Prepared in cooperation with the Idaho Department of Water Resources

An Evaluation of Seepage Gains and Losses in Indian Creek Reservoir, Ada County, Idaho, April 2010–November 2011




Scientific Investigations Report 2013–5047

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

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors, Datums, and Abbreviations and Acronyms

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Energy	
calorie per second per square foot (cal/ft^2)	45.04	watts per square meter (W/m^2)

Conversion Factors, Datums, and Abbreviations and Acronyms

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
	Volume	
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
milliliter (mL)	0.03381	ounce (oz.)
	Flow rate	
centimeter per day (cm/d)	0.3937	inch (in.)
meter per second (m/s)	3.281	foot per second (ft/s)
millimeter per day (mm/d)	0.03937	inch per day (in/d)
milliliter per day (mL/d)	0.03381	ounce per day (oz/d)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Energy	
joule (J)	0.02390	calorie
joule per cubic meter (J/m^3)	0.006767	calorie per cubic foot (cal/ft^3)
watts per square meter (W/m^2)	0.022204	calories per second per square foot [$(cal/s)/ft^2$]
	Specific Heat	
joule per kilogram (J/kg)	0.002388	calories per gram (cal/g)

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

$$°F=(1.8×°C)+32.$$

Datums

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

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83), Universal Transverse Mercator (UTM) zone 11.

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

Conversion Factors, Datums, and Abbreviations and Acronyms

Abbreviations and Acronyms

E	evaporation
ESRI	Environmental Systems Research Institute
GIS	geographic information system
GPS	global positioning system
GRSAT	Graphical Rating and Shift Application Tool
IDWR	Idaho Department of Water Resources
NGS	National Geodetic Survey
OPUS	Online Position Users Service
RAWS	Remote Automated Weather Station
RTK	real-time kinematic
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

An Evaluation of Seepage Gains and Losses in Indian Creek Reservoir, Ada County, Idaho, April 2010–November 2011

By Marshall L. Williams and Alexandra B. Etheridge

Abstract

The U.S. Geological Survey, in cooperation with the Idaho Department of Water Resources, conducted an investigation on Indian Creek Reservoir, a small impoundment in east Ada County, Idaho, to quantify groundwater seepage into and out of the reservoir. Data from the study will assist the Idaho Water Resources Department's Comprehensive Aquifer Management Planning effort to estimate available water resources in Ada County. Three independent methods were utilized to estimate groundwater seepage: (1) the water-budget method; (2) the seepage-meter method; and (3) the segmented Darcy method. Reservoir seepage was quantified during the periods of April through August 2010 and February through November 2011.

