In cooperation with the National Park Service and Southern Nevada Water Authority

Evaluating Lake Stratification and Temporal Trends by using Near-Continuous Water-Quality Data from Automated Profiling Systems for Water Years 2005–09, Lake Mead, Arizona and Nevada

Scientific Investigations Report 2012–5080

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

Cover. U.S. Geological Survey Lake Mead Monitoring Station at Temple Basin, Lake Mead, Arizona and Nevada, January 2009. Photograph by Ronald J. Veley.

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
liter (L)	61.02	cubic inch (in^3)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)

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

$°F=(1.8\times°C)+32$

Vertical coordinate information is referenced to the U.S. Geological Survey datum, adjustment of 1912, locally known as the “Power House Datum.” Add 0.17 meter to convert to datum of 1929, leveling of 1935. Add 0.13 meter to convert to datum of 1929, leveling of 1940. Add 0.12 meter to convert to datum of 1929, leveling of 1948. Add 0.01 meter 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 (NGVD 29) and was formerly called “Sea-level Datum of 1929.” As of 2010, the standard datum used throughout industry is the North American Vertical Datum of 1988 (NAVD 88). The transformation between NAVD 88 and NGVD 29 is non-linear. Software may be used to convert the elevations from NGVD 29 to NAVD 88.

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.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Acronyms and abbreviations

ADAPS	Automated Data-Processing System
DO	dissolved oxygen
LVB3	Las Vegas Bay (Site 3) station
MAL	maximum allowable limits
masl	meters above sea level (reference to the “Power House Datum”)
NPS	National Park Service
NWIS	National Water Information System
NWQL	National Water-Quality Laboratory
SC	specific conductance
SNAME	station name
SNWA	Southern Nevada Water Authority
SOP	standard operating procedures
STAID	station identification number
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
%FS	percent fluorescence

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Abstract

The U.S. Geological Survey, in cooperation with the National Park Service and Southern Nevada Water Authority, collected near-continuous depth-dependent water-quality data at Lake Mead, Arizona and Nevada, as part of a multi-agency monitoring network maintained to provide resource managers with basic data and to gain a better understanding of the hydrodynamics of the lake. Water-quality data-collection stations on Lake Mead were located in shallow water (less than 20 meters) at Las Vegas Bay (Site 3) and Overton Arm, and in deep water (greater than 20 meters) near Sentinel Island and at Virgin and Temple Basins. At each station, near-continual depth-dependent water-quality data were collected from October 2004 through September 2009. The data were collected by using automatic profiling systems equipped with multiparameter water-quality sondes. The sondes had sensors for temperature, specific conductance, dissolved oxygen, pH, turbidity, and depth. Data were collected every 6 hours at 2-meter depth intervals (for shallow-water stations) or 5-meter depth intervals (for deep-water stations) beginning at 1 meter below water surface.

Data were analyzed to determine water-quality conditions related to stratification of the lake and temporal trends in water-quality parameters. Three water-quality parameters were the main focus of these analyses: temperature, specific conductance, and dissolved oxygen. Statistical temporal-trend analyses were performed for a single depth at shallow-water stations [Las Vegas Bay (Site 3) and Overton Arm] and for thermally-stratified lake layers at deep-water stations (Sentinel Island and Virgin Basin). The limited period of data collection at the Temple Basin station prevented the application of statistical trend analysis.

During the summer months, thermal stratification was not observed at shallow-water stations, nor were major maxima or minima observed for specific-conductance or dissolved-oxygen profiles. A clearly-defined thermocline and well-defined maxima and minima in specific-conductance and dissolved-oxygen profiles were observed at deep-water stations during the summer months. Specific-conductance maxima were likely the result of inflow of water from either the Las Vegas Wash or Muddy/Virgin Rivers or both, while the minima were likely the result of inflow of water from the Colorado River. Maxima and minima for dissolved oxygen were likely the result of primary productivity blooms and their subsequent decay.

Temporal-trend analyses indicated that specific conductance decreased at all stations over the period of record, except for Las Vegas Bay (Site 3), where specific conductance increased. Temperature also decreased over the period of record at deep-water stations for certain lake layers. Decreasing temperature and specific conductance at deep-water stations is the result of decreasing values in these parameters in water coming from the Colorado River. Quagga mussels (*Dreissena rostriformis bugensis*), however, could play a role in trends of decreasing specific conductance through incorporation of calcite in their shells. Trends of decreasing turbidity and pH at deep-water stations support the hypothesis that quagga mussels could be having an effect on the physical properties and water chemistry of Lake Mead. Unlike other stations, Las Vegas Bay (Site 3) had increasing specific conductance and is interpreted as the result of lowering lake levels decreasing the volume of lake water available for mixing and dilution of the high-conductance water coming from Las Vegas Wash. Dissolved oxygen increased over the period of record in some lake layers at the deep-water stations. Increasing dissolved oxygen at deep-water stations is believed to result, in part, from a reduction of phosphorus entering Lake Mead and the concomitant reduction of biological oxygen demand.

Introduction

Lake Mead on the Colorado River is one of the most intensely used reservoirs in the western United States. The lake was formed following completion of the Hoover Dam in 1936. The lake provides recreational and drinking water to Southern Nevada and also, through controlled releases from Hoover Dam, provides over 22 million users along the Lower Colorado River access to drinking, industrial, irrigation, and recreational water. Lake Mead is composed mainly of four basins (Gregg, Temple, Virgin, and Boulder) and the Overton Arm (fig. 1). The Colorado River provides approximately 97 percent of the water for the lake, while an estimated 1.5 percent comes from the combined inflow from the Muddy and Virgin Rivers (Southern Nevada Water Authority, 2011). In addition, the lake receives an estimated 1.5 percent of its water from treated wastewater, stormwater and urban runoff, and groundwater seepage from the Las Vegas urban area through Las Vegas Wash (Southern Nevada Water Authority, 2011). Lake Mead is listed as critical habitat for the endangered razorback sucker (*Xyrauchen texanus*) and supports important sport fisheries for striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), and channel catfish (*Ictalurus punctatus*). The lake and its surrounding riparian habitats also support significant bird populations that includes large numbers of wintering bald eagles (*Haliaeetus leucocephalus*) and the endangered southwestern willow flycatcher (*Empidonax traillii extimus*) (Barnes and Jaeger, 2011).

A number of water-quality and limnology studies have focused on Boulder Basin of Lake Mead because the water supply for the Las Vegas Valley is obtained through intakes in Boulder Basin near Saddle Island, and recreational use historically has been concentrated mostly in areas of Boulder Basin (Fischer and Smith, 1983; Lieberman, 1995; Labounty and Horn, 1997; Labounty and others, 2003; Rowland and others, 2006). Fewer studies have focused on other areas of Lake Mead, such as the Overton Arm, and Temple and Virgin Basins (Paulson and Baker, 1984). A reconnaissance study to

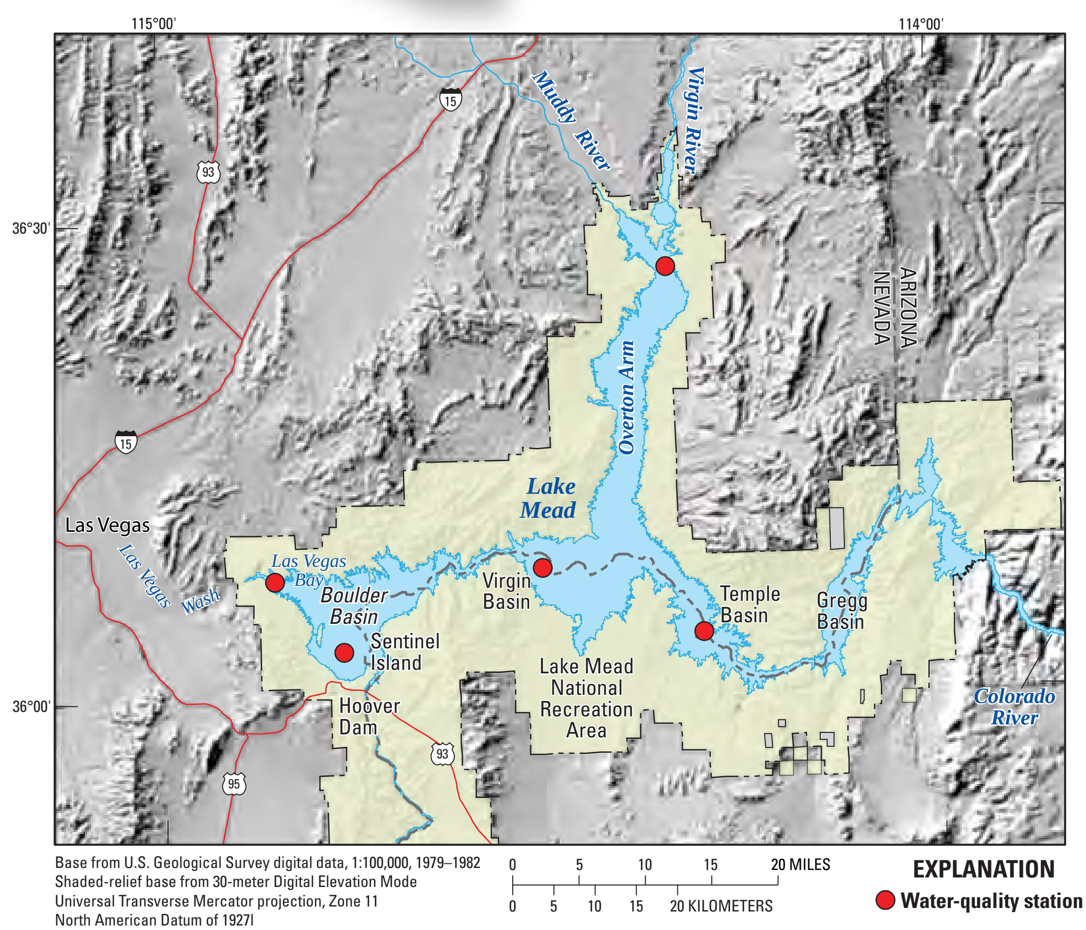

Figure 1. Locations of U.S. Geological Survey Lake Mead water-quality monitoring stations.

investigate the occurrence of selected human-health pharmaceutical compounds in water collected from five sites on Lake Mead was completed by the U. S. Geological Survey (USGS) in 2001 that did include the Overton Arm and Virgin Basin portion of the lake (Boyd and Furlong, 2002). The USGS also has conducted lake-wide studies on the occurrence and distribution of endocrine disruptors (Patiño and others, 2003; Rosen and others, 2006 and 2010; Goodbred and others, 2007; Leiker and others, 2009; Rosen and van Metre, 2010) and hydrocarbons (Lico and Johnson, 2007).

Since October 2000, the USGS has operated near-continual, depth-dependent water-quality monitoring stations on Lake Mead, Arizona and Nevada (Rowland and others, 2006). Initially, two stations were located in Boulder Basin, one in Las Vegas Bay (2000), and the other near Sentinel Island (2002). The data from these two stations, collected up until September 30, 2004, are published in Rowland and others, 2006. In 2005, the USGS added stations in the Overton Arm and Virgin Basin. A fifth station was added in Temple Basin during 2008.

Purpose and Scope

The purpose of this report is to present near-continuous water-quality data collected from Lake Mead to better understand inflow, circulation, and ecosystem processes that influence the lake's water quality. A better understanding of the physical and chemical processes that affect Lake Mead water quality will aid in the management of this important water resource. Water-quality monitoring at Lake Mead included the following tasks: (1) collecting near-continual, depth-dependent water-quality data at locations throughout the lake, (2) assessing temporal trends in water-quality parameters collected at each location, and (3) reporting near real-time water-quality parameter data on the internet.

Near-continual data are summarized and presented in this report for selected chemical and physical water-quality parameters collected at the lake for water years 2005–09 (a water year is the 12-month period from October 1 through September 30 of the following year and is designated by the calendar year in which it ends). The near-continual depth-dependent water-quality parameters collected, disseminated, and archived during the study were temperature, specific conductance (SC), dissolved oxygen (DO), pH, and turbidity. During this study, these data were disseminated as near-real-time water-quality data at a persistent URL (*http://nevada.usgs.gov/water/lmqw/map.htm*) and archived in the USGS National Water Information System (NWIS) database.

The USGS water-quality monitoring stations on Lake Mead were located in both shallow and deep-water sites (fig. 1; table 1). The shallow-water stations were located at Las Vegas Bay (Site 3)—LVB3—and Overton Arm. The deep-water stations were located near Sentinel Island and at Virgin and Temple Basins. The shallow-water stations were located in water less than 20 meters deep, while the deep-water stations were in water deeper than 20 meters (fig.1). The Las Vegas Bay station was located near where the Las Vegas Wash enters Lake Mead (fig. 1). The Las Vegas Bay station was established to provide baseline monitoring of the water entering Lake Mead from the Wash, which includes treated municipal wastewater effluent, stormwater and urban runoff, and groundwater seepage from the Las Vegas urban area. The Las Vegas Bay station was moved three times since it was established in 2000 to adapt to decreasing water levels of Lake Mead (fig. 2). The data collected at the third location of the Las Vegas Bay station (LVB3) were used for the purpose of this report. Sentinel Island, which previously had existed as a meteorological-only station, was outfitted with water-quality monitoring equipment in 2002 to expand the scope of the baseline monitoring beyond Las Vegas Bay (fig.1). Water quality in Virgin and Muddy Rivers, tributaries to Overton Arm, are affected by return flows from irrigated agricultural fields, dairy operations, periodic storm-water runoff from seasonal thunderstorms, discharge of cooling water from power plants, and discharge of municipal wastewater. The Overton Arm station was sited near the confluence of Muddy and Virgin Rivers on the thalweg of the Virgin River as part of an effort to establish baseline monitoring of these inputs (fig.1). At the same time, a station was established on the thalweg of the Colorado River in Virgin Basin near the Narrows that separates Virgin and Boulder Basins (fig. 1). The Virgin Basin station was designed to capture baseline data of the lake's water as it enters the Boulder Basin area of the lake. In addition to potential impacts from inflow from Muddy and Virgin Rivers, persistent drought conditions in the Upper Colorado River Basin for the past 10 years could have affected the limnology of Lake Mead (U.S. Bureau of Reclamation, 2011a) as well as lowering the lake levels (fig. 2). As

Table 1. Location and period of record for the U.S. Geological Survey Lake Mead water-quality stations during water years 2005–09.

