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Evaporation from Lake Mead, Arizona and Nevada, 1997–99

Scientific Investigations Report 2006-5252

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

Cover: Photograph of Lake Mead, Arizona-Nevada, looking east from Boulder Basin.
(Photograph taken by Craig L. Westenburg, U.S. Geolological Survey, March 31, 1998)

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By Craig L. Westenburg, Guy A. DeMeo, and Daron J. Tanko

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Conversion Factors, Datums, and Acronyms and Symbols

Conversion Factors

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	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
inch per day (in/day)	25.4	millimeter per day
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
miles per hour (mi/hr)	0.447	meters per second
Knot	1.609	kilometer per day
	Energy flux	
Watts per square foot (W/ft^2)	10.7643	Watts per square meter
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
Bar	100	kilopascal (kPa)

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:

$$°C=(°F-32)/1.8$$

Datums

Vertical coordinate information is referenced to the U.S. Geological Survey datum, adjustment of 1912, locally known as "Power House Datum." Add 0.55 foot to convert to datum of 1929, leveling of 1935. Add 0.43 foot to convert to datum of 1929, leveling of 1940. Add 0.40 foot to convert to datum of 1929, leveling of 1948. Add 0.03 foot to convert to datum of 1929, leveling of 1963. No elevations have been converted to datum of 1929. Datum of 1929 is known as National Geodetic Vertical Datum of 1929 (NVGD of 1929) and was formerly called "Sea-Level Datum of 1929."

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

Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms and Symbols

	Meaning
γ	empirical constant (equation 2)
ρ	density of evaporated water (equations 1, 3)
γ_c	psychrometric constant (equation 3)
E	evaporation rate (equations 1, 3)
e_0	vapor pressure of saturated air at temperature of the water surface (equations 2, 3)
e_a	vapor pressure of the air above the water surface (equations 2, 3)
L	latent heat of vaporization (equations 1, 3)
P	atmospheric pressure (equation 2)
Q_θ	change in energy stored in a body of water (equations 1, 3)
Q_v	net energy advected into a body of water (equation 1)
Q_b	net energy lost by the body of water through the exchange of long wave radiation between the atmosphere and the body of water (equation 1)
Q_n	net radiation (equation 3)
Q_r	reflected solar radiation (equation 1)
Q_s	solar radiation incident to the water surface (equation 1)
R	Bowen ratio (equations 1, 2)
R_n	monthly net radiation at Water Barge Cove
T_0	temperature of water (equations 2, 3)
T_a	temperature of the air (equations 2, 3)
USGS	United States Geological Survey

Evaporation from Lake Mead, Arizona and Nevada, 1997–99

By Craig L. Westenburg, Guy A. DeMeo, and Daron J. Tanko

Abstract

Lake Mead is one of a series of large Colorado River reservoirs operated and maintained by the Bureau of Reclamation. The Colorado River system of reservoirs and diversions is an important source of water for millions of people in seven Western States and Mexico. The U.S. Geological Survey, in cooperation with the Bureau of Reclamation, conducted a study from 1997 to 1999 to estimate evaporation from Lake Mead. For this study, micrometeorological and hydrologic data were collected continually from instrumented platforms deployed at four locations on the lake, open-water areas of Boulder Basin, Virgin Basin, and Overton Arm and a protected cove in Boulder Basin. Data collected at the platforms were used to estimate Lake Mead evaporation by solving an energy-budget equation. The average annual evaporation rate at open-water stations from January 1998 to December 1999 was 7.5 feet. Because the spatial variation of monthly and annual evaporation rates was minimal for the open-water stations, a single open-water station in Boulder Basin would provide data that are adequate to estimate evaporation from Lake Mead.

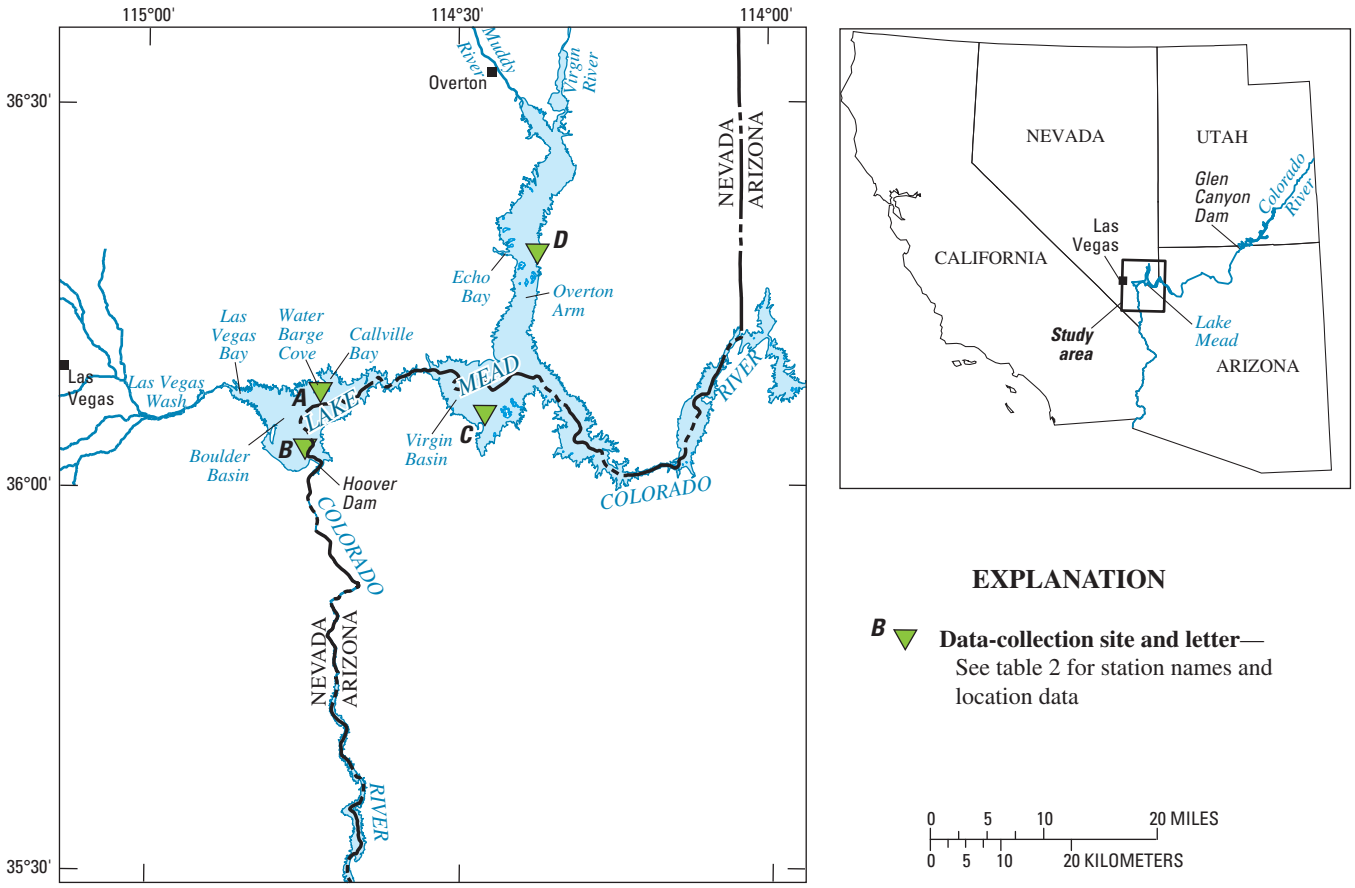
Introduction

Description of Study Area

Lake Mead is the largest reservoir by volume in the United States and was formed when Hoover Dam was completed in 1935 (fig. 1). It took until July 1941 for water to fill Lake Mead, which has a maximum surface elevation of 1,229 ft, a maximum surface area of 162,700 acres, and a maximum available capacity of 27,377,000 acre-ft (Bureau of Reclamation, 1967). At the maximum elevation of 1,229 ft Lake Mead extends 65.9 mi upstream of Hoover Dam and has a maximum width of 9.3 mi (LaBounty and Horn, 1997, p. 95). The average lake elevation from 1942 (first complete calendar year of full pool) to 1995, based on monthly end-of-month elevations, is 1,169.9 ft (retrieved at URL: http://www.usbr.gov/lc/riverops.html), which corresponds to a lake surface area of 125,600 acres.

The drainage area of Lake Mead at Hoover Dam is about 171,700 mi^2 (Tadayon and others, 2000, p. 90). Ninety-seven percent of the inflow into Lake Mead is from the Colorado River (13.12 million acre-ft/yr, Tadayon and others, 2000, p. 80) with the remaining 3 percent from the combined flow of Las Vegas Wash (148,000 acre-ft/yr; Jones and others, 2000, p. 94), Muddy River (11,700 acre-ft/yr; Jones and others, 2000, p. 55), Virgin River (176,000 acre-ft/yr; Jones and others, 2000, p. 55), and ephemeral streams. The average annual release from Hoover Dam from 1935 to 1999 was about 10.1 million acre-ft (Tadayon and others, 2000, p. 99). Flow of the Colorado River at Diamond Creek (130 mi upstream of Hoover Dam) in calendar year 1999 was 12.69 million acre-ft, while the release from Hoover Dam was 11.04 million acre-ft (Tadayon and others, 2001, p. 110 and 128). Retention time for Lake Mead averages 3.9 years, depending on release and flow patterns.

Lake Mead is in an environment with a warm, arid climate. From 1961 to 1990, the average maximum air temperature was 105.9ºF for Las Vegas, Nev., and 107.8ºF for Overton, Nev. (fig. 1), whereas the average minimum air temperature was 33.6ºF and 28.0ºF, respectively (table 1). Average annual precipitation (1961–90) was 4.13 in. for Las Vegas and 3.31 in. for Overton (table 1). This warm, arid environment is conducive for high rates of evaporation. Sparsely vegetated, gentle to moderately sloping alluvial fans and steep, barren, rocky cliffs surround the lake. Generally, the adjacent hills rise to low or moderate height above the lake surface. The vast majority of lake is exposed to winds from the southwest to southeast.



Base from U.S. Geological Survey digital data 1:100,000 scale, 1987:
Universal Transverse Mercator Projection, Zone 11

Figure 1. Location of study area and evaporation stations, Lake Mead, Arizona and Nevada.

Table 1. Average maximum and average minimum air temperature and average annual precipitation at Las Vegas and Overton, Nevada, 1961–90.

[Data for Las Vegas and Overton obtained from Desert Research Institute at www.wrcc.dri.edu. The period 1961–90 was selected because it coincides with official National Climatic Data Center records for Las Vegas. The 1961–90 data for Overton are unofficial]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
National Weather Service Office, McCarran Airport, Las Vegas, Nevada													
	Air temperature, in degrees Fahrenheit												
Average maximum	57.3	63.3	68.8	77.5	87.8	100.3	105.9	103.2	94.7	82.1	67.4	57.5	80.5
Average minimum	33.6	36.8	43.8	50.7	60.2	69.4	76.2	74.2	66.2	54.3	42.6	33.9	53.7
	Precipitation, in inches												
Average	0.48	0.48	0.42	0.21	0.28	0.12	0.35	0.49	0.28	0.21	0.43	0.38	4.13
Overton, Nevada													
	Air temperature, in degrees Fahrenheit												
Average maximum	62.0	66.0	72.2	81.8	91.0	100.5	107.8	105.4	97.8	87.7	69.8	60.7	83.8
Average minimum	28.0	32.5	38.0	45.9	53.3	61.6	69.6	69.7	59.1	49.7	37.7	30.5	48.1
	Precipitation, in inches												
Average	0.20	0.19	0.29	0.36	0.14	0.10	0.11	0.21	0.45	0.16	0.61	0.49	3.31

Background

Lake Mead is one of a series of large Colorado River reservoirs operated and maintained by the Bureau of Reclamation. The Colorado River system of reservoirs and diversions is an important source of water for millions of people in seven Western States and Mexico. The series of reservoirs along the Colorado River ensures a reliable supply of water for municipal and agricultural uses; allows for the generation of hydroelectric power; reduces the occurrence of uncontrolled floods within the basin; provides ecological habitat for numerous aquatic, riparian, and avian species; and provides a source of water-based recreation for millions of people.