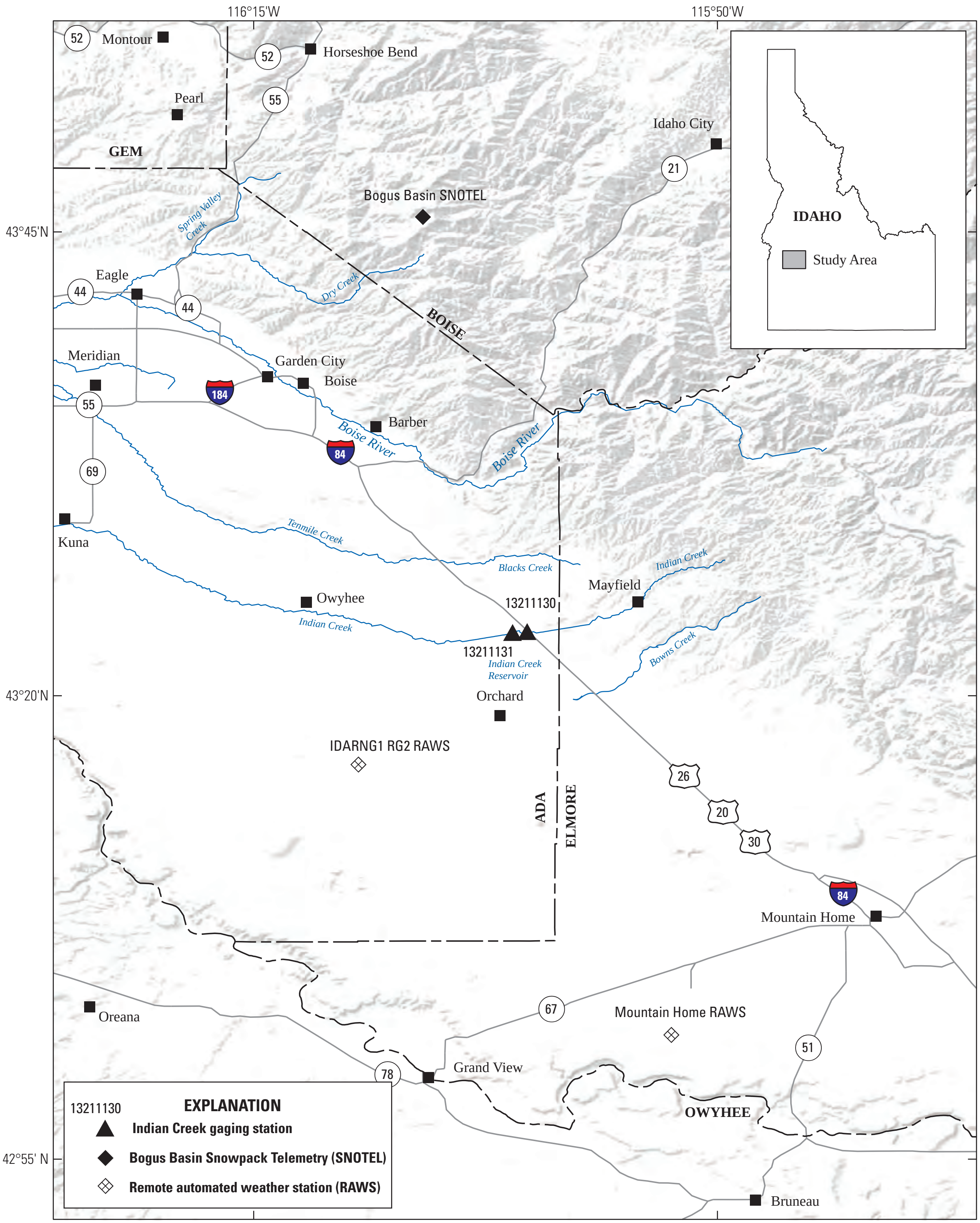
With the water-budget method, all measureable sources of inflow to and outflow from the reservoir were quantified, with the exception of groundwater; the water-budget equation was solved for groundwater inflow to or outflow from the reservoir. The seepage-meter method relies on the placement of seepage meters into the bottom sediments of the reservoir for the direct measurement of water flux across the sediment-water interface. The segmented-Darcy method utilizes a combination of water-level measurements in the reservoir and in adjacent near-shore wells to calculate water-table gradients between the wells and the reservoir within defined segments of the reservoir shoreline. The Darcy equation was used to calculate groundwater inflow to and outflow from the reservoir. Water-budget results provided continuous, daily estimates of seepage over the full period of data collection, while the seepage-meter and segmented Darcy methods provided instantaneous estimates of seepage. As a result of these and other difference in methodologies, comparisons of seepage estimates provided by the three methods are considered semi-quantitative.

The results of the water-budget derived estimates of seepage indicate seepage to be seasonally variable in terms of the direction and magnitude of flow. The reservoir tended to gain water from seepage of groundwater in the early spring months (March–May), while seepage losses to groundwater from the reservoir occurred in the drier months (June–October). Net monthly seepage rates, as computed by the water-budget method, varied greatly. Reservoir gains from seepage ranged from 0.2 to 59.4 acre-feet per month, while reservoir losses to seepage ranged from 1.6 and 26.8 acre-feet per month. An analysis of seepage meter estimates and segmented-Darcy estimates qualitatively supports the seasonal patterns in seepage provided by the water-budget calculations, except that they tended to be much smaller in magnitude. This suggests that actual seepage might be smaller than those estimates made by the water-budget method.