[Coordinate information is referenced to the North American Datum of 1983 (NAD 83) Abreviations:°, degrees; ', minute; ", seconds]

Station Name	Location		Period of Operation
	Latitude	Longitude	
Las Vegas Bay (Site 3)	36° 07' 00"	114° 50' 51"	October 5, 2004 to April 30, 2009
Sentinel Island	36° 03' 14"	114° 45' 05"	October 1, 2004 to September 30, 2009
Overton Arm	36° 26' 01"	114° 20' 45"	January 20, 2005 to June 17, 2009
Virgin Basin	36° 09' 01"	114° 32' 10"	February 10, 2005 to September 30, 2009
Temple Basin	36° 03' 10"	114° 17' 23"	July 29, 2008 to September 30, 2009

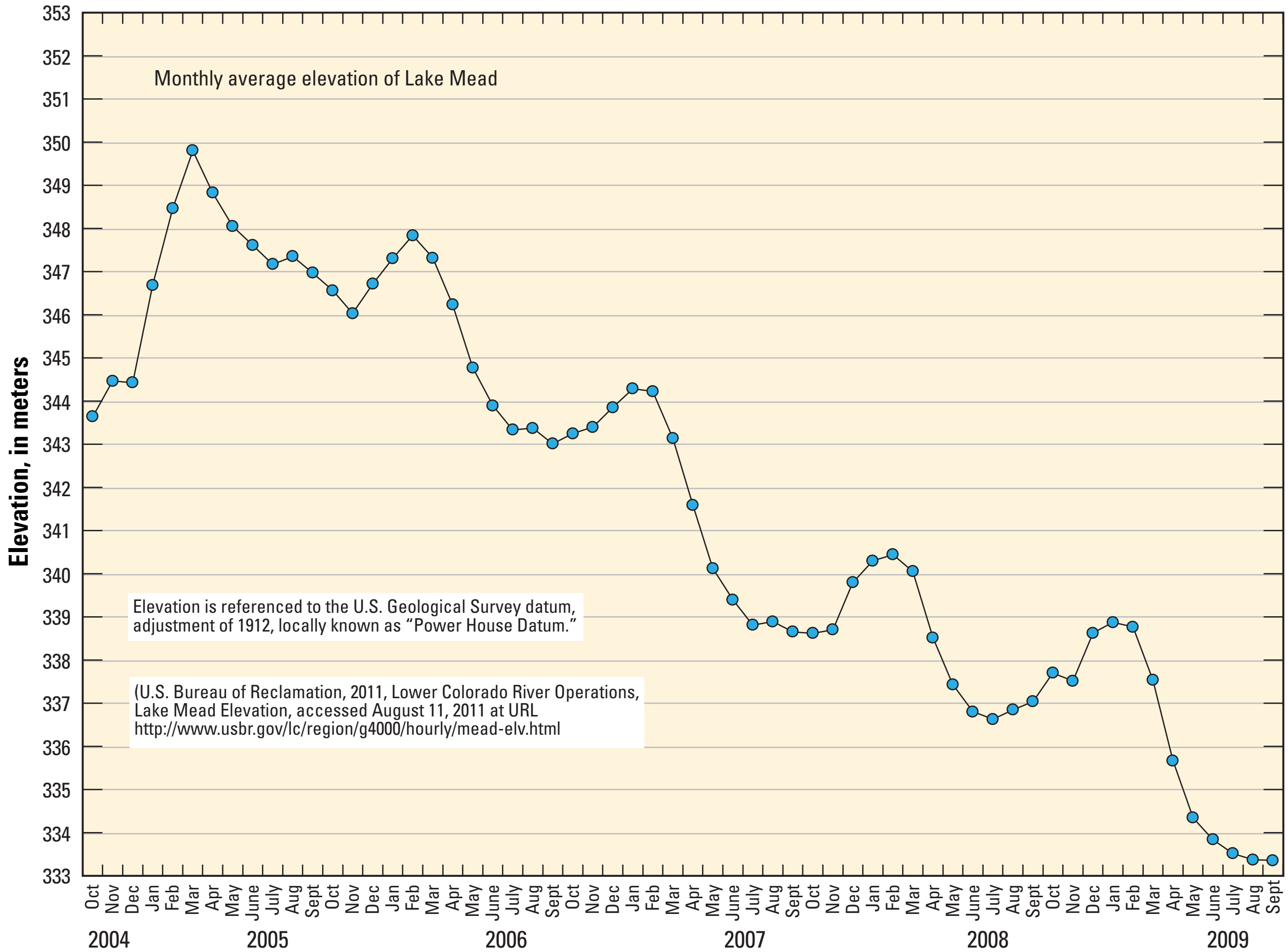

Figure 2. Monthly average elevation of Lake Mead from October 2004 to September 2009.

noted, the Colorado River provides an estimated 97 percent of inflow water to Lake Mead. To collect baseline data of the river's input to the lake prior to mixing with the waters of Overton Arm upon entering Virgin Basin, the fifth, and final, monitoring station of this study was established in Temple Basin on the thalweg of the Colorado River (fig. 1).

Equipment and Methods

The study utilized automated variable-depth profiling systems to collect near-continual water-quality data at each water-quality station on the lake (fig. 1). Standard operating procedures (SOP) for instrument calibration and field data collection were established to ensure consistent data-collection protocols and to minimize system failures (Appendices 1 and 2). Additionally, data were processed, reviewed for quality, and archived by using consistent records computation methods (Rowland and others, 2006; Wagner and others, 2006).

Profiling Equipment

The water-quality stations on Lake Mead were equipped with a profiling system manufactured by YSI Incorporated (YSI). Each system typically included the following equipment (fig. 3):

- YSI variable-depth-winch assembly
- YSI 6600 multiparameter water-quality sonde
- Campbell Scientific CR10X data logger/sensor control module
- Wavecom GSM cellular modem package
- 12 volt, 95 amp hour battery
- 30 watt solar panel for charging the battery

The profiling system was programmed to transport the sonde to user-defined depths. The CR10X microprocessor controlled the winch assembly, operated a multi-parameter water-quality sonde, stored data collected by the sonde, and controlled a modem for data transmission. Data were transmitted to a secured USGS base station for daily data review, processing, programming updates, and troubleshooting, as needed. The multi-parameter water-quality sonde was equipped with sensors for temperature, SC, DO, pH, turbidity, and depth. Manufacturer specifications are provided for each type of sensor in table 2. The system was housed on a floating platform that measured approximately 2.1 x 4.6 meters.

Note that the YSI variable-depth-winch assembly was not installed at the LVB3 station until March 24, 2005. Prior to this, the deployment system used at this station to deliver the sonde to the desired depths was a variable-buoyancy-profiling system described and discussed in Rowland and others, 2006.

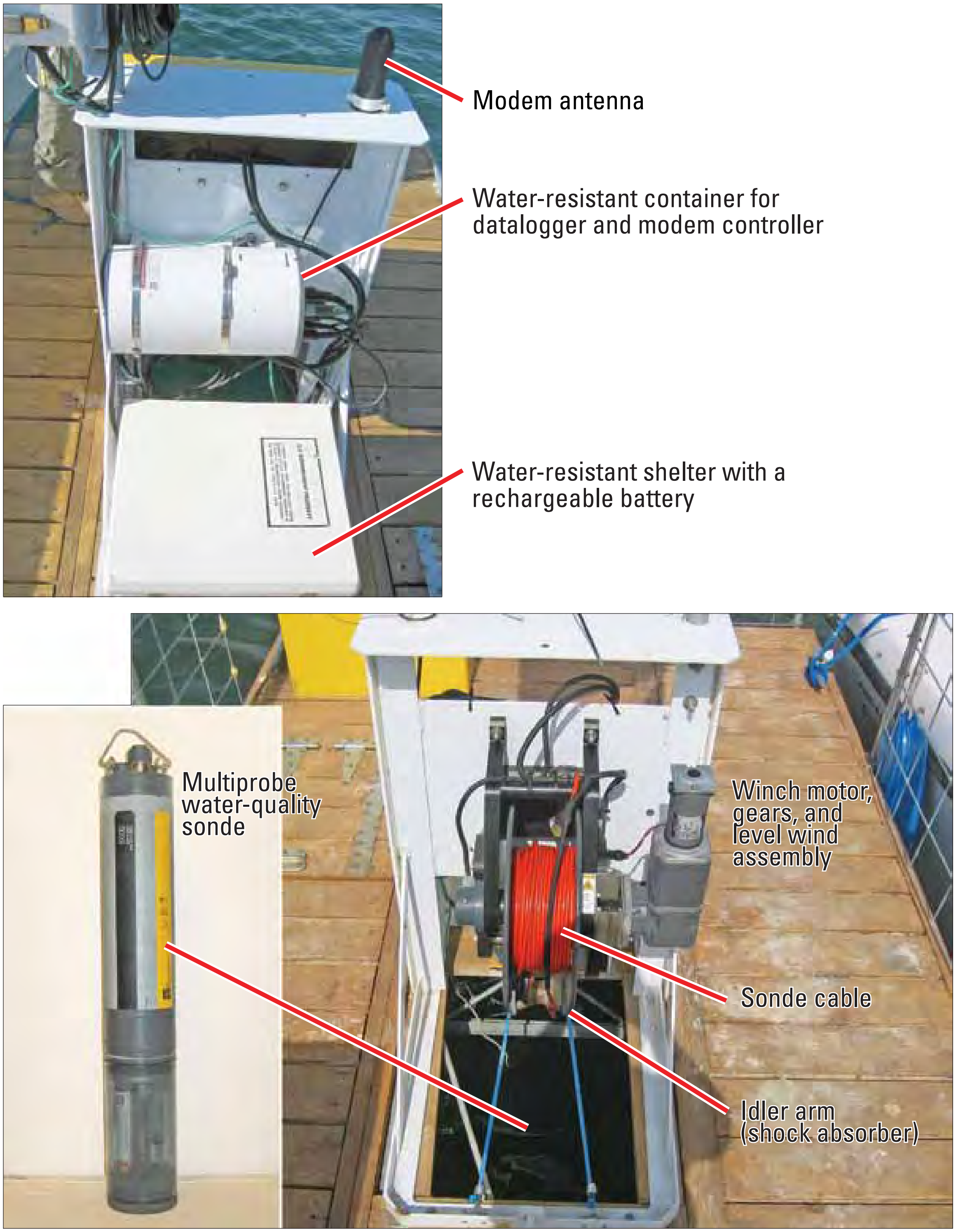

Figure 3. Variable-depth-winch system components mounted to a t-frame.

Field Methods

Water-quality data collection and processing SOP were established and followed during field visits to ensure consistent methods and protocol (Rowland and others, 2006; Wagner and others, 2006). On the basis of these procedures, a Station Visit Sheet (Appendix 1), Sonde Calibration Check Sheet (Appendix 2), and sonde calibration criteria (table 3) were developed to better address environmental conditions at Lake Mead, technical needs of the study, and specific requirements of the profiling system and sensors.

For this study, five water-quality stations were in operation during the period of data collection, from water years 2005–2009 (fig. 1). Data-collection depth increments varied between the shallow and deep-water stations. Data were collected at 2-meter depth increments at the shallow-water stations (LVB3 and Overton Arm), and at 5-meter depth increments at the deep-water stations (Sentinel Island, Virgin Basin, and Temple Basin). The shallowest data-collection depth was 1 meter below the water surface at all of the stations. The maximum depths from which data were collected during the study by station were 19 meters at LVB3 in 2005, 17 meters at Overton Arm in 2005 and 2006, 86 meters at Sentinel Island in 2005, 91 meters at Virgin Basin in 2008 and 2009, and 81 meters at Temple Basin in 2009. During site visits to the shallow-water stations, total water depth usually was measured using a weighted tape measure and periodically measured using a commercial depth finder. A commercial depth finder was used to measure the water depths at the deep-water stations. The total water depth measured was used to determine what the end depth for each station's profile should be to ensure that the sonde would not contact the bottom of the lake. Data were collected every 6 hours, with the first collection of the day scheduled at a few minutes after midnight. Between profiles, the sonde would remain submerged at a predetermined depth at each respective station (parking depth).

Typically, site visits were performed every 2 weeks for each water-quality station. Upon arrival at a station, an inspection for damage or repairs needed to the exterior of the station or the platform was performed. These observations, if any, were recorded on the Station Visit Sheet (Appendix 1). The in situ pre-cleaned sensor readings at parking depth were recorded on the sheet. After the sonde was removed from the lake and cleaned, an in situ reading (at the same pre-cleaned depth, i.e., parking depth) also was recorded as post-cleaned values for each sensor. Next, a calibration check of the sensors was performed by using established procedures (Rowland and others, 2006; Wagner and others, 2006). The calibration checks for each sensor were recorded on the Sonde Calibration Check Sheet (Appendix 2). The sensors were calibrated, if necessary, on the basis of established calibration criteria (table 3). Once the calibration checks and any necessary calibrations were completed, the sonde was returned to its parking depth, and post-calibration in situ values were recorded on the Station Visit Sheet.

Table 2. Manufacturer specifications for sensors used to measure physical and chemical parameters at U.S. Geological Survey Lake Mead water-quality stations[1].

[Abreviations: ºC, degrees Celsius; µS/cm, microsiemens per centimeter; %, percent; unit, standard pH unit; mg/L, milligrams per liter; FNU, formazin nephelometric unit; m, meters]

Sensor	Range	Accuracy
Temperature, Thermistor	–5 to 50ºC	0.15ºC
Specific Conductance, 4 electrode cell with autoranging	0 to 100,000 µS/cm	0.5% of reading plus 1 µS/cm
Dissolved oxygen, ROX® optical with mechanical cleaning	0 to 50 mg/L	0 to 20 mg/L: the greater of 1% of the reading, or 0.1 mg/L; 20 to 50 mg/L: 15% of the reading
pH, glass combination electrode	0 to 14 unit	0.2 unit
Turbidity, optical, 90 degree scatter with mechanical cleaning	0 to 1,000 FNU	The greater of 0.3 FNU or 2% of the measured value
Depth, deep	0 to 200 m	0.3 m

[1] From YSI Incorporated* (6-Series Multiparameter Water-Quality Sondes, User Manual, Revision F, September 2009).
*Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Table 3. Calibration criteria for sensors used to measure physical and chemical water parameters at U.S. Geological Survey Lake Mead water-quality stations[1].