The demand for Colorado River water has increased greatly as the population of the Southwestern United States has grown and as the maintenance and the development of ecological habitats has become a priority. Recent (2000) estimates of demand for Colorado River water in the Lower Colorado River Basin (parts of Utah, Arizona, Nevada, and California) are for irrigation of 2.7 million acres of land and municipal supply for 18 million people (Paul Matuska, Bureau of Reclamation, Lower Colorado River Regional Office, written commun., 2000). In contrast, Stanley (1960, p. 84) estimated that in 1949 Colorado River water was used to irrigate 500,000 acres of crops in Arizona and California and 300,000 acres of crops in Mexico and was used as municipal supply for 3.5 million people in California. Bureau of Reclamation (2000, p. 1) reported that in 1999 a total 10.95 million acre-ft of Colorado River water was used by the lower basin States (7.98 million acre-ft) and Mexico (2.97 million acre-ft).

Accurate estimates of water-budget components of a reservoir system are required to manage increased demands for available water supplies. Budget components such as withdrawals, diversions, return flows, change in storage contents, and tributary inflows usually can be quantified with direct measurements. Natural losses from the reservoir system, such as open-water evaporation, seepage, and evapotranspiration from riparian vegetation, are quantified using methods that are more indirect. These components typically are estimated with a variety of methods such as empirically derived relations developed with data collected at other locations, calculations using data and results from regional studies, statistically distributing water-budget residuals to selected components, or applying reasonable assumptions about the hydrodynamics of a reservoir system.

Open-water evaporation is a significant loss of water from Lake Mead. From 1953 to 1994, evaporation of water from Lake Mead was estimated to be 6.4 ft/yr, or about 791,000 acre-ft/yr (based on an average surface area of 125,600 acres). From 1955 to August 1995, the U.S. Geological Survey (USGS) computed Lake Mead evaporation using a mass-transfer method. Data required for using this method are wind speed and water temperature, collected at a floating platform in Boulder Basin, and air temperature and vapor pressure, collected at an airport in Las Vegas, Nev., and reported by the National Weather Service (Harbeck, 1958a). In September 1995, the Bureau of Reclamation removed the floating platform from the lake and the wind-speed and water-temperature data required for the evaporation computation were no longer available. Alternative data sources (such as National Park Service data) were investigated, but due to the empirical nature of the method, were determined to be inadequate for estimating evaporation rates.

As a result, the Bureau of Reclamation proposed a cooperative study with the USGS to develop a method to estimate Lake Mead evaporation rates and to evaluate previously reported rates. The method developed by the USGS would be transferable to other large open-water areas managed by the Bureau of Reclamation or other agencies in the arid Southwest.

Purpose and Scope

This report presents the results of a study to refine estimates of evaporation from Lake Mead. Previously, estimated evaporation from Lake Mead (1955–95) may not be representative because of the methods used, and because some data used in the mass-transfer method were collected in the Las Vegas Valley rather than at the surface of the lake. In this report, previously used methods of computing evaporation are described, evaluated, and compared to those used in the current study for data collected for 1997–99, and to alternative methods of computing evaporation using modern (2005) equipment and techniques. Additionally, selected data collected during previous and current studies are summarized, including monthly and annual Lake Mead evaporation rates for 1952–95 and 1997–99.

To better refine estimates of evaporation from Lake Mead, atmospheric and water properties were collected from 1997 to 1999 at four floating platforms, which were installed in water of varying depth and fetch to sample differing environmental conditions at the lake. Near-continual data collected at Overton Arm, Boulder Basin, Virgin Basin, and near Callville Bay (fig. 1) were used with an energy-budget method to determine daily, monthly, and annual evaporation rates for 1997–99.

Estimating Evaporation from Lake Mead

Lake Mead evaporation was computed using micrometeorological data collected at four floating instrumented platforms deployed in Water Barge Cove near Callville Bay, in Boulder Basin near Sentinel Island, in the Virgin Basin, and in the Overton Arm near Echo Bay (fig. 1). Platform station identifier, name, and date of installation are listed in table 2.

The platform in Water Barge Cove (site A) was in a relatively shallow cove protected from prevailing winds (figs. 1 and 2). The platforms in Boulder Basin near Sentinel Island (site B), Virgin Basin (site C), and Overton Arm (site D) were in different areas of the lake that are representative of open-water conditions in each basin. The depth of water at the four platforms fluctuated during the study due to water-level changes of Lake Mead. Lake elevation ranged from less than 1,196 ft in February 1997 to almost 1,216 ft in September 1998 (fig. 3).

Figure 2. Four floating platforms on Lake Mead. Photographs taken by Craig L. Westenburg, U.S. Geological Survey.

Table 2. Site information for four floating instrumented platforms used to collect data to compute evaporation from Lake Mead, Arizona and Nevada, 1997–99.

[**Symbol**: –, not applicable]

Site	Station name	Location		Installation		Removal	
		Latitude	Longitude	Date	Water depth (feet)	Date	Water depth (feet)
A	Water Barge Cove	36º07'40"	114º43'36"	01-31-97	35	02-09-00	50
B	Sentinel Island	36º03'15"	114º45'05"	06-23-97	336	–	–
C	Virgin Basin	36º05'54"	114º27'45"	04-09-98	81	01-27-00	85
D	Overton Arm	36º18'31"	114º22'40"	03-01-99	65	05-05-00	61

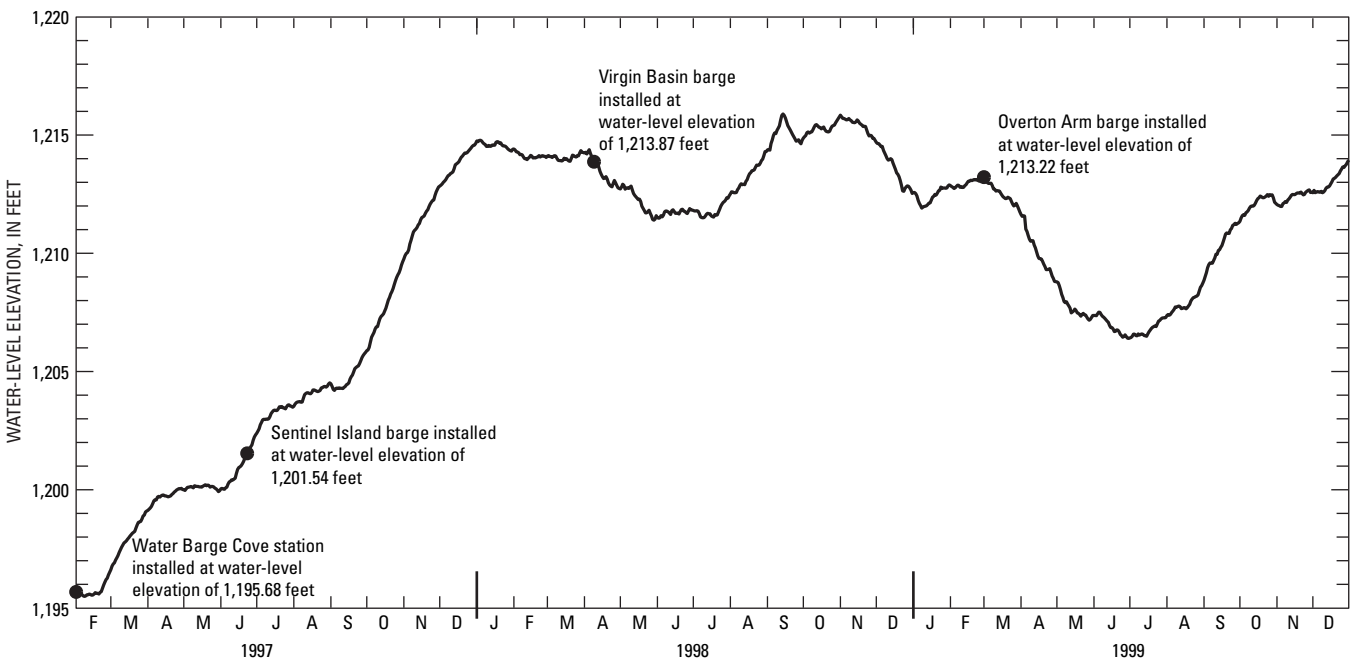


Figure 3. Lake Mead daily water-level elevation and date of station installation, February 1997–December 1999.

Each floating platform was equipped with instruments to measure and record meteorological data and water temperature. Air temperature and relative humidity were measured with a temperature-humidity probe (THP), wind speed and direction were measured with an anemometer and wind monitor, net radiation was measured with a net radiometer, and water temperature was measured at various depths with temperature probes (fig. 4, table 3). A two-point mooring system was used to secure each barge to prevent drifting and maintain the directional aspect of the wind monitor and net radiometer. The number of months with complete data, collected at four floating platforms for 1997–99, used to compute evaporation from Lake Mead is listed in table 4.

Table 3. Description of data, collected at four floating instrumented platforms, used to compute evaporation from Lake Mead, Arizona and Nevada, 1997–99.

[Symbol: –, no remark]

Type of measurement	Instrument used	Associated energy-budget term	Remarks
Net radiation	Net radiometer	Net radiation	–
Air temperature	Temperature-humidity probe	Bowen ratio	Measured 6.6 feet above the water surface.
Relative humidity	Temperature-humidity probe	Bowen ratio	Measured 6.6 feet above the water surface.
Water-surface temperature	Temperature probe	Bowen ratio, latent heat of vaporization	–
Water temperature below the surface	Temperature probe	Change in energy stored in water	Measured 3.3, 6.6, and 9.9 feet below surface or 6.6, 13.2, and 19.8 feet below water surface.
Wind speed	Anemometer	None	Measured 6.6 feet above the water surface.
Wind direction	Wind monitor	None	Measured 13.2 feet above the water surface, except 33.0 feet at Sentinel Island.