Although the results of all three methods indicate that there is some water loss from the reservoir to groundwater, the seepage losses may be due to rewetting of unsaturated near-shore soils, possible replenishment of a perched aquifer, or both, rather than through percolation to the local aquifer that lies 130 feet below the reservoir. A lithologic log from an adjacent well indicates the existence of a clay lithology that is well correlated to the original reservoir's base elevation. If the clay lithologic unit extends beneath the reservoir basin underlying the fine-grain reservoir bed sediments, the clay layer should act as an effective barrier to reservoir seepage to the local aquifer, which would explain the low seepage loss estimates calculated in this study.

Introduction

The U.S. Geological Survey (USGS) in cooperation with the Idaho Department of Water Resources (IDWR) conducted an investigation to evaluate seepage gains and losses for Indian Creek Reservoir (fig. 1), a small impoundment about 16 mi southeast of Boise, Idaho. The central issue addressed by the study is the nature of groundwater/surface-water interaction between the local aquifer system and the reservoir. This information is vital to the understanding of the availability of water-resources in Ada County, Idaho. Data from the study will assist the Idaho Water Resources Department's Comprehensive Aquifer Management Planning (CAMP) effort to estimate available water resources in Ada County.



Created from Environmental Systems Research Institute base map (multiple sources), Web Mercator Auxiliary Sphere, December 2009.

0 10 20 MILES
0 10 20 KILOMETERS

Figure 1. Indian Creek Reservoir study area, Idaho.