[Abreviations: ºC, degrees Celsius; µS/cm, microsiemens per centimeter; %, percent; mg/L, milligrams per liter; unit, standard pH unit; FNU, formazin nephelometric unit; m, meter]

Water-Quality Parameter	Calibration Criteria
Temperature	0.2°C
Specific conductance	The greater of 5 µS/cm or 3% of the measured value
Dissolved oxygen	0.3 mg/L
pH	0.2 unit
Turbidity	The greater of 0.5 FNU or 5% of the measured value
Depth	0.3 m

[1] Wagner and others, 2006, and project criteria for depth.

Water samples also were collected during site visits as part of an effort to determine if a linear relationship could be established between values obtained from a YSI chlorophyll sensor and laboratory values of chlorophyll concentration. The traditional method of obtaining chlorophyll concentrations involves sampling procedures and extensive laboratory analysis that were not amenable to project objectives. For this study, surface grab and 4.6-meter integrated samples were collected at all stations for chlorophyll *a* and *b* and pheophytin *a* analyses. The samples were filtered and frozen on site and then sent to the USGS National Water Quality Laboratory (NWQL) for analysis. The chlorophyll sensor was used to record percent fluorescence (%FS) values by using the sensor's relative fluorescence-unit parameter mode for each of the samples collected and sent to NWQL. The chlorophyll *a* concentrations from the NWQL analyses (Appendices 3–7) and the recorded %FS values were compared to determine if a linear relationship existed between them. A statistically significant linear relation ($r^2 = 0.46$; F-statistic p-value < 0.05) between chlorophyll *a* and %FS was found. The relation was not sufficiently accurate, however, to confidently predict values of chlorophyll *a* from %FS.

Records Computation

Data processing and the preparation of the data review package are the two main components of records computation. Data collected at the water-quality stations were entered into the USGS NWIS database by using the Automated Data-Processing System (ADAPS)—a suite of USGS programs for managing near-continuous data sets. Data also were posted on a persistent USGS website, *http://nevada.usgs.gov/water/lmqw/map.htm*, as near-real-time provisional data (subject to review and revision pending publication).

Data Processing

The user-defined depths at each of the water-quality stations on Lake Mead were assigned a unique USGS station identification number, STAID, and name, SNAME (Appendix 8). The STAID is a 15-digit number to identify the station and the associated depth-specific data that are stored in NWIS (Rowland and others, 2006). For this study, a total of 76 depth-specific stations were created for the five monitoring stations. The LVB3 and Overton Arm stations each had 10 STAIDs in 2-meter depth increments, whereas the Sentinel Island, Virgin, and Temple stations had 18, 20, and 18 STAIDs in 5-meter depth increments, respectively. The binning criteria assigned a range of depth values to a respective STAID. For example, data collected at a depth that was greater than 6 meters and less than 8 meters at the Overton Arm station were assigned to the 7-meter STAID. The binning criteria established for all of the individual stations for this study can be found in Appendix 8.

The data processing involved a combination of seven automatic and manual steps (fig. 4):

1. Data from each water-quality station are automatically transferred daily to a secure and isolated base-station computer and are checked for completeness and inaccuracies (for example, spikes in the turbidity data that could have resulted from a malfunctioning wiper on the sensor).
2. Raw data files are copied to a UNIX server.
3. Data for specific depth ranges are automatically extracted from the raw data files and copied to depth-specific data files.
4. Depth-specific data files are automatically reformatted into standard data-input files by USGS programs (DECODES or SATIN) and automatically entered into the NWIS database.
5. ADAPS processes are used to manually apply fouling and drift corrections to data recorded at the first measurement depth.
6. Corrections applied to data recorded at the first depth are automatically applied to data recorded at all successive depths in the profile.
7. Corrected (computed) data are retrieved manually from NWIS, and the depth-specific data files are concatenated and then sorted by date and time, creating profile data files.

Fouling and drift corrections (fig. 4—Step 5) were applied by using established USGS criteria (Wagner and others, 2006). Fouling is the difference between the sensor measurements in the same environmental sample before and after the sensors are cleaned (Rowland and others, 2006). Electronic drift is the difference between the cleaned sensor reading in a calibration standard and the calibration standard value (Rowland and others, 2006). Both fouling and drift were assumed to occur at a constant rate between site visits and were applied as a linear interpolation over the time between calibrations. In some cases, however, the fouling or drift corrections can be rejected on the basis of professional discretion. For example, fouling corrections were not applied as found during a 2-week period in water year 2009 at the Temple station when it was determined that the sonde had contacted the bottom. The sensors were exposed to a higher level of sedimentation fouling while in contact with the lake bottom, which biased the results of the fouling values for the sensors. An ‘other’ correction also was used to apply corrections when warranted. For example, DO sensors that utilized membrane technology were used during water years 2005–07. The sensor's membrane could not be cleaned without compromising the integrity of the membrane's material. The in situ sensor was exchanged with a sensor that had been prepared with a new membrane 24-hours prior to the site visits. This meant that the fouling difference, normally the result of the pre and post-cleaning protocol, was not be valid because the DO sensors were not the same sensor. A calibration check of both sensors was performed and recorded as part of the exchange process. The sum of the combined differences from the checks could then be applied as an ‘other’ correction. The membrane sensors were all replaced with optical sensors by the beginning of the 2008 water year. After the deployment of the optical DO sensors, fouling and drift were determined independently and applied independently.

Maximum allowable limits (MAL) are established to define when water-quality data are too poor to correct or publish (Rowland and others, 2006; Wagner and others, 2006; table 4). For example, during a site visit, the calculated difference between the pH-sensor reading in a calibration standard and the calibration standard value is 2.6; this difference exceeds the established MAL for pH (± 2 units) and precludes the data from being used. When the data in this study exceeded MAL, professional discretion was used to determine the point in a given data-collection period where the data deteriorated to values that ended up exceeding MAL and were, therefore, considered unfit for applying corrections or publication.

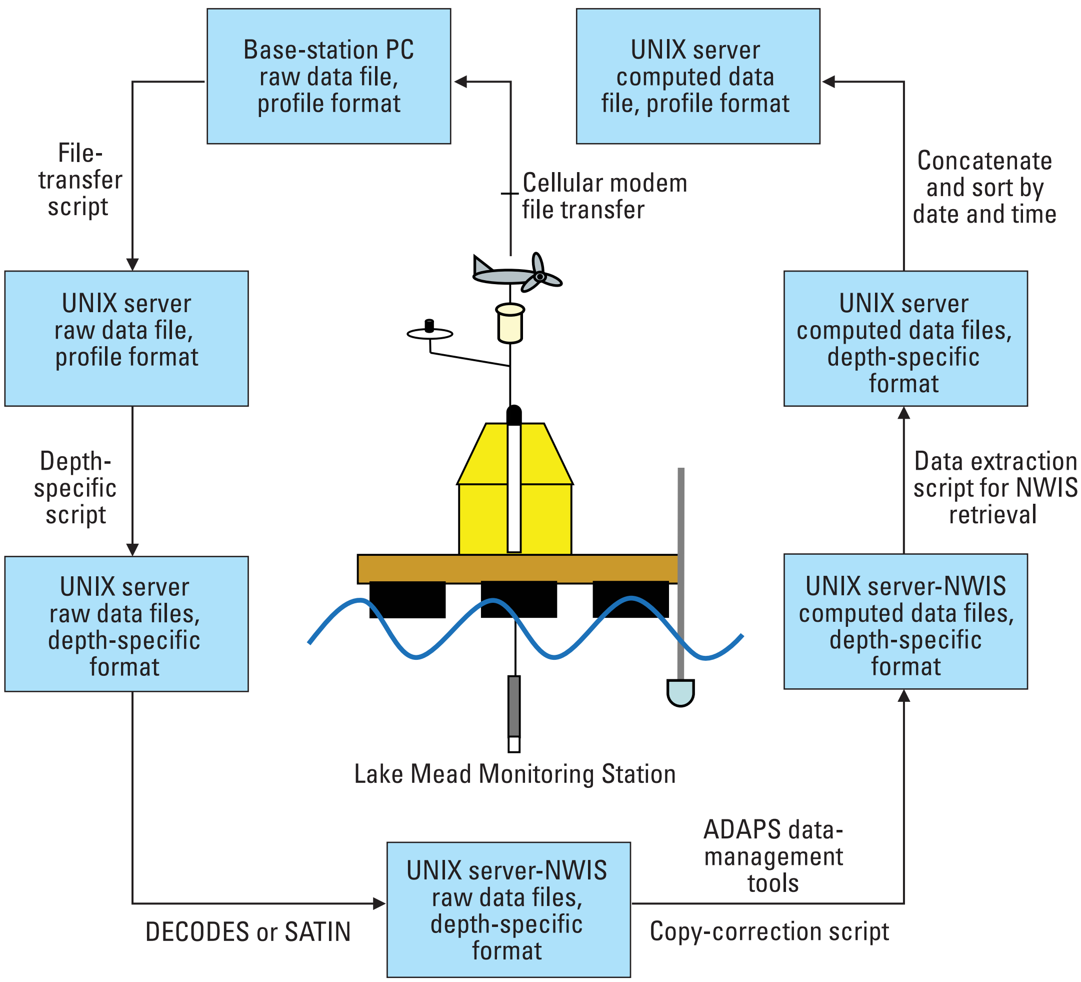

Figure 4. Data-processing flow chart for U.S. Geological Survey Lake Mead water-quality data.

Table 4. U.S. Geological Survey maximum allowable limits for applying corrections and publishing Lake Mead water-quality data[1].
[Abreviations: ºC, degrees Celsius; %, percent; mg/L, milligrams per liter; unit, standard pH unit; FNU, formazin nephelometric unit; m, meter]

Water-Quality Parameter	Limit
Temperature	2.0ºC
Specific conductance	30%
Dissolved oxygen	The greater of 2.0 mg/l or 20%
pH	2.0 unit
Turbidity	The greater of 3.0 FNU or 30%
Depth	1.0 m

[1] From Wagner and others, 2006, and project criteria for depth limit.

Data Review

After the data collected for this study were processed, a data review packet was put together by the study's personnel as part of the final review process prior to publication. The review packets were completed by water year for each station during the study period. Final evaluation of the data was completed by two or more qualified USGS scientists. The review package contained the following items:

- Station analysis with site description
- Station visit sheets (Appendix 1)
- Sonde calibration check sheets (Appendix 2)
- Primary computations table from ADAPS
- Fouling and drift correction tables from ADAPS
- Graphs of individual, uncorrected water-quality parameters for review
- Graphs of individual, corrected water-quality parameters for review
- End of year summary table from ADAPS
- Station analysis from ADAPS

After the packets were reviewed and determined to be final, an accuracy rating was assigned on the basis of the sum of the absolute value of the results of the fouling and calibration checks for each data point. Temperature, SC, DO, pH, turbidity, and depth data were rated as excellent, good, fair, or poor according to established criteria listed in table 5.

The near-continuous %FS data collected by the chlorophyll sensor during this study were not published as part of this report. The fluorescence response detected by the chlorophyll sensor is known to be highly variable and dependent on numerous factors, such as temperature, phytoplankton species variability and population dynamics, fluorescence of non-phytoplankton particles, solar radiation, turbidity, and several other factors (YSI Incorporated, 2006). In addition, an industry-approved field calibration standard was not available for this sensor during the study period. The near-continuous %FS data collected during this study are considered provisional and are subject to further review and revision.

Data Archive

The water-quality data collected from the Lake Mead stations during water years 2005–09 for this study are stored in the USGS NWIS database. The data are stored by STAID (Appendix 8). For the purpose of this report, the final temperature, SC, DO, pH, turbidity, and depth data were retrieved from the database by STAID, concatenated, and sorted by date and time to create final quality-rated profile data files for each respective station by water year (Appendices 9–13). Data that were recorded at each station's respective parking depth during site visits, and data recorded during periods of time when a sonde remained at a static depth, are also a part of the quality-rated data sets found in Appendices 9–13. The data sets that contain the NWQL analyses also are stored in NWIS (Appendices 3–7). The file format used for Appendices 3–7 and 9–13 was Microsoft Excel (version 97–2003). The data also are available in this format at the study's website (*http://nevada.usgs.gov/water/lmqw/map.htm*). The data can be accessed by going to each station's respective webpage, where they are available by water year. The provisional %FS data discussed previously are included as part of the online data sets referenced here.

Table 5. U.S. Geological Survey criteria for rating near-continuous Lake Mead water-quality data[1].

[**Abreviations:** ≤, less than or equal to; ºC, degrees Celsius; >, greater than value shown; %, percent; mg/L, milligrams per liter; unit, standard pH unit; FNU, formazin nephelometric unit; m, meter]

Water-Quality Parameter	Excellent	Good	Fair	Poor
Temperature	≤0.2ºC	>0.2 to 0.5ºC	>0.5 to 0.8ºC	>0.8ºC
Specific conductance	≤3%	>3 to 10%	>10 to 15%	>15%
Dissolved oxygen	The greater of ≤0.3 mg/L or ≤5%	The greater of >0.3 to 0.5 mg/L or >5 to 10%	The greater of >0.5 to 0.8 mg/L or >10 to 15%	The greater of >0.8 mg/L or >15%
pH	≤0.2 unit	>0.2 to 0.5 unit	>0.5 to 0.8 unit	>0.8 unit
Turbidity	The greater of ≤0.5 FNU or ≤5%	The greater of >0.5 to 1 FNU or >5 to 10%	The greater of >1 to 1.5 FNU or >10 to 15%	The greater of >1.5 FNU or >15%
Depth	≤0.3 m	>0.3 to 0.5 m	>0.5 to 0.8 m	>0.8 m

[1] From Wagner and others, 2006, and project criteria for depth rating.

Observations of Near-Continuous Water-Quality Data

The total record of water-quality data collected at each station varied because of differences in deployment dates for individual stations (table 1), as well as lowering of the lake level during the data-collection period (fig. 2). The periods of record at each data-collection station were as follows: LVB3, March 2005 to April 2009; Sentinel Island, October 2004 to September 2009; Overton Arm, January 2005 to June 2009; Virgin Basin, February 2005 to September 2009; and Temple Basin, July 2008 to September 2009 (table 1).