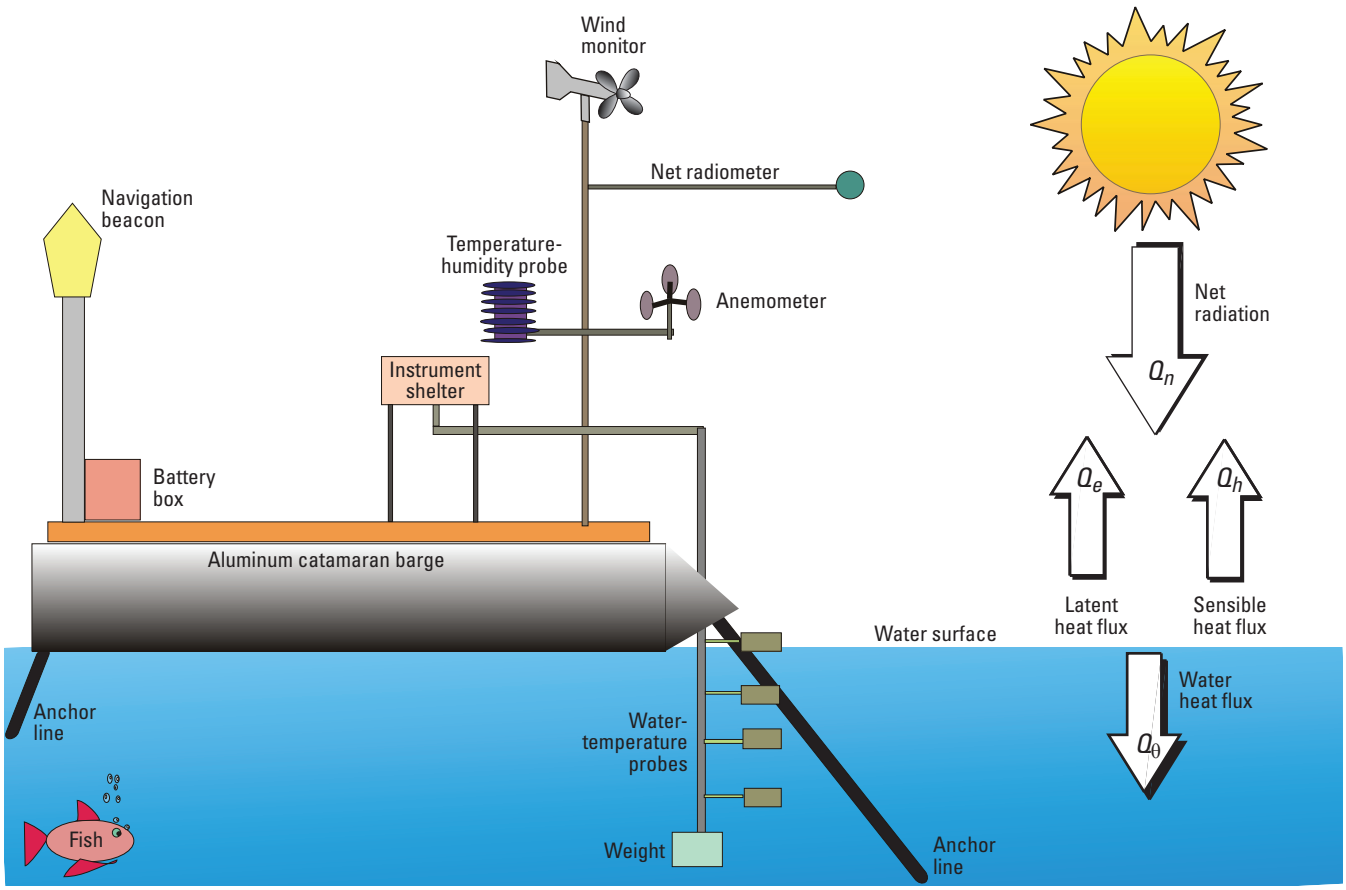


Figure 4. Instrument configuration on floating platforms on Lake Mead, Arizona and Nevada, and of energy fluxes at water surface.

Table 4. Number of months with complete data, collected at four floating instrumented platforms, used to compute evaporation from Lake Mead, Arizona and Nevada, 1997–99.

[Distances are height above water surface, except water temperature, which is depth below water surface. Symbol: –, no data]

Parameter	Water Barge Cove			Sentinel Island			Virgin Basin		Overton Arm
	1997	1998	1999	1997	1998	1999	1998	1999	1999
Air temperature									
6.6 feet	9	12	12	6	12	10	8	12	10
13.2 feet	9	12	–	–	–	–	–	–	–
33.0 feet	–	–	–	6	12	10	–	–	–
Relative humidity									
6.6 feet	9	12	12	6	12	10	8	12	10
13.2 feet	9	12	–	–	–	–	–	–	–
33.0 feet	–	–	–	6	12	10	–	–	–
Wind speed									
6.6 feet	9	12	12	5	12	10	8	12	9
13.2 feet	9	12	–	–	–	–	–	–	–
33.0 feet	–	–	–	6	12	10	–	–	–
Wind direction	–	9	12	–	10	10	–	9	10
Net radiation	9	12	12	6	12	10	8	12	10
Water temperature below surface	9	12	12	6	12	10	8	12	10
3.3 feet	9	12	–	–	–	–	–	–	–
6.6 feet	–	–	–	6	12	10	8	12	10
9.9 feet	9	12	–	–	–	–	–	–	–
13.2 feet	9	12	12	6	12	10	8	12	10
19.8 feet	–	–	–	6	12	10	8	12	10

Energy-Budget Method

The energy-budget method was used to measure evaporation from Lake Mead. This method also was used to quantify evaporation from western reservoirs in the 1950s (Anderson, 1954), and has been used by the USGS on a few long-term lake studies (Sturrock and Rosenberry, 1992; Rosenberry and others, 1993; Swancar and others, 2000). The energy-budget method is the most accurate method for measuring lake evaporation (Winter, 1981). Use of the energy-budget method requires a large amount of data collection, but the effort is important because accurate measurements of lake evaporation are rare. An energy budget is similar to a water budget in that the change in stored energy is equal to the fluxes in and out of the system. Energy drives the process of evaporation because the water at the surface of the lake must absorb a certain amount of energy (latent heat of vaporization; approximately 580 calories per gram) before the water will evaporate. After some derivation, the following equation is used to calculate evaporation from the lake (Anderson, 1954):

$$E = (Q_s - Q_r - Q_b + Q_v - Q_\theta)/[\rho L(R + 1)], \qquad (1)$$

where

E is evaporation rate,
Q_s is the solar radiation incident to the water surface,
Q_r is the reflected solar radiation,
Q_b is the net energy lost by the body of water through the exchange of long-wave radiation between the atmosphere and the body of water,
Q_v is the net energy advected into the body of water,
Q_θ is the change in energy stored in the body of water,
ρ is the density of evaporated water,
L is the latent heat of vaporization, and
R is the Bowen ratio.

Bowen (1926) expressed the ratio as:

$$R = \gamma[T_0 - T_a)/(e_0 - e_a)]P, \qquad (2)$$

where

γ is an empirical constant,
T_0 is the temperature of the water surface,
T_a is the temperature of the air,
e_0 is the vapor pressure of saturated air at the temperature (T_0),
e_a is the vapor pressure of the air above the water surface, and
P is atmospheric pressure.

Net radiation (Q_n) was measured at Lake Mead evaporation platforms and replaces three energy terms (Q_s, Q_r, and Q_b) in equation 1. Net advected energy (Q_v) is disregarded based on the assumption that advected energy is negligible during a 20-minute evaporation period.

Thus, after modifying equation 1 by substituting for net radiation, removing the net advected energy term, and replacing R with equation 2, evaporation can be estimated from measured meteorological and hydrological parameters:

$$E = (Q_n - Q_\theta)/[\rho L \gamma_c[(T_0 - T_a)/(e_0 - e_a)] + 1], \quad (3)$$

where $\gamma_{c,}$ is a psychrometric constant, a product of γ and P (Laczniak and others, 1999, p. 20–21).

Meteorological Data

Meteorological and water temperature data were used to compute evaporation rates for Lake Mead. Measurements were made every 10 or 30 seconds and were averaged for 20-minute periods. Some of the missing or incorrect 20-minute data were estimated or computed to maximize the amount of data available for the evaporation computation. Where data were missing for short periods, they were estimated from trends of the data before and after the periods of missing or incorrect data. Where data were missing or incorrect for longer periods, they were computed from other available data at that station, data from another station, or data for another year. Typically, a regression was developed with two sets of measurements for a different period, but for similar environmental conditions, using a complete set of data. The regression was then used to estimate the missing or incorrect data from a complete set of data.

Monthly values of meteorological data and water temperatures were computed from 20-minute averaged data collected at each station for 1997, 1998, and 1999 (table 5). Average daily air temperature was about the same at all four platforms (fig. 5), whereas relative humidity and water temperature were similar at the open-water platforms. Generally, water temperature was higher and relative humidity was lower at the sheltered cove platform (Water Barge Cove) than at the open-water platforms.

Daily air temperature, water temperature, and relative humidity at the Sentinel Island station were compared for 1997, 1998, and 1999 (fig. 6). Air temperature varies from year to year, but the seasonal pattern is consistent. The maximum daily air temperature occurs about mid-July, with some daily average air temperatures exceeding 95ºF, and the minimum daily air temperature occurs from late December through February. Water temperature did not vary much from year to year. Maximum daily water temperature occurs in late July to early August and the minimum daily water temperature occurs in late February. Relative humidity fluctuated from day to day and differed greatly from year to year (fig. 6). However, there is a seasonal pattern of high relative humidity in January that gradually decreases to a low at the end of June, followed by a gradual increase to higher relative humidity in December.

Daily average wind-speed and direction data for 1999 are plotted in figure 7. Points are plotted a distance from the origin relative to the wind speed and in the direction from the origin that represents wind direction (measured with zero degrees (0º) corresponding to a north wind). Thus, a daily average wind speed of 5 mi/hr with a direction of 120º would be plotted on the circle representing 5 mi/hr and in the lower right quadrant. Daily average wind speeds of less than 1 mi/hr were not plotted to avoid a dense cluster of points at the origin. Wind direction was predominately from the southeast to the southwest, occasionally from the northwest, and rarely from the northeast. Most daily wind speeds were less than 10 mi/hr. The Virgin Basin location experienced more daily wind greater than 10 mi/hr than other locations.

Table 5. Monthly mean meteorological and water-temperature data measured at four floating instrumented platforms on Lake Mead, Arizona and Nevada, 1997–99.

[Symbol: –, no data]

Site	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1997												
Air temperature, in degrees Fahrenheit												
Water Barge Cove	–	54.3	62.6	66.2	90.32	83.12	86.9	88.9	81.3	68.4	58.5	48.6
Sentinel Island	–	–	–	–	–	–	90.1	90.7	81.9	76.8	59.7	50.4
Virgin Basin	–	–	–	–	–	–	–	–	–	–	–	–
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Water temperature at water surface, in degrees Fahrenheit												
Water Barge Cove	–	55.9	59.5	62.1	68.5	78.1	81.9	84.4	82.6	74.1	66.2	59.9
Sentinel Island	–	–	–	–	–	–	79.7	82.6	81.1	79.9	65.8	57.2
Virgin Basin	–	–	–	–	–	–	–	–	–	–	–	–
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Water temperature, in degrees Fahrenheit, measured at 6.6 feet below the water surface												
Water Barge Cove	–	55.9	58.6	61.3	75.0	77.0	80.6	83.1	81.5	73.4	65.8	59.7
Sentinel Island	–	–	–	–	–	–	79.0	81.7	80.4	72.9	65.5	59.5
Virgin Basin	–	–	–	–	–	–	–	–	–	–	–	–
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Relative humidity, in percent												
Water Barge Cove	–	40	34.9	33.6	25.0	29.6	31.5	37.9	47.9	37.5	47.9	43.0
Sentinel Island	–	–	–	–	–	–	33.8	38.5	50.1	44.0	50.1	45.7
Virgin Basin	–	–	–	–	–	–	–	–	–	–	–	–
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Wind speed, in miles per hour, measured at 6.6 feet above the water surface												
Water Barge Cove	–	6.02	5.12	6.91	6.35	7.52	5.48	6.38	4.54	5.37	3.53	4.41
Sentinel Island	–	–	–	–	–	–	5.75	–	7.16	7.63	6.69	7.83
Virgin Basin	–	–	–	–	–	–	–	–	–	–	–	–
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
1998												
Air temperature, in degrees Fahrenheit												
Water Barge Cove	49.8	50.5	56.3	61.2	69.4	79.0	89.1	89.8	80.6	67.8	56.7	49.1
Sentinel Island	51.1	51.3	56.8	61.2	69.4	78.8	89.1	89.8	81.0	68.7	58.3	50.9
Virgin Basin	–	–	–	61.9	68.4	77.2	87.1	87.8	78.8	66.7	56.1	48.4
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Water temperature at water surface, in degrees Fahrenheit												
Water Barge Cove	56.7	55.8	57.9	61.0	68.4	75.0	84.2	85.6	82.2	72.7	65.3	59.5
Sentinel Island	55.8	54.7	56.3	59.4	65.1	72.5	81.0	83.3	81.0	71.6	65.0	59.4
Virgin Basin	–	–	–	59.0	63.3	70.5	80.6	82.9	79.9	70.2	63.9	57.9
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Water temperature, in degrees Fahrenheit, measured at 6.6 feet below the water surface												
Water Barge Cove	56.7	56.1	58.3	61.2	68.3	74.7	83.3	84.7	81.7	72.3	65.3	59.7
Sentinel Island	56.1	55.0	56.3	59.4	64.8	72.0	81.1	83.5	81.0	71.6	65.0	59.4
Virgin Basin	–	–	–	59.4	64.0	71.2	81.3	83.5	80.6	70.9	64.4	58.6
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Relative humidity, in percent												
Water Barge Cove	55.3	58.0	50.3	43.3	36.2	33.1	37.7	36.4	41.9	38.5	47.4	41.8
Sentinel Island	57.0	58.6	50.3	43.3	37.0	34.3	39.2	38.3	44.0	41.7	47.6	45.6
Virgin Basin	–	–	–	44.2	39.5	36.6	43.6	43.2	48.8	46.3	52.8	51.3
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Wind speed, in miles per hour, measured at 6.6 feet above the water surface												
Water Barge Cove	4.38	7.65	5.91	6.85	7.14	6.00	6.17	6.40	6.13	5.10	4.88	6.60
Sentinel Island	6.58	9.57	8.37	8.26	9.17	7.87	7.67	7.36	6.89	7.94	7.47	9.44
Virgin Basin	–	–	–	8.19	9.87	9.15	8.03	8.05	8.43	7.87	7.70	9.04
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–