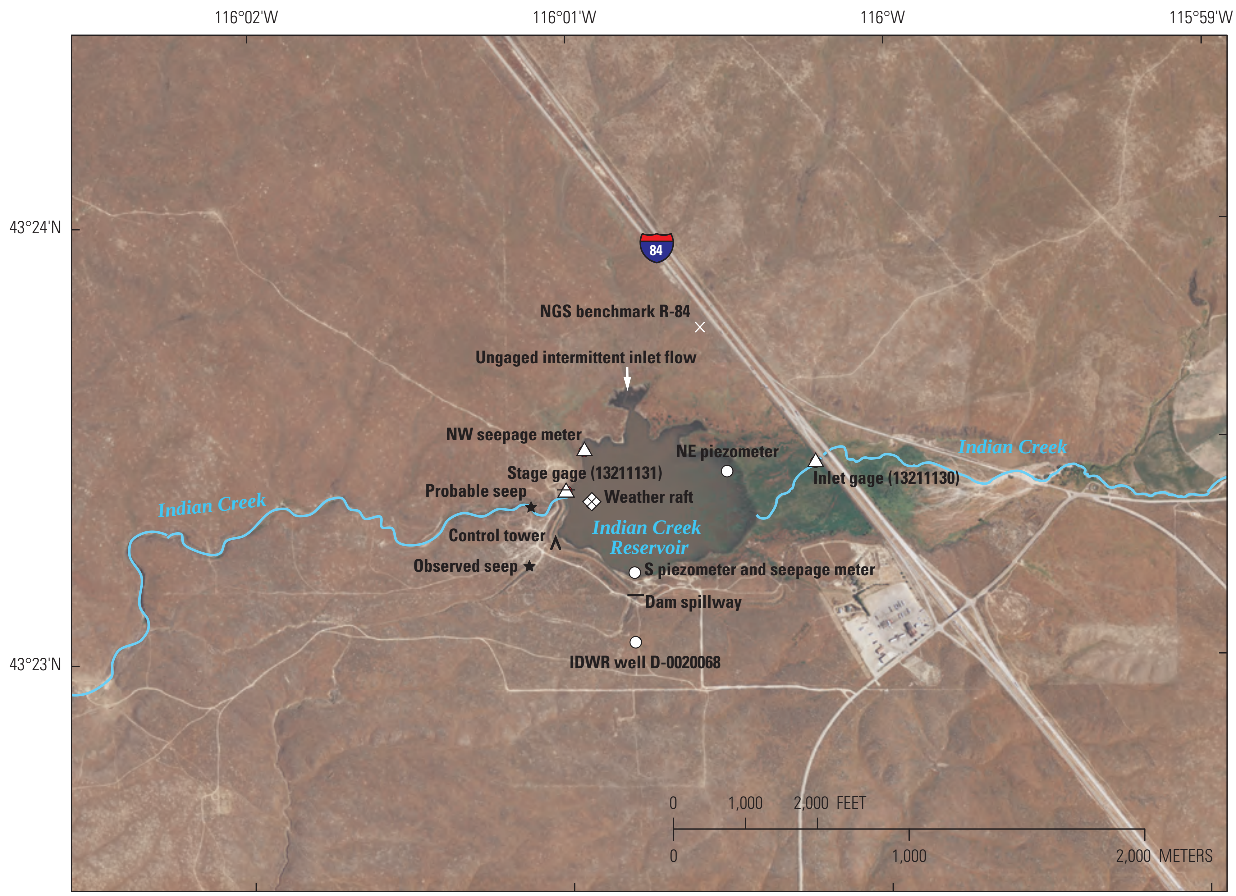
Purpose and Scope

This report provides an evaluation of three independent methods used to estimate seepage from and into Indian Creek Reservoir. The three methods used to estimate seepage are the water-budget method, the seepage-meter method, and the segmented Darcy method. Seepage was estimated for the periods April through August 2010 and February through November 2011.

Study Area Description

Ada County is in southwestern Idaho (fig. 1) and, according to U.S. Census Bureau statistics (U.S. Census Bureau, 2010), is the most populous county in the state (392,000 people), and has a land surface area of 1,052 mi^2. The Boise River runs along the base of and roughly parallel to the foothills and mountains at the northern part of the county. The annual precipitation recorded at the Mountain Home Remote Automated Weather Station (RAWS) was 10 in. in 2010, and 10.4 in. in 2011 (Western Regional Climate Center, 2012b). The Bogus Basin Snowpack Telemetry (SNOTEL) site, operated by the U.S. Department of Agriculture's Natural Resources Conservation Service in Boise County, is just north of the Ada County border, and recorded snow-water equivalencies of 91 percent of average in May 2010, and 155 percent of average in May 2011, as compared to the monthly averages from May for 1971–2000 (Natural Resources Conservation Service, 2012).

Indian Creek Reservoir (formerly known as Orchard Reservoir), is a small impoundment near the eastern border of Ada County. It was created in 1892 with an originally estimated surface area of 125 acres and storage capacity of 4,737 acre-ft at the base of a 43-mi^2 drainage (Soil Conservation Service, 1950). The drainage area was revised by the U.S. Geological Survey and is now estimated at 51.5 mi^2 (U.S. Geological Survey, 2009). Indian Creek is the primary contributor to the reservoir; there is no surface-water outlet, and only one unmeasured seep was observed in October 2011 on the downgradient side of the reservoir (fig. 2). The reservoir is southwest of Interstate 84 (fig. 2), and is surrounded by low-lying hills with grasses, sagebrush, and herbaceous vegetation. The reservoir is at the base of the foothills and mountains to the north-northwest, with the topography sloping off gradually to the south and southwest.



Base map from National Agriculture Imagery Program (NAIP), 2011 natural color 1-meter infrared ortho imagery from U.S. Department of Agriculture, Farm Service Agency.

Figure 2. Locations of sites in and near Indian Creek Reservoir, Ada County, Idaho. (IDWR, Idaho Department of Water Resources; NGS, National Geodetic Survey; NW, northwest; NE, northeast; S, south.)

The maximum daily mean temperature measured during the study was 27.4°C in July 2011, and the minimum daily mean temperature was 1.1°C in November 2011. The reservoir periodically freezes in the winter.