Initial analysis of water-quality data from the stations included observations of conditions primarily related to stratification of the lake and the relation of stratification to public-water-supply intake structures in the lake. Temporal trends in water-quality values also were analyzed at each station. Stratification observations and trend analyses were performed for three main water-quality parameters: temperature, SC, and DO. These parameters were selected because they had the longest and highest quality records at each station and because they provided the most insight into the overall conditions of the lake with respect to water quality and ecosystem health. All values of parameters analyzed for stratification and trends were arithmetic means (averages) of all measurements taken during each month of the period of record. Because of periodic losses of data for some parameters due to equipment failure or excessive fouling or drift, the total number of measurement values in each month varied. In addition, the deepest data-collection point at the stations varied in distance above the lake bed as a result of equipment limitations (such as cable length) or preventing the sensors from contacting the bottom (avoiding fouling of sensors which would bias the data). For example, the station with the biggest discrepancy during the first few years of the study was the Virgin Basin station. The surface to bottom depth at the Virgin station approached depths that reached approximately 115 meters, while only having the equipment capability to go to depths that reached 81 meters. The limited period of data collection at the Temple Basin station prevented the application of temporal-trend analyses.

Stratification and Temporal-Trend Analysis

To better understand the stratification and water-quality temporal trends in Lake Mead (fig. 1) for the purpose of this report, monthly profiles were developed by using selected water-quality data for each station (Appendices 14–18). The upper three plots presented in Appendices 14–18 show averaged temperature, DO, and SC profile data as a function of depth. Depth below surface of the lake is referenced to the “Power House Datum.” The maximum and minimum values recorded for each parameter in the profile during the data-collection period for each graph also are shown. The number of individual depth-dependent profiles used to compute the average is displayed within the explanation for the plots. The average monthly elevations of the lake stage and the estimated elevation of the lake bottom at each respective monitoring station (Twichell and others, 2004) also are displayed on these plots. In addition, the plot for the Sentinel Island water-quality monitoring station (Appendix 16) provides the elevation of public-water-supply intakes (two existing and one proposed) operated by the SNWA. The bottom plot shows the elevation of the lake stage (in meters) as a function of time for individual water years. The bottom plot also shows a shaded section that indicates the time span that was used for the average, maximum, and minimum values presented in the upper three plots.

Lake Stratification

Observations of the selected water-quality parameters revealed the presence of thermal stratification at some of the stations in Lake Mead. The identification of thermal stratification in the Lake was based on visual observation of temperature profiles at each station. The approximate depth ranges of thermal stratification layers (i.e., epilimnion, metalimnion, and hypolimnion) at each station displaying stratification can be found in table 6. At Sentinel Island, it was possible to identify the location of thermal stratification of the lake with respect to the elevation of the two water intakes used by SNWA to provide drinking water to the Las Vegas Valley, as well as a proposed lower third intake.

Las Vegas Bay (Site 3)

Little development of a thermocline was observed at the LVB3 station. When the elevation of the lake was greater than 340 meters above sea level (masl; referenced to the “Power House Datum”), a decrease in temperature of about 5 degrees Celsius (°C) between the surface-water and the temperature at the deepest measurement of around 20 meters was observed during the summer months (Appendix 14). As the elevation of the lake dropped below about 340 masl, temperatures were essentially the same at all depths at this station. The maximum temperatures at 1 meter were around 30°C in summer, while the temperatures in January were around 13°C and nearly constant at all depths. Temperature ranges were greater in summer than in winter and were greater when the elevation of the lake was less than 340 masl, as opposed to elevations above that (Appendix 14).

Table 6. Depth ranges representing the approximate location of thermal layers in Lake Mead at U.S. Geological Survey water-quality stations where thermal stratification was present.

Station Name	Depth (meters)		
	Epilimnion	Metalimnion	Hypolimnion
Sentinel Island	0–12	12–35	35-bottom
Virgin Basin	0–7	7–35	35-bottom
Temple Basin	0–7	7–35	35-bottom

No major seasonal SC maxima or minima were observed at this station. From December to February, however, SC values increased with increasing depth (Appendix 14). A minor SC maximum was observed during the summer months (for example, July 2005, Appendix 14) when the elevation of the lake was above about 340 masl. The SC maximum was at about 8–12 meters in depth.

No major seasonal DO maxima or minima were observed at this station. A decrease in DO with depth was observed during summer months and when the elevation of the lake was above 340 masl. This decrease in DO with depth was muted or absent when the elevation of the lake was less than 340 masl (Appendix 14).

Overton Arm

Like the LVB3 station, little development of a seasonal thermocline was observed at the Overton Arm station. When the elevation of the lake was above 340 masl, water temperature decreased about 5°C from the surface to the deepest measurement at around 15 meters during the summer months (Appendix 15). When the elevation of the lake dropped below about 340 masl, temperatures were essentially the same at all depths at this station. The maximum temperatures at 1 meter were around 30°C in summer, while, in January, the temperatures were around 10°C at all depths. Temperatures ranges were higher in the summer months than winter months, and this range increased when the elevation of the lake was less than 340 masl (Appendix 15).

No major seasonal SC maxima or minima were observed at this station. From December to February, SC values were highest at the deepest sampling depths in the lake, and displayed the same pattern of increasing SC with depth observed at LVB3 (Appendix 15).

No major seasonal DO maxima or minima were observed at this station. A decrease in DO concentrations with depth was observed during summer months when the lake elevation was above 340 masl (Appendix 15). This decrease was muted or absent when the elevation of the lake was less than 340 masl. Concentrations of DO closely followed the same pattern with depth as was observed at LVB3 (Appendix 14).

Sentinel Island

A seasonal thermocline began forming at the Sentinel Island station in May and reached peak development in August. From October to December, the thermocline weakened and moved deeper in the water column (Appendix 16). From January to April, no major thermocline was observed at this station (Appendix 16). At the height of thermocline development at this station, the epilimnion was about 12 meters thick, the metalimnion extended from about 12–35 meters in depth, and the hypolimnion extended from about 35 meters to the bottom of the lake. The maximum temperatures in the epilimnion were around 28°C in August, while, in January, the temperatures were around 13°C at all depths.

The SNWA public-water-supply intakes (No. 1 and 2), situated at approximately 305 masl, were located near the base of the metalimnion from May through August and within the metalimnion as it decayed and moved deeper in depth from October through December (Appendix 16). A proposed new third intake (No. 3), situated at approximately 262 masl, was located within the hypolimnion throughout the year (Appendix 16).

A seasonal maximum and minimum in SC formed at Sentinel Island during the summer months and reached peak development in August. At its peak, the SC maximum extended from about 0–10 meters in depth, while the SC minimum extended from about 10–25 meters in depth (Appendix 16). Both the maximum and minimum began decaying in September and moved deeper in the water column through December. No major SC maxima or minima were observed from January through May.

Intakes No. 1 and 2, as well as a proposed No. 3, were located below the SC maximum and minimum at all times of the year. Intakes No. 1 and 2, however, were situated within the SC maximum briefly in November of each year as it decayed and moved deeper in the water column (Appendix 16).

A low-magnitude seasonal DO maximum began forming near the base of the epilimnion at depths of around 5–20 meters in June and reached peak development during July (Appendix 16). In August, the DO maximum rapidly decayed and was followed by the development of a low-magnitude DO minimum, which reached peak development in October. The DO minimum was most prominent at depths of around 25–45 meters. No major DO maxima or minima were observed from January through May (Appendix 16).

In general, Intakes No. 1 and 2 were located above or within the DO minimum from October through December. The proposed Intake No. 3 was located below the DO maximum and the DO minimum at all times throughout the year (Appendix 16).

Virgin Basin

A seasonal thermocline formed at the Virgin Basin station in May and reached peak development in August. From September through December, the thermocline weakened and moved deeper in the water column (Appendix 17). No significant thermocline was observed from January through April (Appendix 17). At the height of thermocline development at this station, the epilimnion was about 7 meters thick, the metalimnion extended from about 7–35 meters in depth, and the hypolimnion extended from about 35 meters to the bottom of the lake. The maximum temperatures in the epilimnion were around 29°C in August, while the temperatures in January were around 12°C at all depths (Appendix 17).

A prominent seasonal SC minimum developed in July and persisted through September. From October through December, the SC minimum decayed and moved deeper in the water column (Appendix 17). At its peak in August, the

SC minimum extended from about 5–25 meters in depth. No major SC maxima or minima were observed from January through June (Appendix 17).

A low-magnitude seasonal DO maximum formed at this station in June and reached peak development in July. The DO maximum was followed by the formation of a DO minimum, which shortly thereafter reached peak development in September. At their peaks, the depth of the DO maximum was about 5–15 meters, while the depth of the DO minimum was about 15–35 meters. From January through May, no major DO maxima or minima were observed (Appendix 17).

Temple Basin

A seasonal thermocline formed at the Temple Basin station in May and reached peak development in August. From September through December, the thermocline weakened and moved deeper in the water column (Appendix 18). No major thermocline was observed from January through April (Appendix 18). At the height of thermocline development at this station, the epilimnion was about 7 meters thick, the metalimnion extended from about 7–35 meters in depth, and the hypolimnion extended from about 35 meters to the bottom of the lake. The maximum temperatures in the epilimnion were around 28°C in August, while the temperatures in January were around 13°C at all depths (Appendix 18).

A prominent seasonal SC minimum developed at this station in July and reached peak development in August. From September through December, the SC minimum decayed and moved deeper in the water column (Appendix 18). At its peak in August, the SC minimum extended from about 5–30 meters in depth, and SC increased rapidly above and below it. No major SC maxima or minima were observed from January through June (Appendix 18).

Two low-magnitude seasonal DO minima formed in June and persisted through October. The most prominent DO minimum formed at a depth of about 45–60 meters. Both minima decayed and moved deeper in the water column from October through December. No major DO maxima or minima were observed from January through May (Appendix 18).

Water-Quality Temporal-Trends Analyses

Seasonal Kendall trend analyses (Helsel and Hirsch, 1993) were performed on monthly average values of temperature, SC, and DO for each thermally-defined lake layer at deep-water stations at Sentinel Island and Virgin Basin and for one shallow depth at shallow-water stations at LVB3 and Overton Arm. The period of record at the Temple Basin station was too short to perform temporal trend analyses. For all temporal-trend analyses, monthly average values were used as proxies for seasons.

For deep-water stations, lake layers were identified from observations of the thermal stratification at each station (see previous section). Seasonal trend analyses were performed by lake layers even when stratification of the lake was not observed, which was common during the winter months. Depth of the approximate middle of the epilimnion, metalimnion, and hypolimnion was used to represent each lake layer in the temporal-trend analyses (table 6). The middle depth of each layer was assumed to represent the average water-quality conditions of each layer in each month for the temporal- trend analyses.

For shallow-water stations, where lake stratification did not occur, a single shallow-depth value was selected for temporal-trend analyses. Shallow depths were the only ones that could be consistently maintained throughout the period of record as the level of the lake lowered. The depths for trend analyses at shallow-water stations were as follows: LVB3, 3 meters; Overton Arm, 1 meter.

The results of the trend analyses for deep-water stations are presented in table 7. The results of the trend analyses for shallow-water stations are presented in table 8. Italicized values in each table indicate statistical significant tau values at the 95 percent confidence interval ($\alpha = 0.05$). The period of record for water-quality data at each station also is included in each table.

Each station had at least one tau value indicating a significant temporal trend for at least one water-quality parameter. At the Sentinel Island station, a significant trend of decreasing temperature was observed in the hypolimnion

Table 7. Seasonal Kendall tau values from temporal-trend analyses of water-quality parameter values (monthly averages) by station and thermally-defined lake layer for deep-water U.S. Geological Survey Lake Mead water-quality stations.

Station Name	Period of Record	Water-Quality Parameter	Seasonal Kendall tau (italicized if statistically significant)		
			Epilimnion	Metalimnion	Hypolimnion
Sentinel Island	October 2004–September 2009	Temperature	–0.1	-0.18	***–0.36***
		Specific Conductance	***–0.7***	***–0.73***	***–0.8***
		Dissolved Oxygen	–0.11	***0.24***	***0.28***
Virgin Basin	February 2005–September 2009	Temperature	–0.13	***–0.42***	***–0.32***
		Specific Conductance	***–0.88***	***–0.88***	***–0.95***
		Dissolved Oxygen	***0.34***	0.24	***0.36***

(table 7). Similarly, significant temporal trends of decreasing temperature were observed in the metalimnion and hypolimnion at the station in the Virgin Basin. Significant temporal trends of decreasing SC were observed in all lake layers at both deep-water stations and at the station in the Overton Arm. Except for the LVB3 station, where the only significant temporal trend was an increase in SC (table 8), decreasing SC was the temporal trend most commonly found among the stations (tables 7 and 8). In addition, the tau values for SC trends at the deep-water stations were all 0.7 or greater, indicating a strong relation (table 7). Significant temporal trends in increasing DO were observed in the metalimnion and hypolimnion at the station near Sentinel Island and in the epilimnion and the hypolimnion at the station in the Virgin Basin (table 7).

Correlations between Lake Elevation and Water-Quality Parameters

Spearman correlations (Helsel and Hirsch, 1993) were performed between monthly average values of water-quality parameters and the elevation of Lake Mead (in masl) for the period of record at each station, except Temple Basin. The same water-quality parameters were examined as those analyzed for trends, including temperature, SC, and DO. As in the temporal-trend analyses, correlations were performed for each lake layer at deep-water stations and for one shallow depth at shallow-water stations. The results of the correlation analyses for shallow-water and deep-water stations are presented in tables 9 and 10, respectively. Italicized values in tables 9 and 10 indicate statistically significant rho values at the 95 percent confidence interval ($\alpha = 0.05$); only significant correlations are discussed.

Each station, except for the Overton Arm station, had at least one significant rho value for a water-quality parameter, indicating a significant correlation between the water-quality parameter and Lake Mead elevation (tables 9 and 10). At the LVB3 station, SC was negatively correlated with lake elevation (table 9). At the deep-water stations, the Sentinel Island station and the Virgin Basin station, temperature in the epilimnion was negatively correlated with lake elevation, while SC was positively correlated with lake elevation in every lake layer (table 10). Also, at the Virgin Basin station, temperature in the hypolimnion was positively correlated with lake elevation (table 10).

Table 8. Seasonal Kendall tau values from temporal-trend analyses of water-quality parameter values (monthly averages) by station for shallow-water U.S. Geological Survey Lake Mead water-quality stations.