Table 5. Monthly mean meteorological and water-temperature data measured at four floating platforms on Lake Mead, Arizona and Nevada, 1997–99.—Continued

[Symbol: –, no data]

Site	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1999												
Air temperature, in degrees Fahrenheit												
Water Barge Cove	51.1	52.3	59.5	59.5	72.9	82.9	86.2	87.3	81.7	70.3	59.4	50.9
Sentinel Island	52.2	53.2	59.9	59.5	72.7	82.9	86.4	87.3	82.2	72.9	–	–
Virgin Basin	49.6	51.4	58.1	58.5	70.7	80.6	84.7	85.6	79.7	68.9	58.1	58.2
Overton Arm	–	–	58.1	58.8	71.1	80.8	84.9	86.5	80.6	68.5	57.6	49.6
Water temperature at water surface, in degrees Fahrenheit												
Water Barge Cove	56.1	55.4	58.1	59.9	68.2	77.2	81.1	82.4	80.4	73.6	66.6	59.4
Sentinel Island	55.8	54.9	55.9	58.8	66.2	72.9	79.3	81.5	79.2	72.3	–	–
Virgin Basin	55.0	54.3	55.9	58.1	65.1	71.8	79.7	81.7	79.2	72.3	65.7	59.2
Overton Arm	–	–	56.7	59.7	66.6	75.4	81.9	83.5	81.9	75.0	68.0	60.8
Water temperature, in degrees Fahrenheit, measured at surface and 6.6 feet below water surface												
Water Barge Cove	56.3	55.8	57.9	59.5	68.2	77.2	82.2	83.5	81.9	75.0	68.0	60.8
Sentinel Island	55.9	54.9	55.9	58.6	66.0	73.2	79.7	81.7	80.4	75.2	–	–
Virgin Basin	55.6	54.9	56.7	58.8	65.8	72.5	80.6	82.0	79.7	72.5	65.8	58.8
Overton Arm	–	–	56.7	59.0	65.8	75.0	81.5	82.9	80.1	71.2	64.9	58.1
Relative humidity, in percent												
Water Barge Cove	44.5	43.8	38.3	39.9	31.1	29.0	41.0	35.0	36.5	33.4	40.3	37.4
Sentinel Island	48.4	47.7	39.9	42.8	35.3	28.8	42.7	37.3	39.7	39.0	–	–
Virgin Basin	53.3	52.1	44.2	46.6	38.8	32.8	48.3	42.5	45.8	41.7	48.5	46.7
Overton Arm	–	–	47.1	48.4	39.9	38.4	50.7	42.5	43.2	40.9	47.8	44.5
Wind speed, in miles per hour, measured at 6.6 feet above the water surface												
Water Barge Cove	5.03	5.06	6.42	6.64	7.40	5.91	6.76	6.40	5.15	4.18	3.74	4.77
Sentinel Island	8.05	7.32	8.64	9.19	7.61	9.22	8.55	7.38	8.41	9.02	–	–
Virgin Basin	7.20	7.58	9.11	9.73	8.14	9.75	8.34	7.76	8.21	7.96	6.67	9.26
Overton Arm	–	–	9.24	9.62	8.19	9.37	8.43	7.65	6.47	5.62	8.32	–

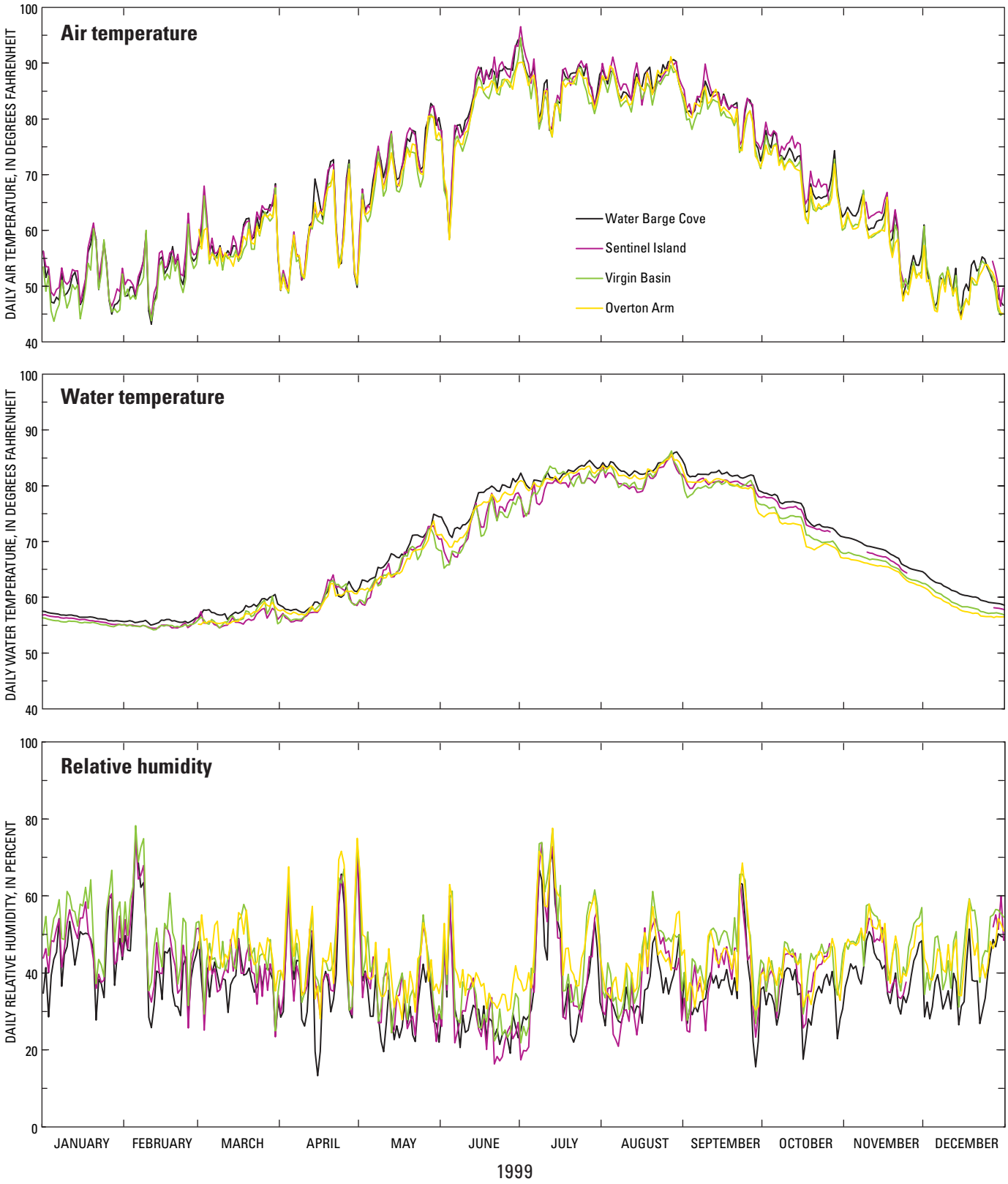


Figure 5. Air temperature, water temperature, and relative humidity collected at four floating instrumented platforms on Lake Mead, Arizona and Nevada, 1999. See figure 1 and table 2 for platform locations and site information.

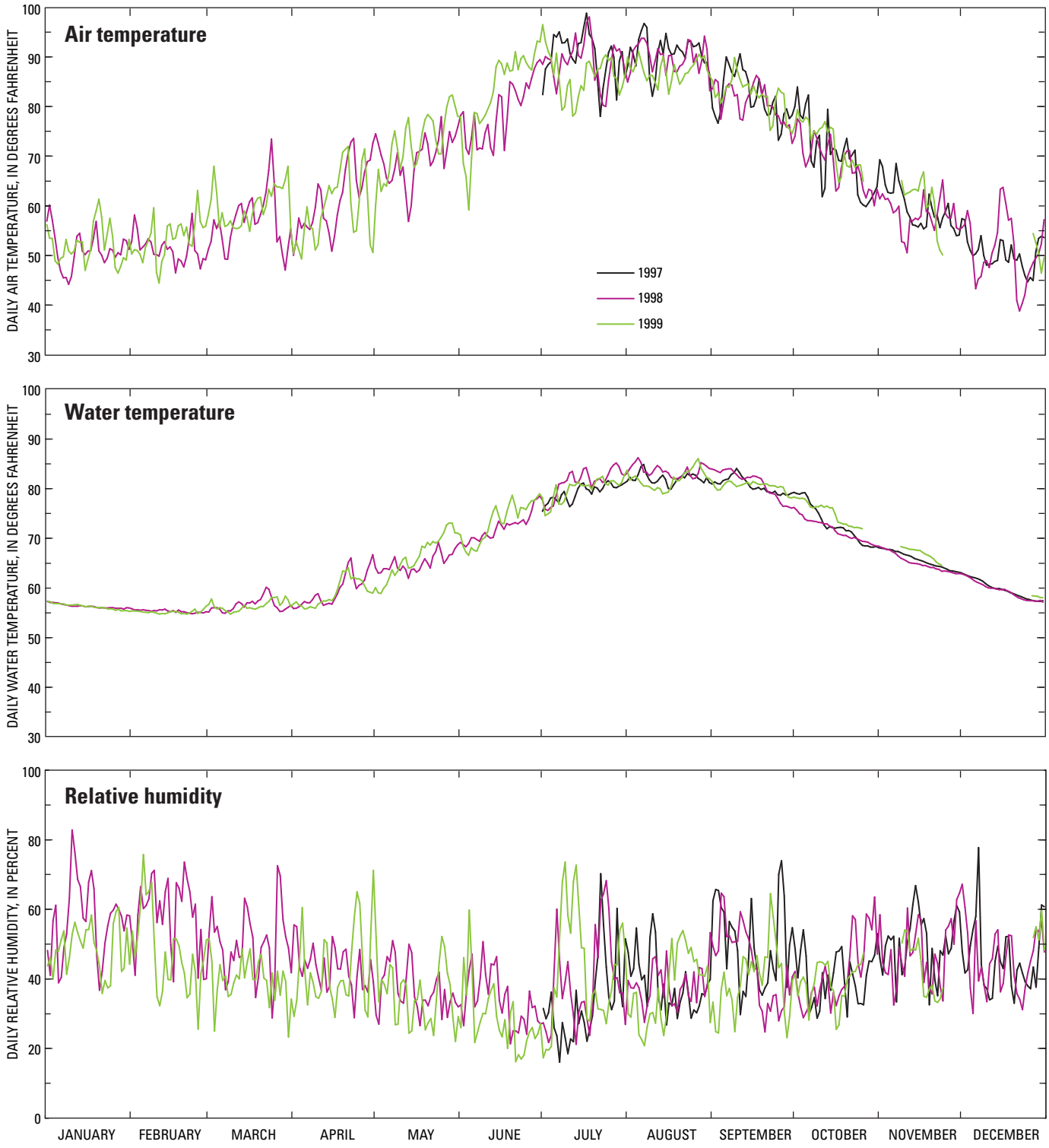


Figure 6. Air temperature, water temperature, and relative humidity collected at the Sentinel Island evaporation station, Nevada, 1997–99.

