Summary statistics of percentage error are calculated from the absolute value of the difference between the method estimate and the reservoir estimate from pan data divided by the reservoir estimate from pan data and multiplied by 100. Reporting the absolute value of the errors reduces the cancelling effects of positive and negative numbers.

Publishing support provided by
Lafayette Publishing Service Center

Information regarding water resources in Texas is available at
http://tx.usgs.gov/

Harwell—**Estimation of Evaporation from Open Water**—SIR 2012–5202