Station Name	Period of Record	Water-Quality Parameter	Seasonal Kendall tau (italicized if statistically significant)
Las Vegas Bay (Site 3)	October 2004–April 2009	Temperature	0.12
		Specific Conductance	***0.58***
		Dissolved Oxygen	0.15
Overton Arm	January 2005–June 2009	Temperature	–0.14
		Specific Conductance	***–0.37***
		Dissolved Oxygen	0.17

Table 9. Spearman rho values for water-quality parameter values (monthly averages) relative to Lake Mead elevation for shallow-water U.S. Geological Survey water-quality stations.

Station Name	Period of Record	Water-Quality Parameter	Spearman rho (italicized if statistically significant)
Las Vegas Bay (Site 3)	October 2004–April 2009	Temperature	–0.231
		Specific Conductance	***–0.409***
		Dissolved Oxygen	–0.155
Overton Arm	January 2005–June 2009	Temperature	–0.216
		Specific Conductance	0.048
		Dissolved Oxygen	0.061

Table 10. Spearman rho values for water-quality parameter values (monthly averages) relative to Lake Mead elevation for deep-water U.S. Geological Survey water-quality stations and thermally-defined lake layers.

Station Name	Period of Record	Water-Quality Parameter	Spearman rho (italicized if statistically significant)		
			Epilimnion	Metalimnion	Hypolimnion
Sentinel Island	October 2004–September 2009	Temperature	***–0.284***	–0.161	0.211
		Specific Conductance	***0.443***	***0.777***	***0.892***
		Dissolved Oxygen	0.173	0.426	–0.025
Virgin Basin	February 2005–September 2009	Temperature	***–0.276***	0.290	***0.432***
		Specific Conductance	***0.767***	***0.804***	***0.915***
		Dissolved Oxygen	0.044	0.067	–0.137

Results and Discussion

The discussion of results is divided into three areas: 1) observations of lake stratification, 2) temporal-trend analyses, and 3) correlation analyses. Additionally, the discussions of lake stratification and trend analyses have also been grouped by shallow-water and deep-water stations because of differences in the results by water depth. Shallow-water stations included LVB3 and Overton Arm, and the deep-water stations included Sentinel Island and Virgin Basin.

Observations of Lake Stratification—Shallow-Water Stations

Shallow-water stations showed little development of thermal stratification during the summer months. When the elevation of the lake was above 340 masl, shallow-water stations showed a decrease in temperature with depth during the summer months (Appendices 14 and 15). This thermal gradient was muted or absent when lake levels dropped below 340 masl, and temperatures in the water column showed little variability with depth. During summer months, temperatures were at or near 30°C in the water column, while in the winter temperatures were 12–14°C.

No major seasonal SC maxima or minima were observed at the shallow-water stations. Both shallow-water stations, however, and particularly the LVB3 station exhibited an increase in SC at the greatest depths during the winter months (fig. 5). This likely represents dense, higher-conductance water from either the Las Vegas Wash or the Muddy/Virgin Rivers moving as underflow within the hypolimnion at these stations (LaBounty and Burns, 2005; Rosen and others, 2010; fig. 5).

No major seasonal DO maxima or minima were observed at the shallow-water stations; however, during the summer months, DO concentrations decreased with depth, which probably represents an increase in sediment-oxygen demand. An example of this potential demand was observed at Overton Arm (fig. 6). Primary productivity is likely occurring near the top of the water column while degradation of the organic material formed by the primary productivity is occurring throughout the water column and within sediment at the bottom of the lake. At the sediment/water interface, biologic respiration and decomposition of organic material by benthic organisms and bacteria is causing a reduction of dissolved oxygen in the water column.

Observations of Lake Stratification—Deep-Water Stations

At deep-water stations, a thermocline began forming in May and showed peak development in August. From September through December, the thermocline decayed and moved deeper in the water column. In general, no thermocline was observed from January through March at deep-water stations, and the lake appeared to be thermally equilibrated with depth. When the thermocline was well-developed, temperatures in the epilimnion at deep-water stations peaked at around 30°C, while hypolimnion temperatures were 11–15°C year-round.

Previous studies have indicated that certain areas of Lake Mead, primarily Boulder Basin, do not always completely

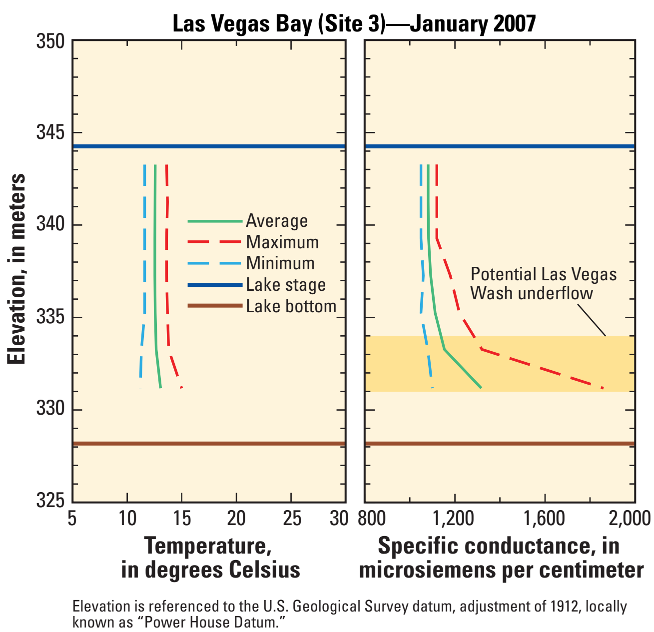

Figure 5. Temperature and specific-conductance profiles at the U.S. Geological Survey Las Vegas Bay (Site 3) station on Lake Mead for January 2007.

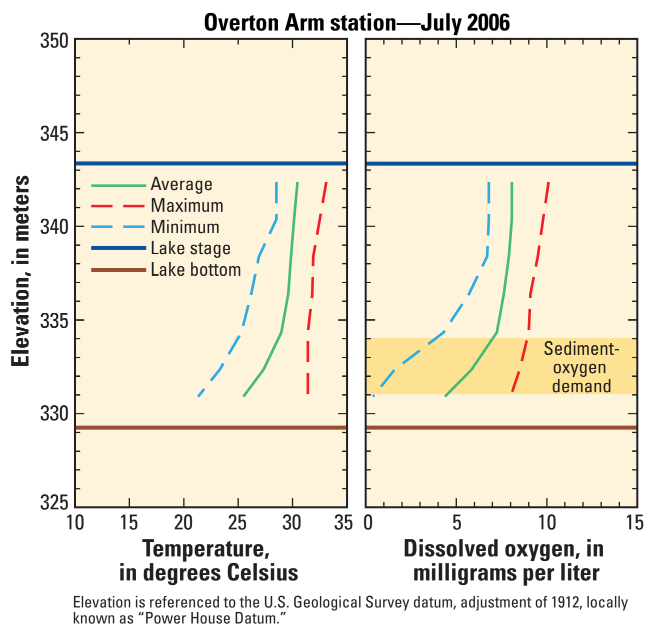

Figure 6. Temperature and dissolved-oxygen profiles at the U.S. Geological Survey Overton Arm station on Lake Mead for July 2006.

thermally destratify in the winter (LaBounty and Horn, 1997; LaBounty and Burns, 2005). LaBounty and Horn (1997) indicated that water in the Boulder Basin of Lake Mead has only a 40 percent chance of complete seasonal thermal destratification in any year. Data from this study indicate that all deep-water stations appeared to undergo thermal destratification in the winter (Appendices 16–18).

A maximum and minimum in SC formed at the Sentinel Island station mainly during the summer months. The SC maximum could be the result of high-conductance water from Las Vegas Wash moving as interflow along the base of the epilimnion, whereas the SC minimum could be the result of low-conductance water from the Colorado River moving as interflow within the metalimnion (fig. 7). LaBounty and Burns (2005) observed high-conductance water from the Las Vegas Wash moving as interflow into the Boulder Basin between the epilimnion and metalimnion. This interflow was observed in the late summer and fall and was based on SC values as well as perchlorate, nitrate, and orthophosphorus values. They also noted an interflow of low-conductance Colorado River water directly beneath the Las Vegas Wash interflow, but only when inflow from the Colorado River was normal or above normal (LaBounty and Burns, 2005). The SC profile observed by LaBounty and Burns (2005) resulting from both Las Vegas Wash and Colorado River inflow is very similar to the pattern observed at the Sentinel Island station, although the magnitude of the SC maxima and minima observed in this study is lower (fig. 7).

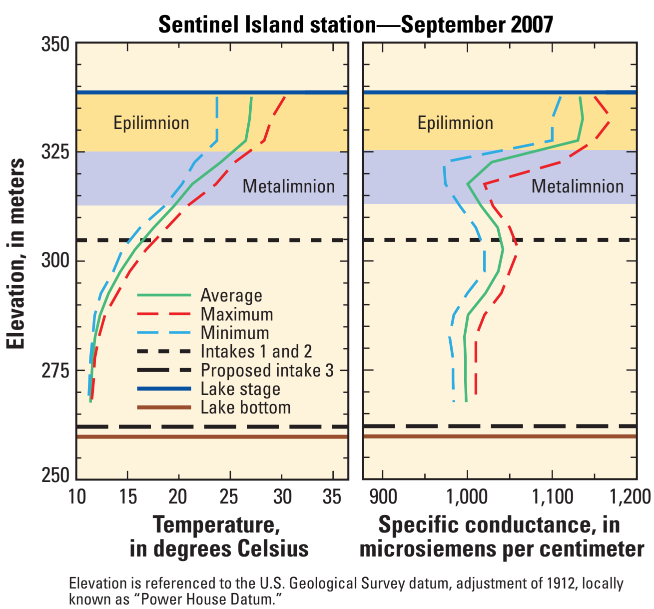

Figure 7. Temperature and specific-conductance profiles at the U.S. Geological Survey Sentinel Island station on Lake Mead for September 2007. Potential inflow from Las Vegas Wash and the Colorado River are shown in the epilimnium and metalimnium, respectfully.

Prominent SC minima developed at both Temple Basin and Virgin Basin stations in July and persisted through September. These minima formed near the top of the metalimnion. Similar to the low conductance interflow observed at Sentinel Island, these SC minima are thought to result from low conductance water from the Colorado River moving as interflow along the top of the metalimnion (LaBounty and Burns, 2005).

Maxima in DO developed at the Sentinel Island and Virgin Basin stations within or near the base of the epilimnion, with peak development usually in July. A lesser DO maximum that also peaked in July formed within the epilimnion at Temple Basin. These DO maxima are believed to coincide with maximum phytoplankton productivity in the photic zone of the lake (fig. 8). On the basis of data from 2000 to 2004, peak biovolume production for all species of phytoplankton in the Boulder Basin of Lake Mead occurs in July (LaBounty

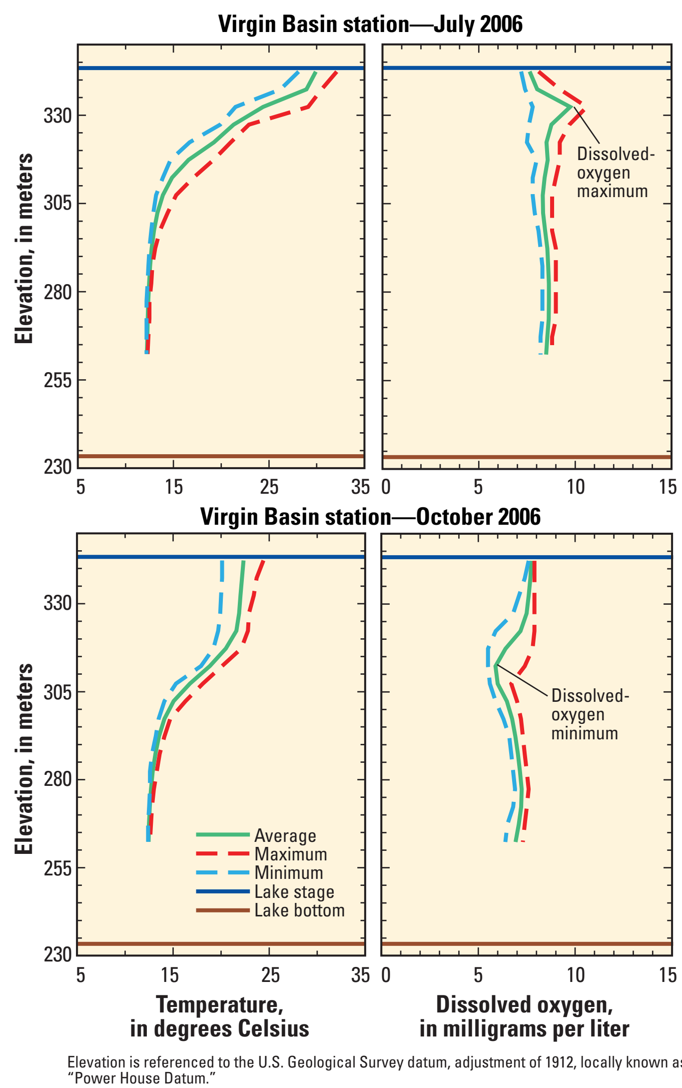

Figure 8. Temperature and dissolved-oxygen profiles at the U.S. Geological Survey Virgin Basin station on Lake Mead for July 2006 and October 2006.

and Burns, 2005). Previous work has shown that peak phytoplankton production in Lake Mead is associated with a notable oxygen maximum in the epilimnion. In a study of Lake Mead water quality by the U.S. Bureau of Reclamation (USBR) in the 1960s, DO was highest near the top of the metalimnion. (U.S. Bureau of Reclamation, 1967). At Sentinel Island and Virgin Basin, the development of DO minima near the top of the metalimnion followed the maxima by about 1–2 months. These DO minima are thought to be associated with degradation of organic material following the period of peak production (fig. 8). According to LaBounty and Horn (1997), aerobic respiration by zooplankton accounts for a substantial portion of the DO minima observed in the metalimnion of Lake Mead.

Temporal-Trend Analyses—Shallow-Water Stations

Temporal-trend analyses were performed only at one depth for shallow-water stations; thus, it was not possible to identify differences in trends among thermally stratified lake layers. The only statistically significant trends at shallow-water stations were for SC. Values of SC show a significant positive trend at the LVB3 station (fig. 9) and a significant negative trend at the Overton Arm station. The negative trend at Overton Arm is consistent with the significant negative trends observed in all lake layers at the deep-water stations.