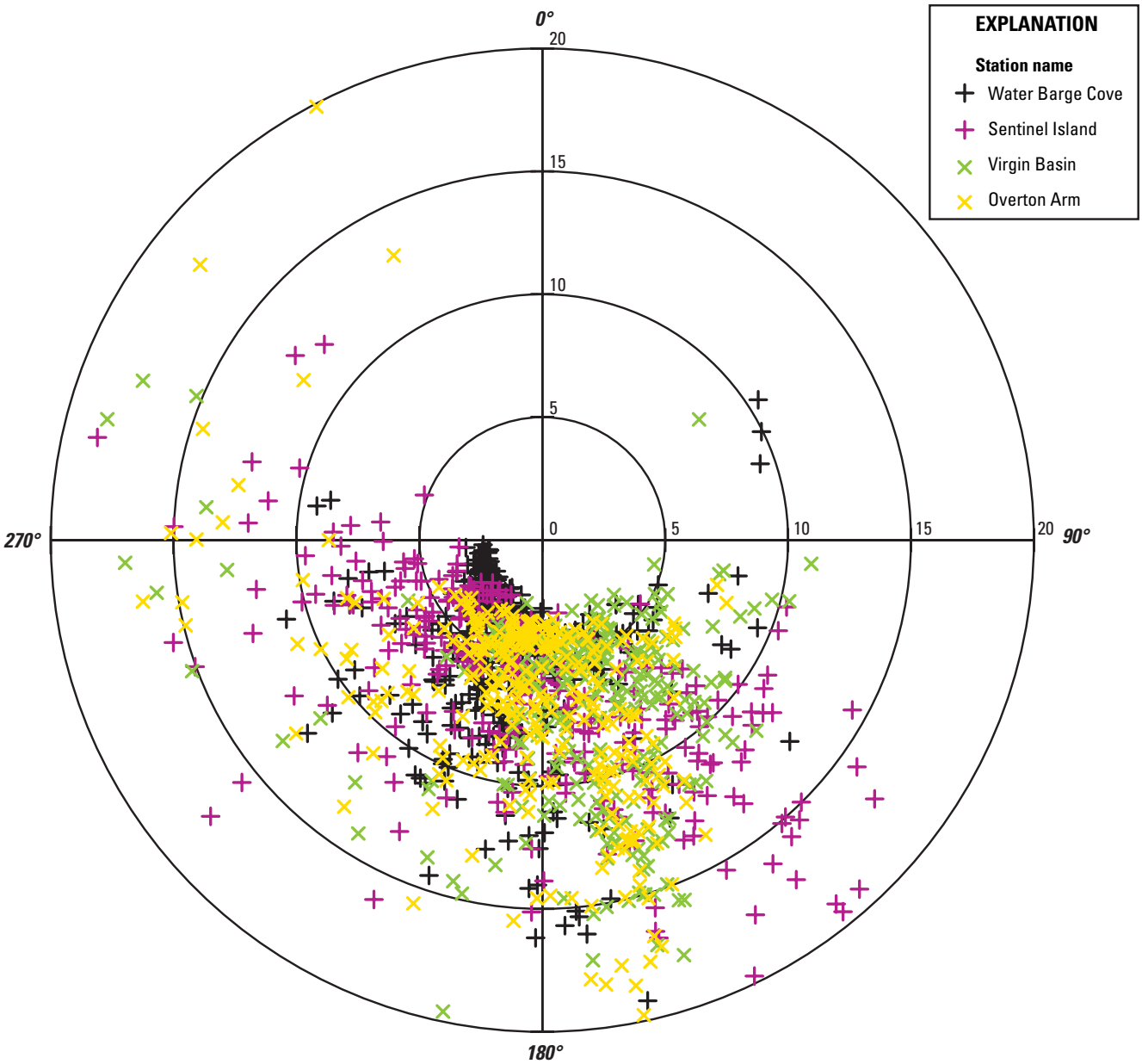


Figure 7. Wind speed and direction at four floating instrumented platforms on Lake Mead, Arizona and Nevada, 1999.

Evaporation Rates

Evaporation rates were computed at 20-minute intervals to evaluate diurnal fluctuations of lake evaporation. The 20-minute period evaporation rates also were used to identify periods of poor or missing energy-budget data. Daily evaporation rates are the sum of 20-minute periods, monthly rates are the sum of daily evaporation and annual rates are the sum of monthly evaporation.

Daily Rates

Daily evaporation rates at the four evaporation stations were compared for calendar year 1999 (fig. 8) and showed similar daily fluctuations. However, the magnitude of fluctuations in daily evaporation was greater at Virgin Basin and Sentinel Island than at Overton Arm or Water Barge Cove. Daily evaporation was greatest from late June through early July and was least from mid-December through late January.

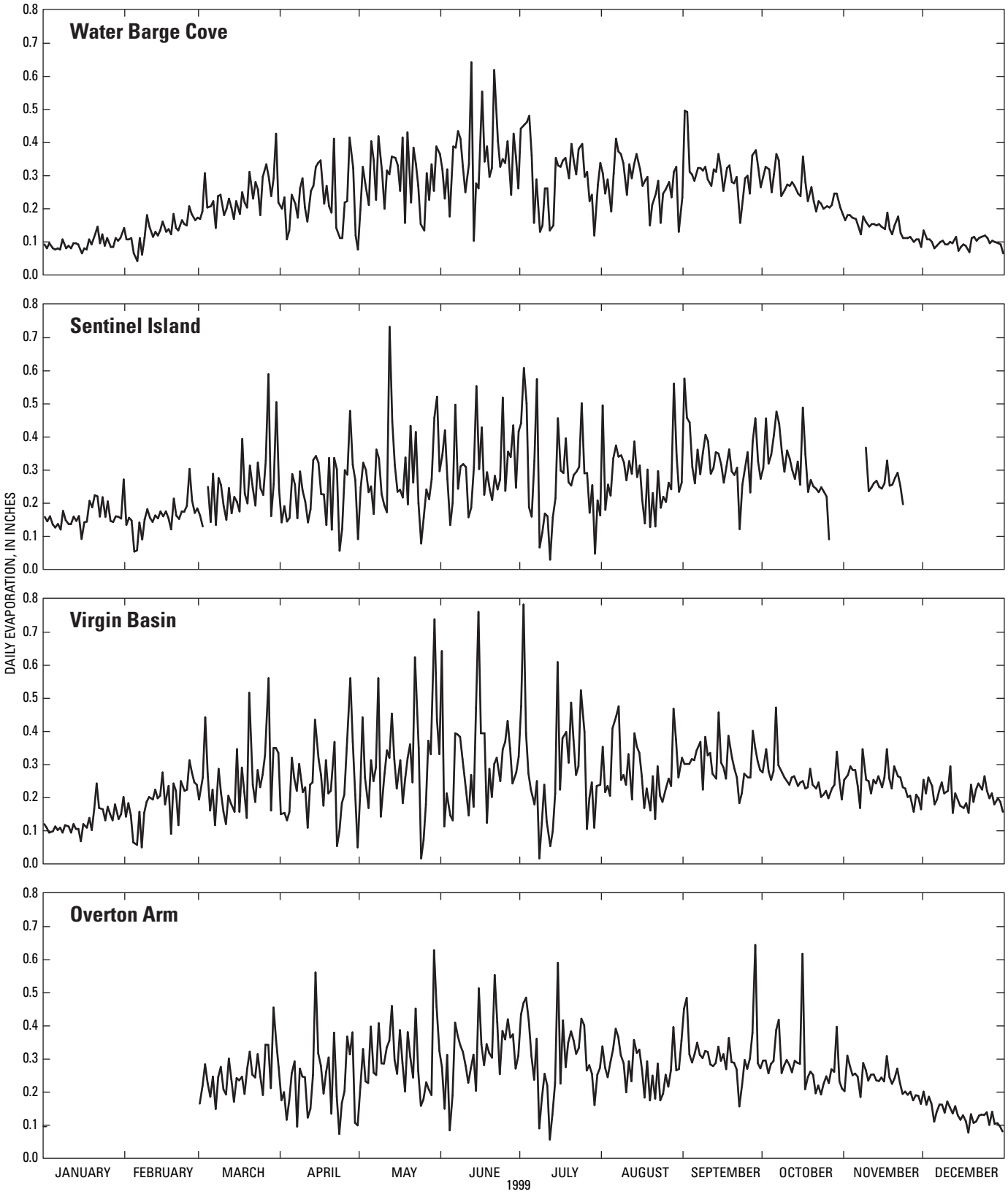


Figure 8. Daily evaporation rates at four floating instrumented platforms at Lake Mead, Arizona and Nevada, 1999.

Monthly Rates

To evaluate the temporal variation in monthly evaporation at each station, monthly evaporation rates for each station were averaged and compared to the total evaporation rate for each month of data collection. Temporal data were available for Water Barge Cove, Sentinel Island, and Virgin Basin stations (table 6); however, monthly data were insufficient for the Overton Arm station to compute average monthly evaporation. Total monthly evaporation rates at three stations, with some exceptions, generally were within 10 percent of average monthly rates; consequently, annual variation in monthly evaporation typically was minimal between 1997 and 1999. Some months, however, exhibited significant differences between average and total evaporation. These differences were as great as 31 percent at Water Barge Cove (February 1997; fig. 9*A*), 14 percent at Sentinel Island (January 1998 and 1999; fig. 9*B*), and 22 percent at Virgin Basin (December 1998 and 1999; fig. 9*C*). Some of the difference in monthly evaporation rates from year to year may be due to errors in meteorological and water-temperature data collected at each station, but year-to-year differences for most months likely are due to actual differences in evaporation.

To evaluate the spatial variation in evaporation, total monthly evaporation rates at all four stations were averaged for every month of data collection and the average was compared to the total monthly evaporation rate at each station (fig. 10*A*). For each station, total monthly evaporation rates compared well to average monthly rates with correlation coefficients of 0.96 or higher. However, total monthly evaporation at Water Barge Cove generally was less than total evaporation rates at the open-water stations when rates were less than 6.5 in. Total monthly evaporation rates for all three open-water stations were nearly equal and compared well to average evaporation rates (fig. 10*B*); correlation coefficients for Sentinel Island and Overton Arm were 0.98, and for Virgin Basin was 0.96. This evaluation suggests that the spatial variation in evaporation is minimal for open-water areas of Lake Mead.

The monthly volume of evaporated water was computed using the average monthly open-water evaporation rate, in feet, and the average monthly surface area of Lake Mead for July 1997 through December 1999, in acres, (calculated from water elevation data at URL: <http://www.usbr.gov/lc/riverops.html> and the Reclamation area capacity tables, Bureau of Reclamation, 1967). The volume of water evaporated in 1 month ranged from 46,000 acre-ft in February 1998 to 126,000 acre-ft in July 1998.

Table 6. Total and average monthly evaporation from Lake Mead at four floating instrumented platforms, Arizona and Nevada, 1997–99.

[Evaporation data, in inches. **Symbol:** –, data not measured or computed]

Site	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Total monthly evaporation, 1997												
Water Barge Cove	–	5.4	9.1	7.9	–	10.8	10.8	9.2	8.3	7.6	4.1	2.6
Sentinel Island	–	–	–	–	–	–	9.1	9.1	8.8	8.7	6.4	4.6
Virgin Basin	–	–	–	–	–	–	–	–	–	–	–	–
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Total monthly evaporation, 1998												
Water Barge Cove	2.9	3.2	6.6	8.2	8.9	10.2	10.1	8.8	8.5	6.7	3.7	2.6
Sentinel Island	3.7	3.6	7.1	7.4	9.9	9.4	10.0	8.9	8.9	8.5	7.3	6.0
Virgin Basin	–	–	–	8.6	9.7	9.1	9.9	8.7	9.7	7.1	5.9	4.1
Overton Arm	–	–	–	–	–	–	–	–	–	–	–	–
Average evaporation, 1998												
All available sites	3.3	3.4	6.9	8.0	9.5	9.6	10.0	8.8	9.0	7.4	5.6	4.2
Open-water sites	3.7	3.6	7.1	8.0	9.8	9.2	9.9	8.8	9.3	7.8	6.6	5.0
Total monthly evaporation, 1999												
Water Barge Cove	3.0	3.8	7.4	6.8	9.2	10.5	9.4	8.7	9.4	8.0	4.3	3.1
Sentinel Island	5.0	4.4	8.1	6.9	9.0	9.2	8.4	8.6	9.9	8.8	6.7	–
Virgin Basin	4.0	5.3	7.9	7.1	9.6	9.3	8.8	8.7	9.1	8.0	7.3	6.5
Overton Arm	–	–	7.8	6.9	9.5	9.5	9.4	8.6	9.5	8.7	7.0	4.1
Average evaporation, 1999												
All available sites	4.0	4.5	7.8	6.9	9.3	9.6	9.0	8.6	9.5	8.4	6.3	4.5
Open-water sites	4.5	4.8	8.0	7.0	9.4	9.4	8.9	8.6	9.5	8.5	7.0	5.3

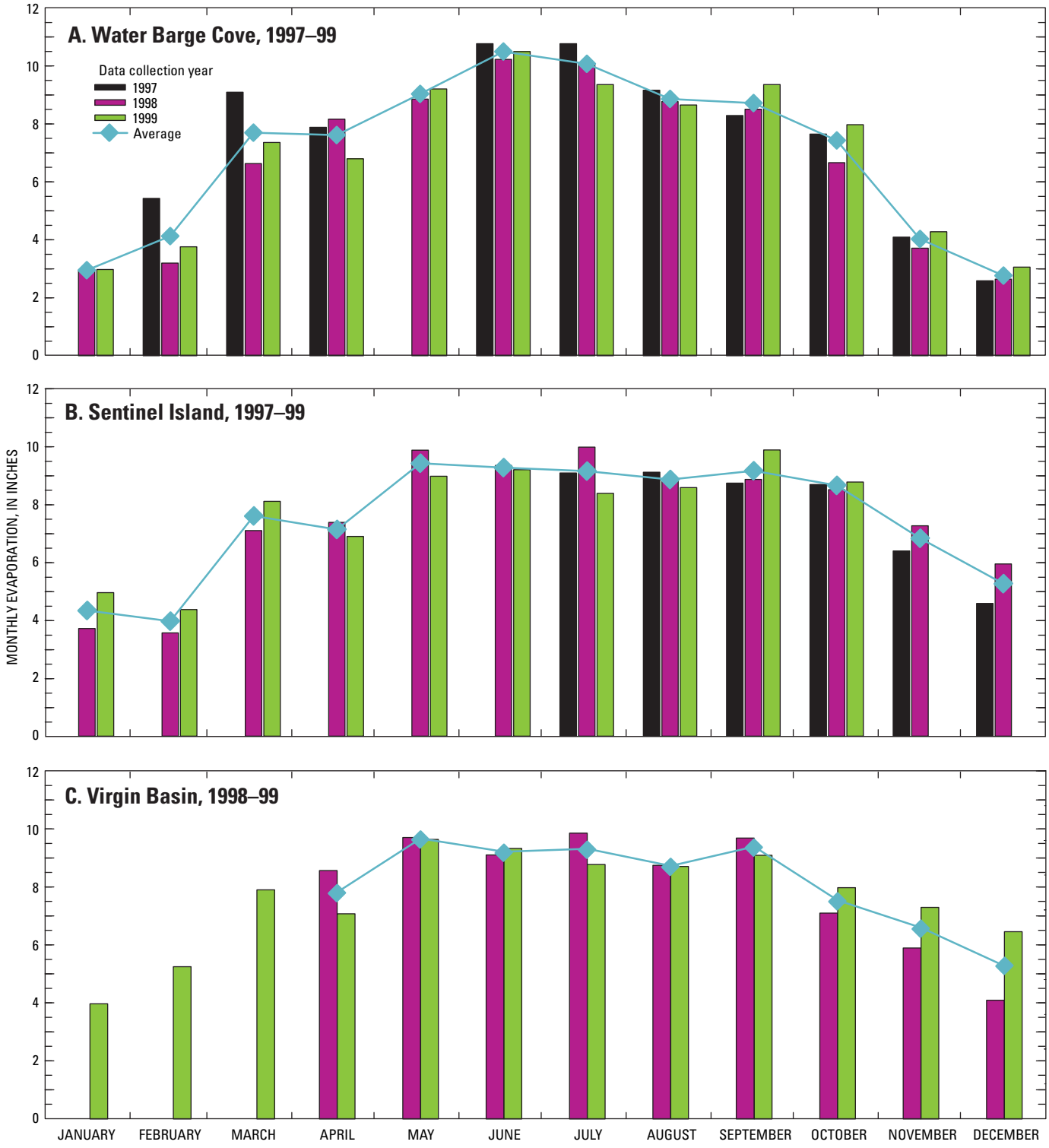


Figure 9. Total and average monthly evaporation at three floating instrumented platforms on Lake Mead, Arizona and Nevada, 1997–99.

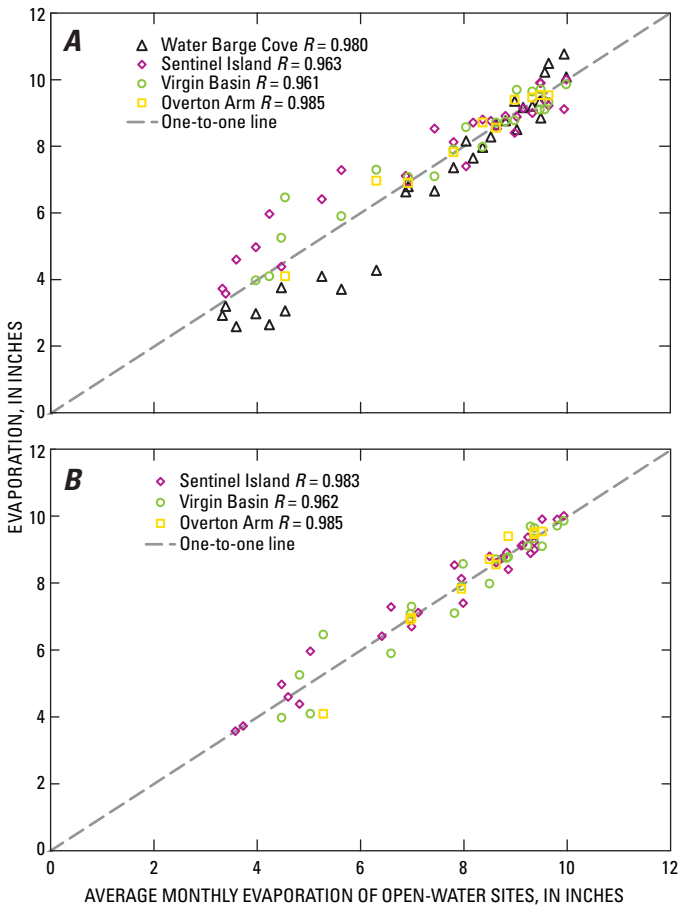


Figure 10. Comparison of total monthly evaporation at (*A*) four evaporation stations with average monthly evaporation at all stations and (*B*) three open-water evaporation stations with average monthly evaporation at open-water stations, April 1998–October 1999. *R* is correlation coefficient.

Annual Rates

The average monthly rates for the Lake Mead open-water evaporation stations were computed for 1998 and 1999. For open-water stations, the sum of the average monthly rates for 1998 was 88.9 in. (7.4 ft) and the sum for 1999 was 90.7 in. (7.6 ft; table 7). For these 2 years, the average annual Lake Mead evaporation rate was 89.8 in. (7.5 ft). Monthly evaporation rates were available for only the Sentinel Island station for January–March 1998, and those rates are used instead of an average rate.

Evaporation rates at the Sentinel Island station are generally representative of evaporation of the lake as a whole. For April 1998 through November 1999, the total evaporation at the Sentinel Island station was 161.3 in., whereas, the total of average monthly evaporation for the open-water stations was 159.9 in. The difference of 1.4 in. is less than 1 percent of the total average open-water evaporation.

The annual volume of water evaporated from Lake Mead exceeded 1.1 million acre-ft in 1998 and 1999 (table 7), which probably is higher than a long-term average annual evaporation due to higher-than-normal lake elevations and corresponding larger-than-normal surface area for the period. For example, the average surface area of Lake Mead was 125,000 acres from 1942 to 1995 and the computed average annual evaporation rate was 7.5 ft from 1997 to 1998, which would equal a long-term average annual volume of 937,500 acre-ft of evaporated water.

Table 7. Average monthly evaporation and computed monthly evaporative loss from Lake Mead, Arizona and Nevada, July 1997–December 1999.

[Evaporation rate, in inches, are average rates for available open-water sites (table 6). Volume of water was computed by multiplying average open-water evaporation rates, converted to feet, by lake-surface area, in acres. Lake-surface area derived from area-capacity tables and mean daily elevation. For October 1997, monthly evaporation at Water Barge Cove was used. **Symbol:** –, data not computed]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
							Evaporation, in inches						
1997	–	–	–	–	–	–	9.1	9.1	8.8	8.7	6.4	4.6	–
1998	3.7	3.6	7.1	8.0	9.8	9.2	9.9	8.8	9.3	7.8	6.6	5.0	88.9
1999	4.5	4.8	8.0	7.0	9.4	9.4	8.9	8.6	9.5	8.5	7.0	5.3	90.7
Average	4.1	4.2	7.5	7.6	9.6	9.3	9.3	8.8	9.2	8.3	6.7	5.0	[1]89.8
							Evaporation, in acre-feet						
1997	–	–	–	–	–	–	112,000	112,000	108,000	109,000	81,000	59,000	–
1998	48,000	46,000	91,000	102,000	125,000	117,000	126,000	113,000	119,000	101,000	85,000	64,000	1,137,000
1999	57,000	61,000	101,000	88,000	117,000	116,000	110,000	108,000	120,000	108,000	89,000	67,000	1,142,000

[1]Average annual evaporation rate is only for 1998–99.