Although the trend of increasing SC observed at the LVB3 station is counter to the decreasing trends in SC observed at the other stations (Appendices 14–18), the correlation analysis also showed a significant negative correlation of SC with lake elevation (table 8). The most plausible explanation for increasing SC at LVB3 is the dramatic loss of the lake elevation that occurred during the sample-collection period. As the water depth decreased over time, less water was available for mixing and dilution of high-conductance water from Las Vegas Wash. The lack of a detectable thermocline at this station indicates that the entire water column can be unstratified during the summer months. A similar trend was not detected at the Overton Arm station (fig. 9) because the Muddy and Virgin Rivers generally carry fewer total dissolved solids than Las Vegas Wash.

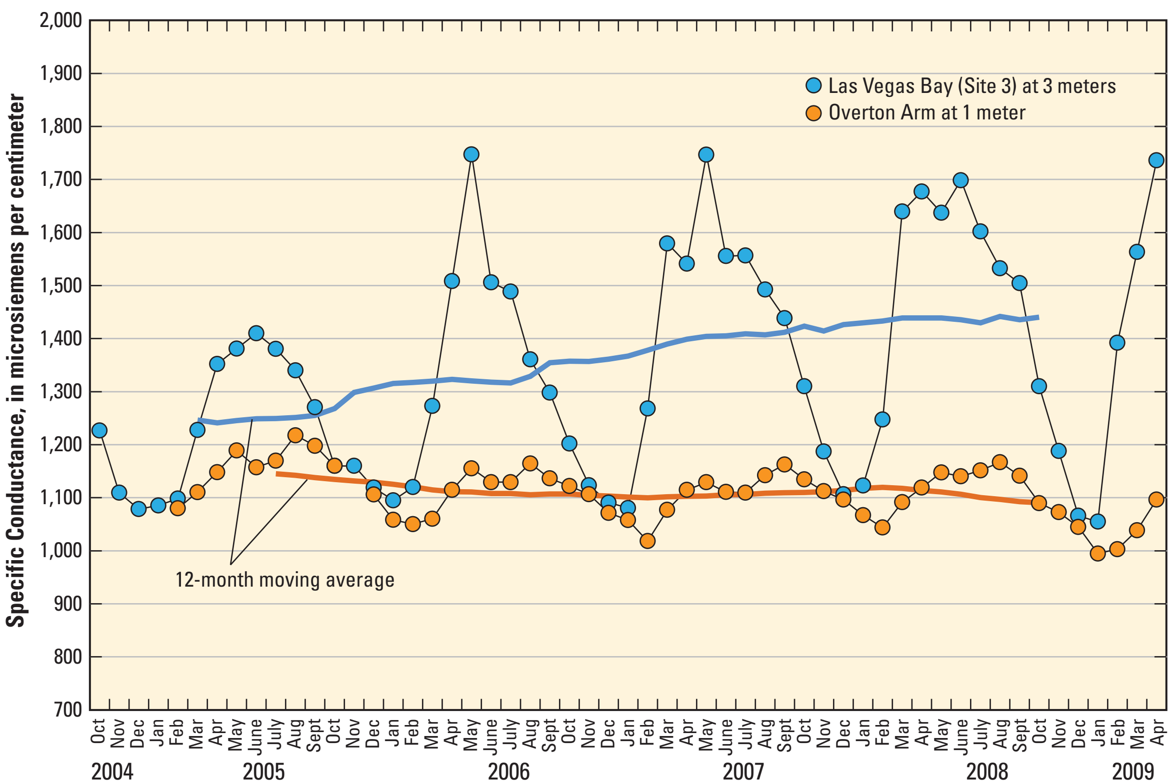

Figure 9. Monthly average values of specific conductance in microsiemens per centimeter from October 2004 to September 2009 at the U.S. Geological Survey Las Vegas Bay (Site 3) and Overton Arm stations on Lake Mead at 3 meters and 1 meter, respectively.

Temporal-Trend Analyses—Deep-Water Stations

Deep-water stations showed significant temporal trends in all variables examined; however, not all lake layers showed significant temporal trends. There was a significant trend of decreasing temperature in the hypolimnion at the Sentinel Island station and in the epilimnion and hypolimnion at the Virgin Basin station (table 7). LaBounty and Burns (2005) found a trend toward decreasing temperature in Boulder Basin in both the metalimnion and the hypolimnion from 1994–2004; however, they offered no explanation for it. An explanation for the decreasing temperature trend observed at these stations is that it results primarily from the decreasing temperature of water entering Lake Mead from the Colorado River. A statistically significant trend (tau = −0.31, p = 0.01) of decreasing temperature of water entering Lake Mead from the Colorado River was measured at Lees Ferry (USGS STAID 09380000; fig. 10).

The most consistent trend observed in the data was that SC decreased significantly in all lake layers at the deep-water stations and at the Overton Arm station (tables 7 and 8). In addition, tau values for SC trends at the deep-water stations were all less than −0.7 indicating that the trend is significant and strong (table 7). A plot of monthly average values of SC in the epilimnion at Sentinel Island shows a consistent decrease throughout the period of record (fig. 11).

The trend in SC values at the water-quality stations was confirmed by data from long-term monitoring at the lake at Colorado River mile 346.4 (CR346.4),which is located approximately 2 kilometers northeast of Sentinel Island in Boulder Basin (Clark County Water Reclamation District, written commun., 2009; fig. 12). The CR346.4 site showed a very similar pattern of decline in SC values as that at the Sentinel Island station from January 2005 to November 2009.

The most likely cause of decreasing SC values is the quality of water entering from the Colorado River. According to LaBounty and Burns (2005), the Colorado River contributes about 97 percent of the annual inflow to Lake Mead. An analysis of data on SC in water from the Colorado River from

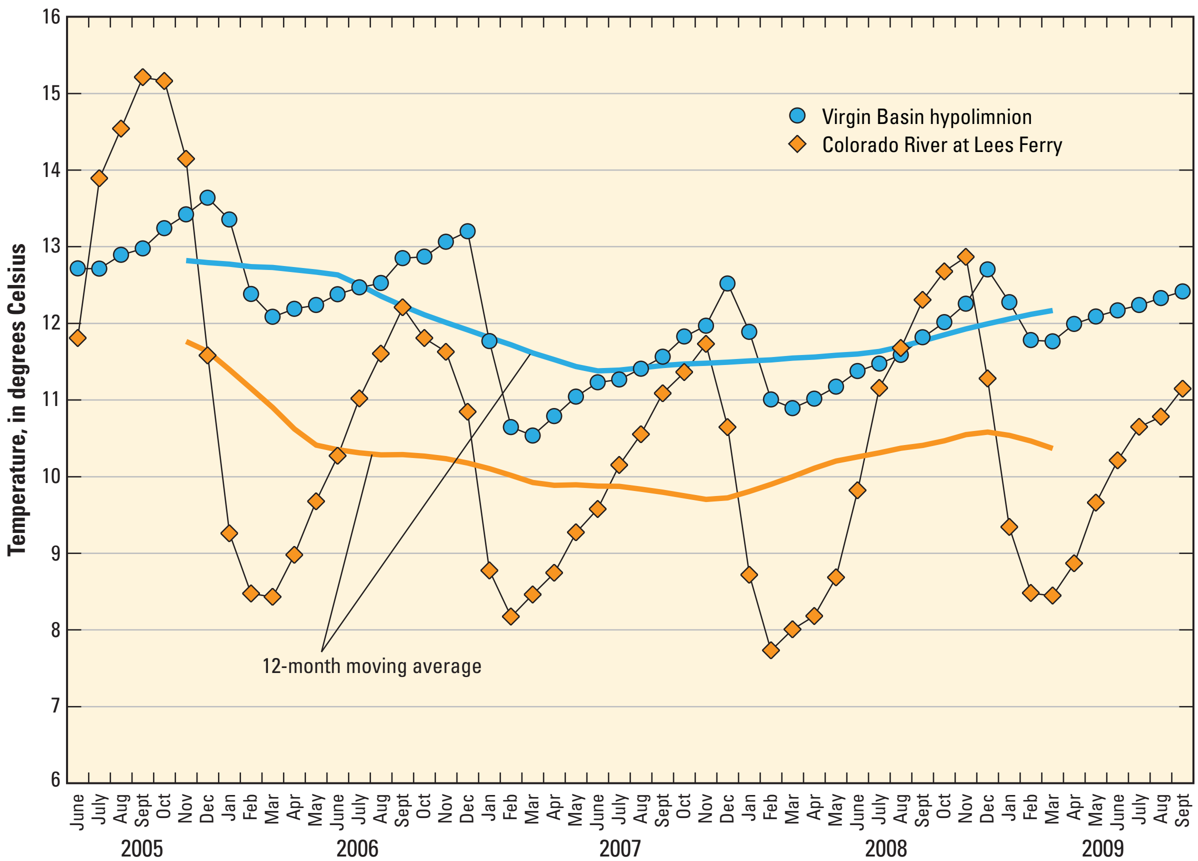

Figure 10. Monthly average values of temperature in degrees Celsius in the hypolimnion from June 2005 to September 2009 at the U.S. Geological Survey Virgin Basin station on Lake Mead and the Colorado River at Lees Ferry, Arizona, station.

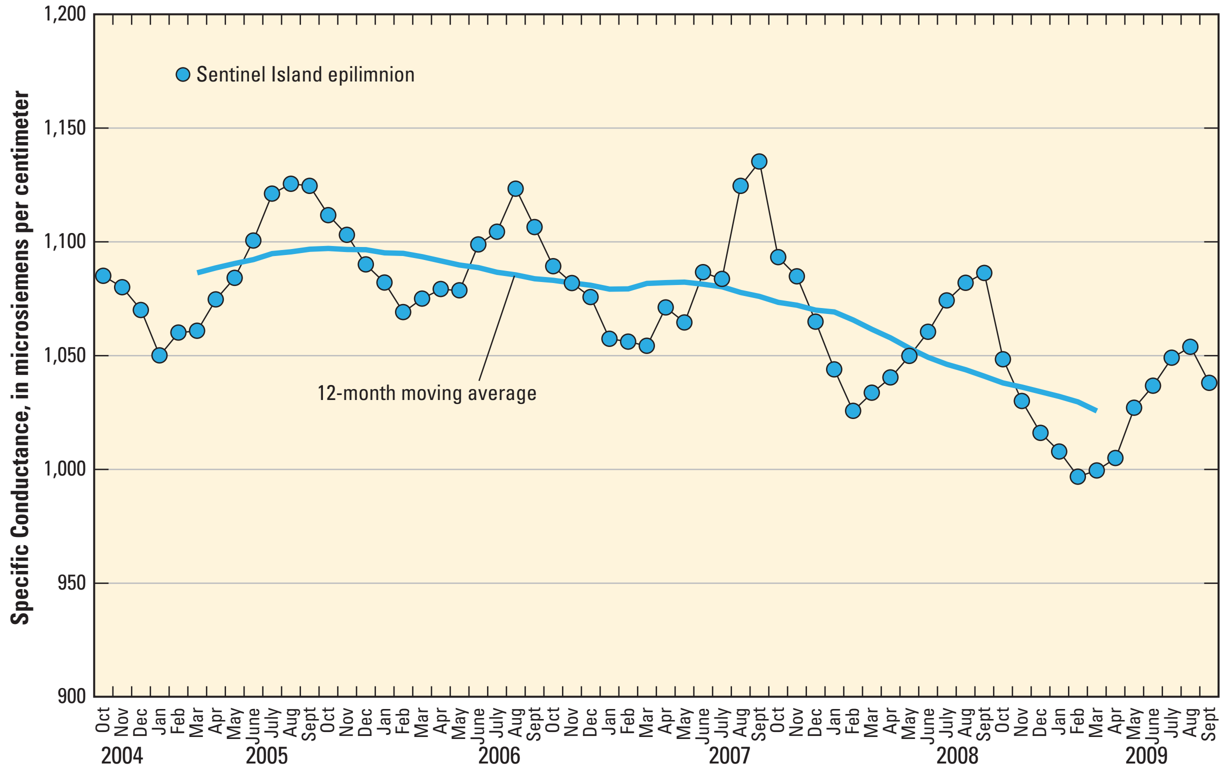

Figure 11. Monthly average values of specific conductance in microsiemens per centimeter in the epilimnion from October 2004 to September 2009 at the U.S. Geological Survey Sentinel Island station on Lake Mead.

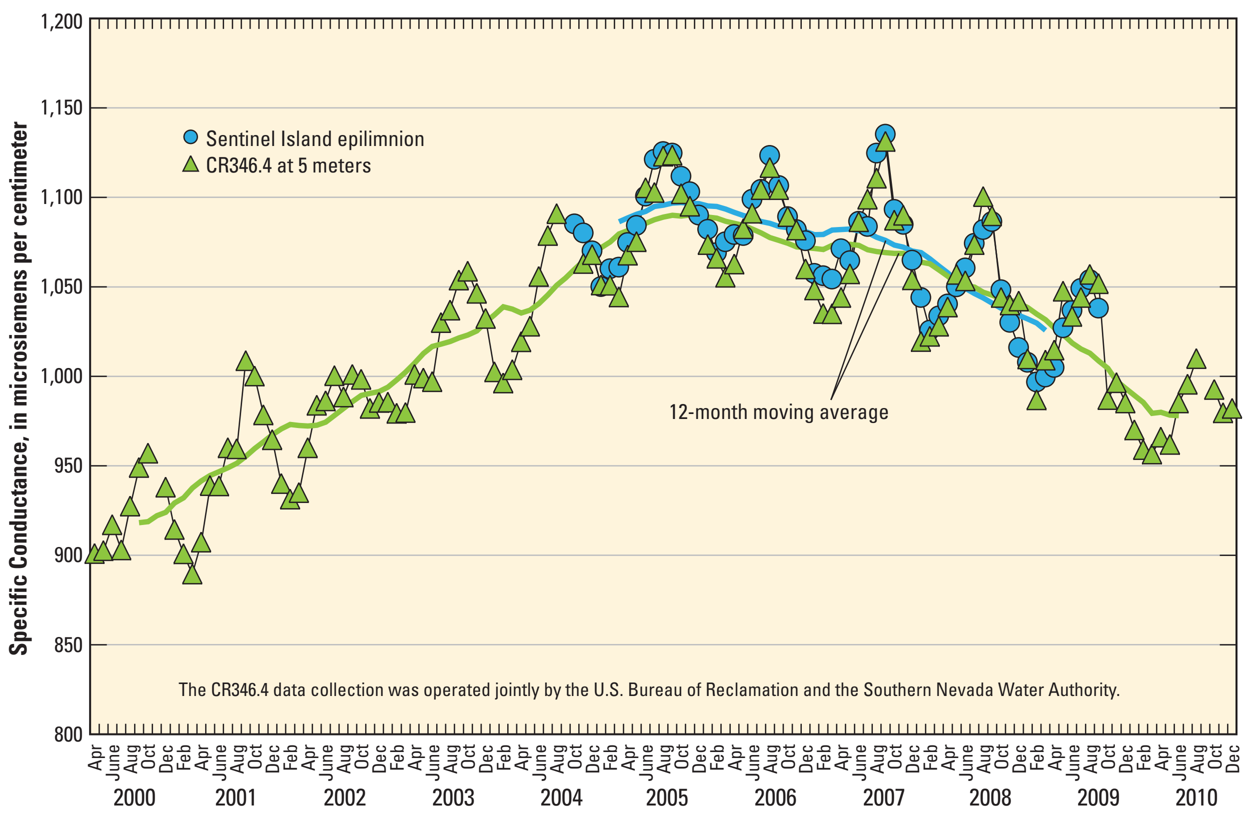

Figure 12. Monthly average values of specific conductance in microsiemens per centimeter at the U.S. Geological Survey Sentinel Island station and at Colorado River mile 346.4 (CR346.4) on Lake Mead.