Previously Reported Evaporation Rates

The reported average annual evaporation of 6.4 ft from 1953 through 1994 (fig. 11, table 8) is 15 percent less than the estimated average annual evaporation of 7.5 ft from 1997 to 1999. The USGS reported monthly evaporation rates for Lake Mead from October 1953–September 1995 (U.S. Geological Survey, 1961–64, 1965–75, 1976–82; Hendricks, 1964; Frisbie and others, 1983–85; Pupacko and others, 1988, 1989a, 1989b, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993; Emett and others, 1994; Clary and others, 1995; Bauer and others, 1996). Harbeck (1958b, table 13, p. 37) reported monthly evaporation rates for March 1952 to September 1953. G.E. Koberg (U.S. Geological Survey, written commun., 1964) revised the reported monthly evaporation rates for October 1952 to September 1962; however, those revised rates were never published. Koberg did not revise the reported monthly rates for March 1952 to September 1952. Previously reported evaporation rates were not entered in a database or summarized in any single publication; these rates were available only from the various publications and written communications.

The average annual evaporation, average monthly evaporation, and standard deviation of monthly rates were compared for two periods of previously estimated Lake Mead evaporation, 1953–73 and 1974–94. Evaporation rates were available for 12 months of each year during those periods and each period consists of 21 years (table 8). The average annual evaporation for 1953–73 is 6.7 ft; whereas, the average annual evaporation for 1974–94 is 6.0 ft. Compared to 1974–94, the mean monthly evaporation during 1953–73 was greater for every month except November.

The standard deviation (variability) of monthly evaporation rates for 1953–73 was less than for 1974–94 for every month except May. Only the annual rates of 5.9 ft in 1965 and 7.4 ft in 1956 differed from the average annual rate of 6.7 ft for 1953–73 by greater than 10 percent. In contrast, annual evaporation was more variable for 1974–94 with rates for 9 years that differed by more than 10 percent from the average annual rate of 6.0 ft. The greater variability probably was related to estimated monthly wind speed due to mechanical problems with the anemometer at Lake Mead.

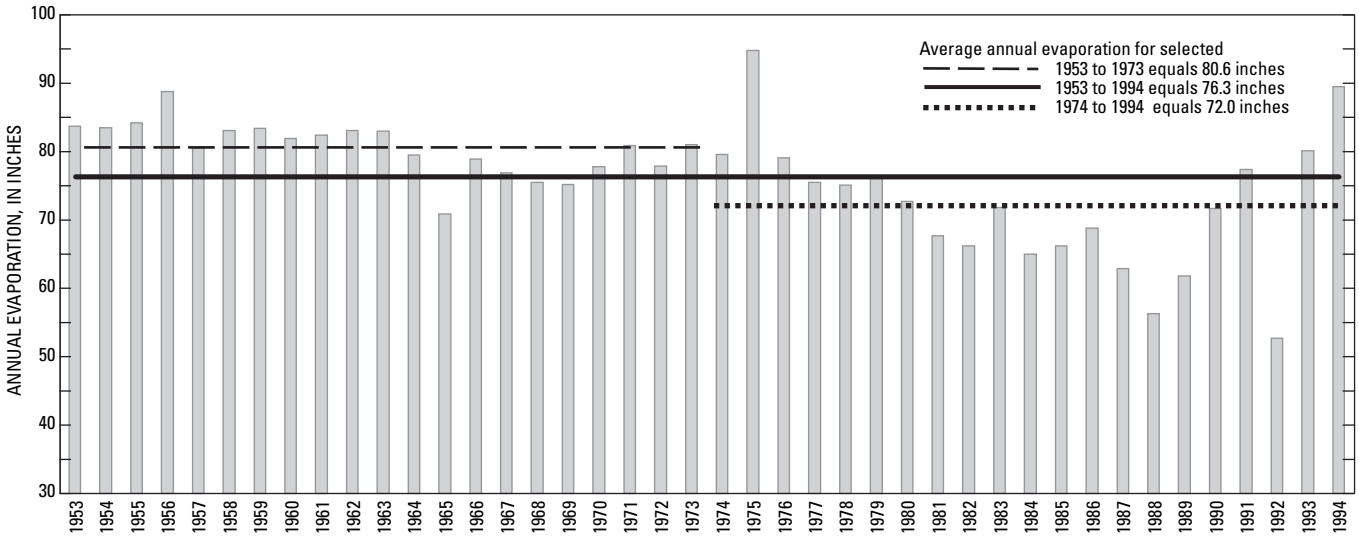


Figure 11. Annual Lake Mead evaporation, 1953–94.

Table 8. Total monthly, total annual, and average monthly Lake Mead evaporation, 1953–95.

[Historical references for this table are U.S. Geological Survey, 1961–64, 1965–75, 1976–82; Hendricks, 1964; Frisbie and others, 1983–85; Pupacko and others, 1988, 1989a, 1989b, 1990; Bostic and others, 1991; Garcia and others, 1992; Hess and others, 1993; Emett and others, 1994; Clary and others, 1995; and Bauer and others, 1996. Symbol: –, no data available]

	Total evaporation, in inches												
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1953	4.1	4.4	4.7	6.2	8.6	8.0	7.6	10.6	8.8	7.3	6.5	6.9	83.7
1954	4.3	3.6	5.9	5.5	8.3	8.3	9.8	9.6	8.4	8.2	5.5	6.1	83.5
1955	5.0	4.2	5.4	7.0	7.3	7.9	9.3	8.1	10.5	7.3	7.6	4.6	84.2
1956	4.1	4.8	5.2	5.9	7.9	9.5	9.3	11.5	7.8	9.1	7.9	5.8	88.8
1957	3.8	2.6	4.8	6.0	6.2	8.3	8.9	10.7	7.6	7.7	8.2	5.7	80.5
1958	4.9	2.7	4.9	4.0	8.1	9.5	10.5	9.6	9.5	8.6	6.5	4.3	83.1
1959	4.2	3.8	5.1	5.1	8.1	8.4	9.6	9.5	9.8	8.0	6.1	5.7	83.4
1960	3.6	4.6	4.6	6.0	7.0	9.0	9.4	11.9	7.1	7.3	5.8	5.6	81.9
1961	3.5	3.7	5.0	5.0	8.2	9.1	9.8	9.0	9.9	8.2	6.3	4.7	82.4
1962	4.5	3.2	6.0	4.2	8.0	8.0	10.2	11.0	8.8	9.2	5.4	4.6	83.1
1963	5.5	3.9	4.7	6.4	7.2	8.0	10.6	10.2	7.5	6.6	7.0	5.4	83.0
1964	5.2	4.8	5.0	6.0	4.6	7.4	10.2	9.3	8.7	6.3	7.1	4.9	79.5
1965	3.4	3.8	4.0	4.2	6.3	7.1	7.9	9.7	9.4	5.2	5.0	4.9	70.9
1966	4.6	3.6	4.1	6.4	6.8	8.0	10.1	10.0	7.4	7.2	5.5	5.2	78.9
1967	4.5	3.5	5.5	6.2	5.6	6.7	7.8	7.6	9.0	8.4	5.1	7.0	76.9
1968	4.0	2.3	4.3	5.8	6.8	7.5	7.0	7.5	8.1	7.7	7.6	6.9	75.5
1969	3.4	3.2	4.3	6.1	5.8	8.5	6.9	8.8	7.8	9.2	5.6	5.6	75.2
1970	4.2	3.1	4.6	5.9	6.8	6.4	7.5	7.3	10.1	9.5	6.8	5.6	77.8
1971	4.3	4.5	5.0	6.3	6.2	7.5	7.8	8.2	10.6	7.7	6.0	6.8	80.9
1972	4.2	2.9	4.2	6.2	7.4	7.5	9.4	8.3	7.9	7.3	5.8	6.8	77.9
1973	4.5	2.2	3.3	4.3	5.7	8.1	11.1	10.5	10.0	8.6	7.5	5.2	81.0
1974	3.6	4.3	4.3	5.6	7.4	7.1	9.4	7.4	8.6	8.9	5.6	7.4	79.6
1975	5.7	6.3	5.6	5.7	6.6	9.2	10.8	12.6	6.9	11.5	9.1	4.8	94.8
1976	3.8	3.6	5.1	5.7	5.2	9.7	8.5	10.6	7.4	7.5	6.0	6.0	79.1
1977	4.1	3.4	5.7	4.4	6.1	6.0	9.4	9.6	9.7	6.5	6.4	4.2	75.5
1978	3.7	3.7	3.4	4.3	6.2	7.9	7.7	10.5	8.6	6.7	5.6	6.8	75.1
1979	4.6	3.3	3.3	4.5	6.5	8.0	8.3	9.0	7.1	9.3	8.1	4.5	76.5
1980	5.1	3.5	4.1	4.0	6.7	7.2	9.4	9.1	6.2	7.9	6.0	3.5	72.7
1981	3.5	2.9	3.2	5.0	4.1	6.9	9.6	6.9	7.7	7.9	5.1	4.9	67.7
1982	3.8	2.3	4.6	3.5	6.5	8.3	6.3	5.8	7.2	6.6	6.4	4.9	66.2
1983	2.4	2.4	3.6	5.6	7.2	8.5	10.3	7.3	5.6	6.5	8.7	3.7	71.8
1984	3.0	3.7	4.4	4.5	5.9	6.5	7.1	6.2	3.8	9.5	5.5	4.9	65.0
1985	3.6	3.7	4.4	3.3	4.8	7.0	7.4	8.4	6.7	5.5	6.4	5.0	66.2
1986	2.8	3.0	3.4	5.6	6.1	5.9	8.0	7.1	9.8	5.9	5.1	6.1	68.8
1987	3.4	3.1	3.8	3.1	5.5	6.6	8.8	7.5	6.8	5.1	3.6	5.6	62.9
1988	3.3	2.1	2.8	3.4	4.7	5.1	6.2	6.2	6.3	4.8	6.8	4.6	56.3
1989	3.5	3.1	4.2	4.5	5.2	4.9	7.6	9.8	4.8	5.2	3.5	5.5	61.8
1990	3.8	3.8	2.7	4.2	7.5	6.8	7.9	8.0	8.4	5.8	7.0	5.8	71.7
1991	2.8	2.0	4.2	2.5	5.8	9.5	8.4	11.2	9.6	9.0	6.9	5.5	77.4
1992	4.1	2.7	2.6	6.0	8.1	5.3	4.7	4.0	3.8	4.2	4.4	2.8	52.7
1993	1.6	3.0	2.4	4.7	8.6	5.1	12.9	9.8	9.4	8.1	9.8	4.7	80.1
1994	4.1	7.3	3.5	5.4	5.4	8.8	9.1	12.7	8.5	8.9	11.2	4.6	89.5
1995	3.2	2.4	2.5	2.6	3.0	8.9	9.3	12.5	–	–	–	–	
	Average monthly												
1953–95	3.9	3.5	4.3	5.0	6.5	7.6	8.8	9.1	8.0	7.5	6.5	5.3	76.0
1953–73	4.3	3.6	4.8	5.7	7.0	8.0	9.1	9.5	8.8	7.8	6.4	5.6	80.6
1974–94	3.6	3.5	3.9	4.5	6.2	7.2	8.5	8.6	7.3	7.2	6.5	5.0	72.0
	Standard deviation												
1953–73	0.6	0.8	0.6	0.9	1.1	0.8	1.3	1.3	1.1	1.1	1.0	0.8	
1974–94	.9	1.3	.9	1.0	1.1	1.5	1.8	2.3	1.8	1.9	2.0	1.1	

Alternative Methods of Estimating Lake Mead Evaporation

Two alternative methods were examined for estimating Lake Mead evaporation: (1) continuing operation of a complete open-water energy-budget station and (2) estimating evaporation with daily net radiation measured at a readily accessible location on Lake Mead.

Based on results of the current study, operation of one complete energy-budget station located in an open-water area of the lake would provide an accurate estimate of evaporation for all of Lake Mead. For example, monthly evaporation for the open-water station at Sentinel Island in Boulder Basin is within 5 percent of the estimated total monthly evaporation of all open-water areas of Lake Mead. This method requires standard measurements of water temperature at and below the water surface, air temperature, relative humidity, and net radiation. Also, because equipment on an open-water barge is exposed to extreme weather and water conditions, routine maintenance of station equipment is necessary.

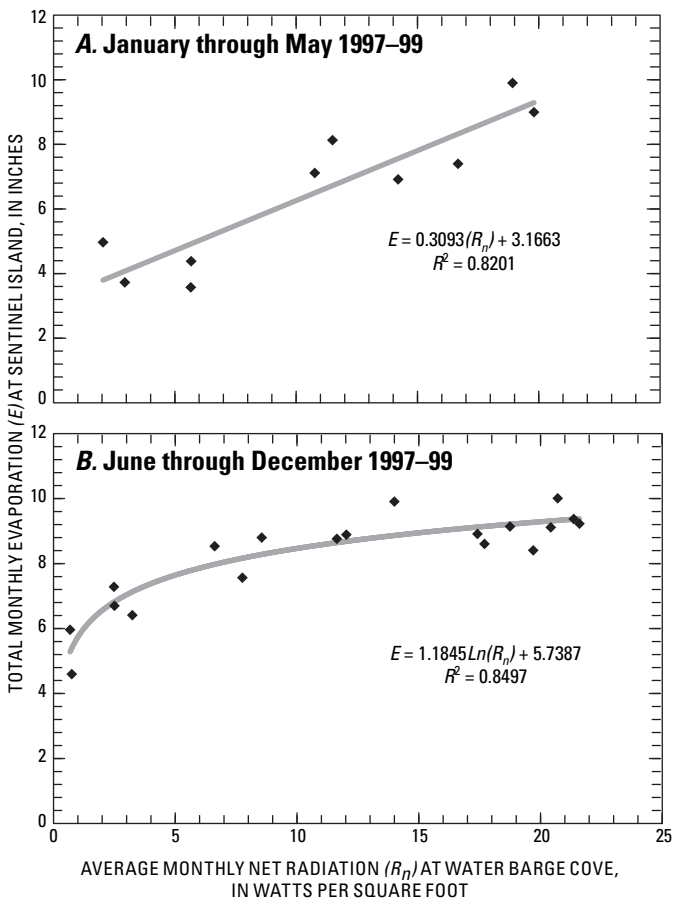


Figure 12. Regression of monthly average net radiation at the Water Barge Cove station and total monthly evaporation at Sentinel Island station for: (*A*) January through May 1997–99 and (*B*) June through December 1997–99. R^2 is coefficient of determination.

A regression of average monthly evaporation at Sentinel Island (table 6) and net radiation at the Water Barge Cove station was developed for 29 months (1997–99) to determine the relation between net radiation at a station that is accessible (Water Barge Cove) and evaporation at an open-water station (Sentinel Island). The regression was developed for two periods of the year: January to May when heat storage in the lake is decreasing (fig. 12*A*), and (2) June to December when heat storage in the lake is increasing (fig. 12*B*). Data were plotted with net radiation at Water Barge Cove as the independent variable and Sentinel Island evaporation as the dependent variable. The coefficient was 0.820 for January to May and 0.850 for June to December, indicating that measurements of monthly average net radiation at Water Barge Cove, or a site with similar environmental conditions on the lake, may be used to approximate lake evaporation.

The accuracy of the net radiation alternative method was evaluated by applying empirical equations derived for each heat-storage period to determine total monthly evaporation and by comparing these estimates to the average monthly evaporation for open-water stations. Monthly average net radiation at Water Barge Cove was used to compute monthly evaporation from July 1997 through December 1999 (30 months) using empirical equations representing the best-fit lines (fig. 12):

$$E = R_n * 0.3093 + 3.1663, \quad (4)$$

(applied from January through May) and

$$E = 1.1845 * Ln(R_n) + 5.7387, \quad (5)$$

(applied from January through May), where R_n is monthly net radiation at Water Barge Cove, in Watts per square foot, and E is monthly evaporation, in inches.

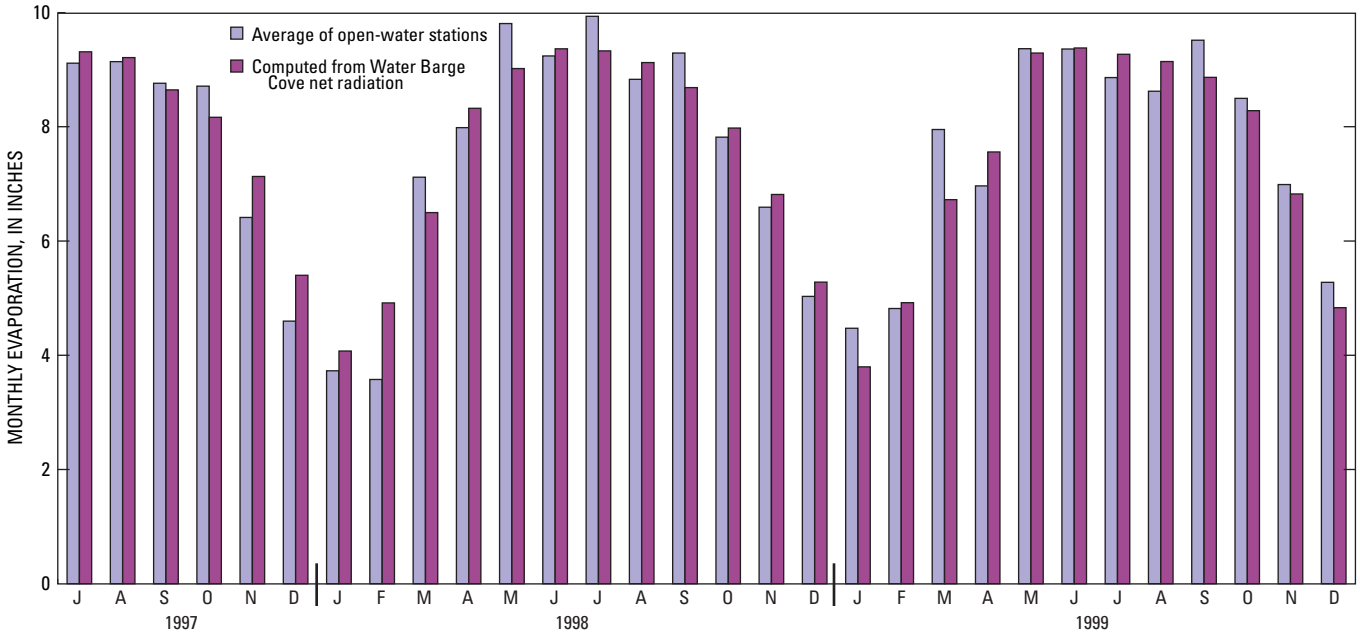


Figure 13. Total monthly evaporation (average of open-water stations) and total monthly evaporation computed from monthly average net radiation at the Water Barge Cove station.

Computed monthly evaporation rates were compared to average monthly evaporation at the open-water stations (fig. 13). The minimum and maximum monthly open-water evaporation rates were 3.6 in. (February 1998) and 9.9 in. (July 1998), respectively. Whereas, the minimum and maximum computed monthly evaporation rates from Water Barge Cove net radiation were 3.8 in. (January 1999) and 9.4 in. (June 1999), respectively. Of the 30 monthly evaporation rates compared, four monthly rates differed from open-water evaporation rates by more than 10 percent (fig. 14). The largest difference in evaporation rates was 37.5 percent for February 1998, and the average difference was 1 percent.

Monthly evaporation rates were summed to compare annual evaporation for open-water stations and computed evaporation using empirical equations. Total open-water evaporation was 7.4 ft compared to a computed evaporation rate of 7.5 ft for 1998 (a 1.4 percent difference). Additionally, open-water evaporation was 7.6 ft compared to a computed rate of 7.4 ft for 1999 (a 2.6 percent difference).

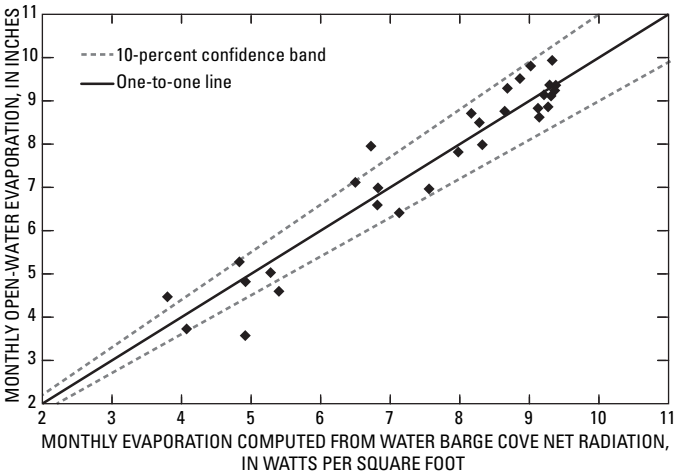


Figure 14. Comparison of total monthly evaporation (average of open-water stations) and monthly evaporation computed from monthly mean net radiation at the Water Barge Cove station.

Summary

Air temperature, relative humidity, wind speed and direction, and water temperature were measured from 1997 to 1998 at four floating instrumented platforms on Lake Mead. One of four floating platforms was in a shallow-water sheltered area of Boulder Basin (Water Barge Cove); the remaining three platforms were in open-water areas of Boulder Basin, Virgin Basin, and Overton Arm. Data were averaged in 20-minute intervals and these averages were used with the energy-budget equation to compute estimates of lake evaporation.

Generally, micrometeorological and water-temperature data were similar at the open-water locations. Relative humidity and wind speed were lower, and water temperature was higher, at the sheltered cove platform (Water Barge Cove) than at the open-water platforms. Air temperature was about the same at all locations.

Monthly evaporation rates were evaluated for temporal variations at each station and spatial variations between stations. At each station, monthly evaporation rates did not significantly vary from year to year for the period of data collection. Moreover, spatial variation in monthly evaporation rates was minimal for the open-water stations. However, monthly evaporation at Water Barge Cove generally was less than monthly evaporation at other stations when the monthly evaporation rate was less than 6.5 in. Estimated monthly evaporation rates were summed for each year of data collection to determine annual evaporation rates. The average annual evaporation rate for Lake Mead from January 1998 to December 1999 was 7.5 ft.

The estimated annual evaporation of 7.5 ft for the period 1997–99 is about 15 percent greater than previously reported annual rates of about 6.4 ft for 1953–94, which was estimated using a mass-transfer equation that was derived initially during a 1952–53 Lake Mead water-loss study. Reported annual evaporation rates from 1953 to 1994 fluctuated from 6 to 7.5 ft/yr prior to 1975; after 1975, annual evaporation rates fluctuated from 4.4 to 7.9 ft/yr.

During the 1997–99 study, monthly average net-radiation data for a shallow-water site (Water Barge Cove) was regressed with monthly total evaporation data for an open-water site (Sentinel Island) to evaluate an alternative method of estimating lake evaporation. Empirical equations derived from this regression were used to compute monthly evaporation rates, and these rates were compared to average monthly evaporation rates at open-water stations. Only 4 of the 30 computed monthly evaporation rates differed from monthly open-water rates by more than 10 percent, indicating that monthly net radiation at Water Barge Cove, or a site with similar environmental conditions on the lake, may be used to approximate lake evaporation. Monthly evaporation rates were summed to compare annual evaporation for open-water sites and computed evaporation using empirical equations. Total open-water evaporation was 7.4 ft compared to a computed evaporation rate of 7.5 ft for 1998 (a 1.4 percent difference). Additionally, open-water evaporation was 7.6 ft compared to a computed rate of 7.4 ft for 1999 (a 2.6 percent difference).

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