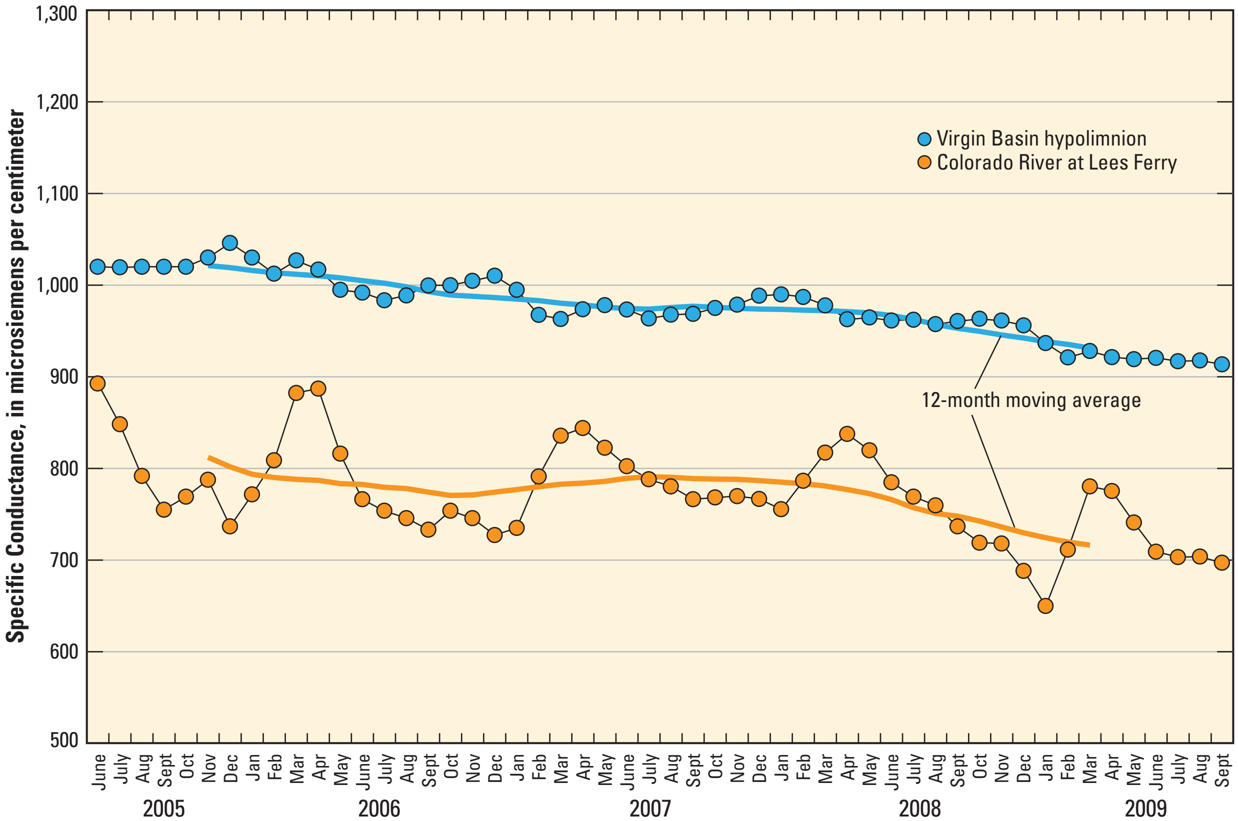

Figure 13. Monthly average values of specific conductance in microsiemens per centimeter in the hypolimnion from June 2005 to September 2009 at the U.S. Geological Survey Virgin Basin station on Lake Mead and the Colorado River at Lees Ferry, Arizona, station.

below Lake Powell at Lees Ferry indicates that there has been a statistically significant decrease (tau = -0.70, p = 0) in SC over the period of data collection for this study (October 2004 to September 2009; fig. 13). In addition, according to LaBounty and Burns (2005), much of the water from the Colorado River enters Lake Mead as underflow within the hypolimnion. If the source of dissolved solids in Lake Mead were solely input from the Colorado River, there would be a strong correspondence between SC values in the river and those in the hypolimnion at monitoring sites near the input of water from the Colorado River, such as the Virgin Basin station. There is a statistically significant positive correlation between SC values at Lees Ferry and in the hypolimnion at the Virgin Basin station from June 2005 to September 2009 (rho = 0.339, p = 0.003).

Another explanation for at least part of the trends in decreasing SC in Lake Mead is the appearance of quagga mussels (*Dreissena rostriformis bugensis*). The presence of quagga mussels in Lake Mead was officially recognized in January 2007. Since then, the mussels have spread throughout much of the lake (Tietjen and others, 2009). Mussels of the genus *Dreissena* (including both quagga and zebra mussels) require dissolved calcium and carbonate for growth because their shells are composed entirely of calcite crystals (Pathy and Mackie, 1993). In addition, species of this genus of mussel have higher calcium requirements than many other freshwater mussels (Cohen and Weinstein, 2001; Whittier and others, 2008). Several researchers have suggested that a decrease in calcium concentration in Lake Ontario from about 1992 to 2008 was the direct result of the rapid growth of mussels of the genus *Dreissena* taking up calcium to build their shells (Barbiero and others, 2006; Dove, 2009).

It is theorized here that at least part of the decline in SC in Lake Mead, as observed at the monitoring stations, could be a result of the incorporation of calcium carbonate in the shells of quagga mussels. Researchers have shown that there is a strong relation between SC and alkalinity in stream water, and values of alkalinity are strongly affected by the concentrations of calcium and bicarbonate in water where the concentrations of these ions dominate (Wetzel, 2001; Kney and Brandes, 2007). Calcium and bicarbonate ions dominate the load of total dissolved solids in the Colorado River system (Stanford and Ward, 1990). In a study of Lake Bourget in France, Groleau and others (2000) found that calcium and bicarbonate were the dominant chemical species contributing to SC, and that there was a direct relation between calcium concentrations and SC. Thus, a decrease in the calcium and bicarbonate concentrations in water in Lake Mead from uptake by quagga mussels should result in a decrease in SC values. The exact amount of decrease in SC, however, is unknown because it is not known how many quagga mussels are in Lake Mead and how much calcium and bicarbonate are removed from solution by each mussel.

To further examine the theory of incorporation of calcium carbonate in quagga mussel shells causing trends of decreasing SC in Lake Mead, trends in pH and turbidity were examined. A decrease in alkalinity related to a decrease in calcium from mineral precipitation in quagga shells should result in an overall decrease in pH (Groleau and others, 2000). The stoichiometric equation for calcite ($CaCO_3$) precipitation (equation 1) dictates a two-fold molar decrease in bicarbonate (HCO_3^-) alkalinity for every one molar decrease in calcium (Ca). This leads to an increase in the partial pressure of carbon dioxide (CO_2) and increased dissociation to carbonic acid (H_2CO_3; equation 2). Consequently, the precipitation of calcite, such as in the shells of quagga mussels, should result in an overall decrease in pH in water (Proft and Stutter, 1993).

$$Ca^{+2} + 2HCO_3 \leftrightarrow CaCO_3 + CO_2 + H_2O \quad (1)$$

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \quad (2)$$

Statistically significant trends of decreasing pH were observed in all lake layers at the deep-water stations in Lake Mead, except for the hypolimnion at Sentinel Island (table 11). Monthly average pH values for the epiliminion for the Sentinel Island station show a decrease during the period of record (fig. 14). Although the 12-month moving average values of pH at Sentinel Island show a decrease during the period of record, the decrease is not consistent through time. Instead, there appears to be a step decrease to lower pH that occurred around the time quagga mussels were first detected in Lake

Table 11. Seasonal Kendall tau values from temporal-trend analyses of pH and turbidity (monthly averages) by station and thermally-defined lake layer for deep-water U.S. Geological Survey Lake Mead water-quality stations.

Station Name	Period of Record	Water-Quality Parameter	Seasonal Kendall tau (italicized if statistically significant)		
			Epilimnion	Metalimnion	Hypolimnion
Sentinel Island	October 2004–September 2009	pH	***–0.40***	***–0.35***	–0.12
		Turbidity	***–0.70***	***–0.73***	***–0.48***
Virgin Basin	February 2005–September 2009	pH	***–0.36***	***–0.37***	***–0.27***
		Turbidity	***–0.40***	***–0.36***	***–0.43***

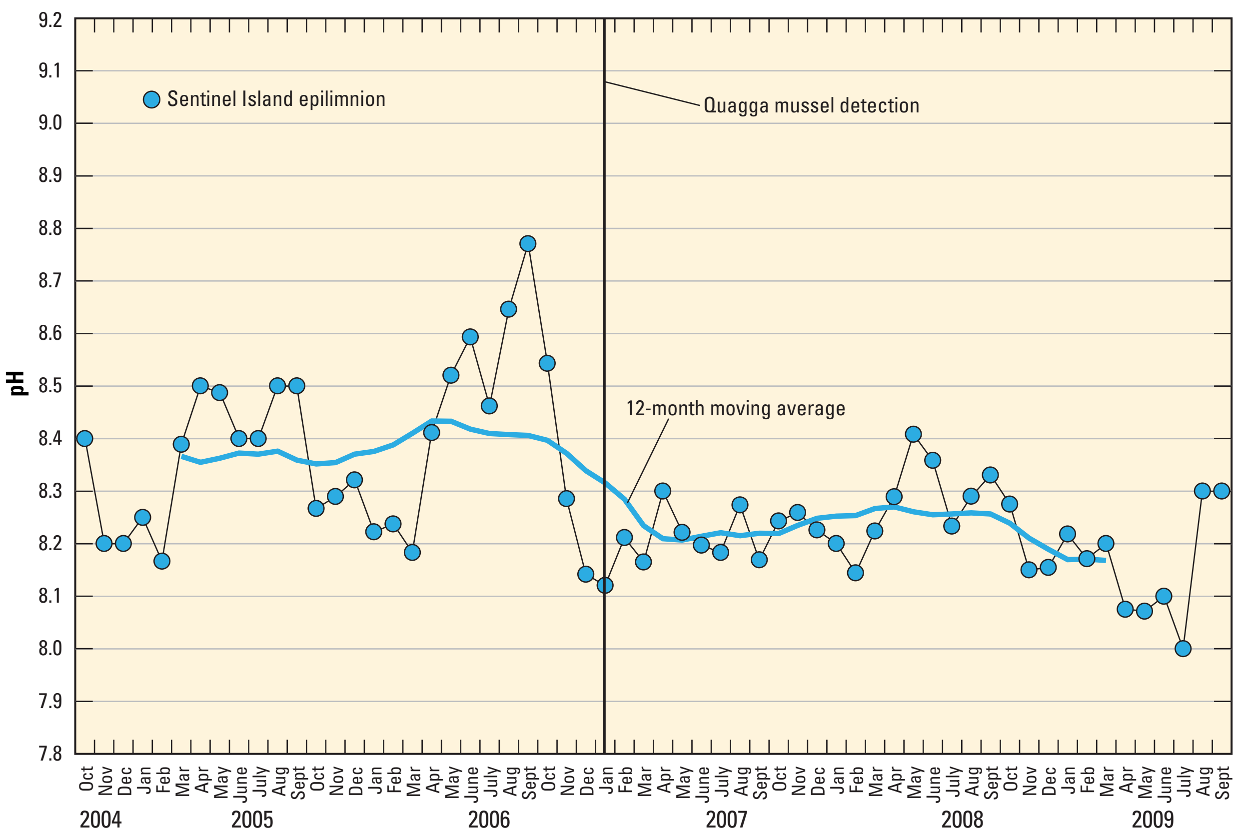

Figure 14. Monthly average pH values in the epilimnion from October 2004 to September 2009 at the U.S. Geological Survey Sentinel Island monitoring station on Lake Mead.

Mead (fig. 14). This is confirmed by comparing the average pH value from September 2004 to December 2006, before the presence of quagga mussels was recognized in January 2007, with the average value from January 2007 to September 2009. The average pH value for the first period was 8.4, and the average value for the second period was 8.2. This decrease in pH is consistent with the geochemical change in water that could be expected as quaggas incoroporate calcium in their shells. The pH decrease could also be due to a decrease in algae activity in the lake as a result of phytoplankton feeding by quagga mussels. However, there are no data for pH in water from the Colorado River at Lees Ferry and it is possible that the decrease in pH during the period of record is partly or wholly the result of changes in pH in water coming from the Colorado River.

Mussels of the genus *Dresissena* decrease suspended sediment and phytoplankton during filter-feeding activities (Fanslow, Nalepa and Lang, 1995; James and others, 2000). According to Barbiero and others (2006), a decline in calcium in Lake Ontario from 1990–2005, which was attributed to uptake of calcium by mussels of the genus *Dreissena*, coincided with a three-fold decrease in turbidity. Turbidity was examined for deep-water stations to determine trends. Because of equipment problems, turbidity data are not available for the Sentinel Island station from June 2007 to February 2008 and at the Virgin Island station from October 2007 to February 2008. Results of the temporal-trend analysis indicate statistically significant decreasing turbidity at both Sentinel Island and Virgin Basin stations and in all lake layers (table 11). Turbidity values in the epilimnion at both stations display strong peaks during the spring of 2005 and 2006, which most likely correspond to peak snowmelt runoff. After the detection of quagga mussels, however, turbidity peaks were strongly attenuated and the overall turbidity pattern appears more random (fig. 15).

Although the trend toward lower SC at the deep-water stations can be explained by a number of physical and biological changes in Lake Mead during the period of record, it is important to put the relatively short time frame of data collected for this study in the context of a longer time frame. The USBR and SNWA have cooperated to collect SC and other physical and chemical water parameters at Lake Mead for many years. One location where data have been collected for an extended period is at CR346.4. Data on SC were collected at CR346.4 from 2000 to 2010 by SNWA and USBR.

Data from the Sentinel Island station and from CR346.4 clearly show a similar trend in SC as displayed by the 12-month moving average lines (fig. 12). The longer period of data from CR346.4, however, reveals that the trend in SC

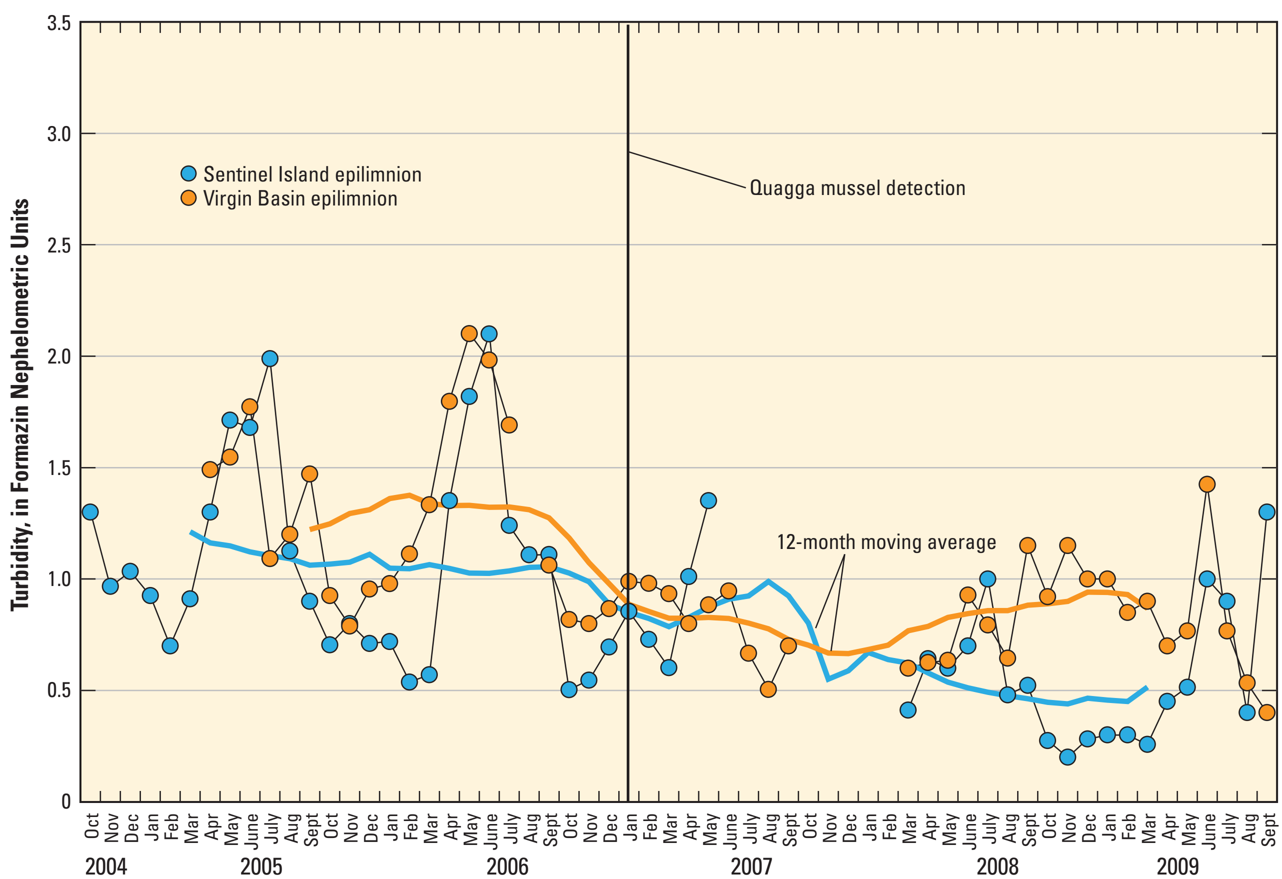

Figure 15. Monthly average turbidity values in formazin nephelometric units in the epilimnion from October 2004 to September 2009 at U.S. Geological Survey Sentinel Island and Virgin Basin stations at Lake Mead.

from the Sentinel Island station is part of a larger trend in SC values of increase from 2000 to about the beginning of 2006 and decrease thereafter (fig. 12). The cause of this long-term trend in SC in Lake Mead is unclear, but it is likely the result of the same factors that caused the trend observed in data from this study, including changes in SC in water from the Colorado River as well as possible incorporation of calcite by quagga mussels.

There were no significant trends in DO concentration at the shallow-water stations, whereas deep-water stations show statistically significant increasing DO concentrations throughout the period of record. A significant increase in DO concentrations was observed in the metalimnion and hypolimnion at Sentinel Island and in the epilimnion and hypolimnion at Virgin Basin (table 7). The increase in DO at Sentinel Island could be the result of a decrease in nutrients and organic matter entering Boulder Basin from Las Vegas Wash as a result of improved treatment of wastewater during, and prior to, the period of record. Decreased nutrients and organic matter entering Boulder Basin would result in lower primary productivity and, thus, lower biological oxygen demand from decay of organic matter. Although the saturation point of DO in water is controlled by temperature, DO concentrations are not controlled by temperature. Most of the time, DO concentrations in the lake are well below saturation and therefore are not affected by a temperature limitation. Near the surface, DO content can be controlled by gas exchange with the atmosphere, but in most areas of the lake DO is most likely controlled by biologic activity. During the summer, DO concentrations in the epilimnion are in a state of supersaturation due to the photosynthetic activity of primary producers. At other times, DO is well below saturation because of demand from bacteria breaking down organic matter.

LaBounty and Burns (2007) found that hypolimnetic oxygen depletion was strongly positively associated with the amount of organic matter and nutrients entering Boulder Basin. They found that higher concentrations of total phosphorus in Boulder Basin increased the hypolimnion oxygen depletion. With enhanced removal of phosphorous from wastewater entering Las Vegas Wash commencing in 2002, hypolimnion oxygen depletion rates in 2005 and 2006 were lower than previous years (LaBounty and Burns, 2007). This trend toward lower hypolimnion oxygen depletion rates from reduced nutrient input to Boulder Basin is likely responsible for the trend of increasing DO concentrations in the hypolimnion at Sentinel Island.

In addition to a decrease in the amount of nutrients and organic matter entering Boulder Basin from Las Vegas Wash, quagga mussels can decrease nutrient concentrations by decreasing the amount of dissolved total phosphorous through filtering and nutrient uptake activities. Hecky and others, (2004) proposed a theory of the re-alignment of phosphorous sources and fate in lakes resulting from the establishment of *Dreissenid* populations as an invasive species. According to the research of Heckey and others (2004), filtering and excrement processes of the mussels cause retention of particulate phosphorous in the nearshore environment and allow less dissolved phosphorous to enter the offshore environment compared with conditions prior to the invasion. This loss of dissolved phosphorus to the offshore environment decreases primary productivity and also decreases decomposer populations.

Correlation Analyses

The correlation analyses were used to provide a framework for understanding results of the trend analyses and to provide further insight into physical and chemical processes affecting water quality at Lake Mead. Only results for SC are discussed because SC was the only parameter with consistently significant correlation values. The elevation of the water level of Lake Mead generally declined during the period of record, although a short period of increasing water level in the lake was observed from about August 2004 to February 2005 (fig. 2). A seasonal Kendall test of lake elevation against time indicated a significant negative trend in lake elevation for the period of record (tau = −0.9407, p = 0). Higher water levels during winter and lower water levels during summer superimposed a cyclical pattern on the overall declining trend. In general, the seasonal pattern results from greater releases from Lake Mead in the summer to provide water for downstream users and decreased releases in the winter (Miller, Paul, Hydrologic Engineer, U.S. Bureau of Reclamation, written commun., 2010).

Because Lake Mead elevation decreased for the period of record, a correspondence between this trend and the lake elevation correlation is demonstrated by (1) a water-quality parameter positively correlated to lake elevation showing a significant decreasing trend or (2) a water-quality parameter negatively correlated to lake elevation showing a significant increasing trend. Such results only were found for SC at LVB3 and the deep-water stations (Sentinel Island and Virgin Basin) in all layers.

According to LaBounty and Burns (2005), when flow to Lake Mead decreases because of decreases in snow-melt runoff, a drop in the lake elevation generally is followed by a pattern of increased conductance (presumably because of the dilution effect of snowmelt). Thus, the drop in elevation in Lake Mead during the period of record should have resulted in an increase in SC, if this were the only variable affecting SC. Although the level of Lake Mead dropped during the period of record, the level of Lake Powell, which is upstream from Lake Mead, increased from early 2005 until late 2009 (U.S. Bureau of Reclamation, 2011b). The increase in the level of Lake Powell during this time was likely from increased meltwater runoff, which decreased SC. Thus, during a time when the level of Lake Mead was dropping, and SC should have been increasing, SC was decreasing because SC in water coming from Lake Powell was decreasing.

Summary

The USGS, in cooperation with the NPS and SNWA, collected water-quality data on Lake Mead as part of a multi-agency monitoring network from October 2004 through September 2009. The purpose of this monitoring was to better understand inflow, circulation, and ecosystem processes that influence water quality at the lake. Analyses of water-quality data were used to evaluate the lake's seasonal stratification changes and longer-term temporal trends in water quality.

Water-quality stations on Lake Mead were located in shallow water (less than 20 meters) at LVB3 and Overton Arm, and in deep water (greater than 20 meters) near Sentinel Island and at Virgin and Temple Basins. At each station, near-continual depth-dependent water-quality data were collected by using automatic profiling systems equipped with multiparameter water-quality sondes. The sondes had sensors for temperature, SC, DO, pH, turbidity, and depth. Data were collected every 6 hours at 3-meter (shallow-water stations) or 5-meter (deep-water stations) depth intervals throughout the water column, beginning at 1 meter below water surface.

Water-quality data were analyzed to determine conditions related to stratification of the lake and temporal trends. Three water-quality parameters were the focus of these analyses: temperature, SC, and DO. Temporal-trend analyses were performed for one depth at shallow-water stations (LVB3 and Overton Arm) and for thermally-stratified lake layers at deep-water stations (Sentinel Island and Virgin Basin).

Observations of the selected water-quality parameters revealed the presence of thermal stratification in some areas of Lake Mead where deep-water stations were located. During the summer, Sentinel Island, Virgin Basin, and Temple Basin stations developed thermal stratification layers. Shallow-water stations at LVB3 and Overton showed little thermal stratification in the summer. Data from this study indicate that all deep-water stations experienced thermal destratification in the winter.

No major temporal SC or DO maxima or minima were observed at the shallow-water stations; however, major SC and DO maxima and minima were observed at deep-water stations during the summer months. The SC maxima at the deep-water stations are interpreted as resulting from high-conductance water that enters from Las Vegas Wash or Muddy/Virgin Rivers and moves as interflow along the base of the epilimnion, while the SC minima could be the result of low-conductance water from the Colorado River moving as interflow within the metalimnion. The DO temporal maxima and minima at deep-water stations are thought to coincide with maximum phytoplankton productivity and its degradation, respectively.

Temporal-trend analyses indicated that SC decreased at all deep-water stations and in all thermally-defined lake layers over the period of record. The temperature also decreased over the period of record at deep-water stations, but only in certain lake layers. Decreasing temperature and SC at deep-water stations is the result of decreasing values in these parameters over time in water coming from the Colorado River. Quagga mussels could play a role in trends of decreasing specific conductance through the incorporation of calcite in their shells. Trends of decreasing turbidity and pH at deep-water stations support the hypothesis that quagga mussels could be having an effect on the physical properties and water chemistry of Lake Mead. Trend analyses indicated that the SC at the LVB3 station increased during the period of record. This is likely a result of lowered lake levels decreasing the volume of lake water available for mixing and dilution of the high-conductance water coming from Las Vegas Wash. In contrast to SC and temperature, DO increased over the period of record at the deep-water stations and in most lake layers. Increasing DO at deep-water stations is believed to be the result of decreased nutrients available for primary productivity because of the improved treatment of wastewater entering Lake Mead since 2002 and uptake of nutrients by quagga mussels since 2007.

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Appendix 1 through 18

Appendix 1: Station Visit Sheet

Appendix 2: Sonde Calibration Check Sheet

Appendix 3: Las Vegas Bay (Site 3) Chlorophyll Data—Water Years 2005–09

Appendix 4: Sentinel Island Chlorophyll Data—Water Years 2005–09

Appendix 5: Overton Arm Chlorophyll Data—Water Years 2005–09

Appendix 6: Virgin Basin Chlorophyll Data—Water Years 2005–09

Appendix 7: Temple Basin Chlorophyll Data—Water Years 2008–09

Appendix 8: Station ID-Name-Binning

Appendix 9: Las Vegas Bay (Site 3) Water-Quality Data—Water Years 2005–09

Appendix 10: Sentinel Island Water-Quality Data—Water Years 2005–09

Appendix 11: Overton Arm Water-Quality Data—Water Years 2005–09

Appendix 12: Virgin Basin Water-Quality Data—Water Years 2005–09

Appendix 13: Temple Basin Water-Quality Data—Water Years 2008–09

Appendix 14: Las Vegas Bay (Site 3) Profiles—Water Years 2005–09

Appendix 15: Overton Arm Profiles—Water Years 2005–09

Appendix 16: Sentinel Island Profiles—Water Years 2005–09

Appendix 17: Virgin Basin Profiles—Water Years 2005–09

Appendix 18: Temple Basin Profiles—Water Years 2008–09

Appendixes 1 through 18 are available as Microsoft Excel or Adobe Acrobat files. These files can be downloaded at *http://pubs.usgs.gov/sir/2012/5080/*.

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