Methods

Methods are presented for the three seepage estimation methods used in this study, the water-budget method, the seepage-meter method, and the segmented-Darcy method. Each method requires different instrumentation and techniques to provide seepage estimates for the reservoir.

Water Budget Method

Water budgets are important for evaluating availability of water resources and the potential sustainability of water supplies for current users and future development. A water budget is area specific, the results of which depend on climate, water resources, human activities, geology, vegetation, and land use (Healy and others, 2007). Analysis of the Indian Creek Reservoir water budget provides an understanding of which water budget components are important to the water balance of the reservoir and can be used to better understand the interaction of the reservoir and groundwater. The water-budget equation used to calculate Indian Creek Reservoir gains or losses to groundwater is as follows:

$$\Delta S - Q_{sw} - P + E = Q_{gw} \quad (1)$$

where

ΔS is the change in reservoir storage (positive values are an increase in storage),

Q_{sw} is the surface water inflow to the reservoir,

P is precipitation to the reservoir,

E is evaporation from the reservoir (evaporation is an outflow component), and

Q_{gw} is reservoir seepage gains and losses (positive values represent reservoir gains from groundwater inflow) to the reservoir.

Streamflow and Precipitation

Surface-water inflow from Indian Creek enters the reservoir from the northeast through an existing channel that was modified in the late 1960s to construct Interstate 84 (fig. 2). The former channel of Indian Creek extends several hundred yards toward the center of the reservoir. An additional intermittent drainage to the northwest also may provide surface-water inflow, but this drainage area was not considered to be a significant contributor during the periods of study because the drainage basin is small (2.8-mi^2). There is no surface-water outflow from the reservoir, and only one unmeasured seep was first observed in October 2011 on the downgradient side of the reservoir (fig. 2). The seep consisted of 50 m of saturated soil at the bottom of a narrow drainage channel with no discernible flow, and only a small amount of ponding at the beginning of the seep.

The Indian Creek above Indian Creek Reservoir streamgage (USGS station 13211130) was operated seasonally from March 2010 to October 2011 and has a 46.3-mi^2 drainage area. This streamgage was installed to quantify surface-water inflow to Indian Creek Reservoir. Daily mean streamflow ranged from 0 to 79 ft^3/s during the study period, with the highest daily streamflow of 79 ft^3/s on January 17, 2011. Runoff to the reservoir ranged from 0 acre-ft in the 2010 study period to 416 acre-ft in the 2011 study period.

Precipitation values for the 2010 study period were obtained from a Remote Automated Weather Station (RAWS; fig. 1) in Mountain Home, Idaho, about 26 mi south-southeast of the reservoir. Precipitation values for 2011 were obtained from the IDARNG1 RG2 RAWS (fig. 1), about 10.6 mi southwest of the reservoir (Western Regional Climate Center, 2012b).

Change in Reservoir Storage

In October 2009, when the reservoir was nearly dry (3,314 ft), a bathymetric survey was completed. The bathymetric survey has a horizontal and vertical accuracy of 1 ft. Survey data were collected using real-time kinematic (RTK) global positioning system (GPS) equipment. A base station was set up over an arbitrary point and a first-order vertical benchmark known to the National Geodetic Survey as R-84 was used as a quality-control point (fig. 2). The Online Position Users Service (OPUS) was used to acquire a precise position for the base station on each day of surveying.

Bathymetric survey points were collected using roving GPS receivers and differential GPS to compute the height and location of each point in real time. Survey points were collected in three ways: (1) on foot using a 2-m survey rod equipped with a bipod, (2) on an all-terrain vehicle with the roving receiver affixed to the vehicle and measured at a known height above ground, and (3) from a kayak using a 2-m rod equipped with a bipod. An attempt was made to collect most GPS data on a 30-m grid, but GPS data in some of the flatter areas near the highway were collected on a 100-m grid.

After all survey data were assembled, OPUS solutions for the base station during each day of data collection were applied to correct all differential GPS survey data. Detailed descriptions of survey methods and metadata are available in appendix A and in Wilson and Richards (2006).

After bathymetric survey data were post-processed, quality-assured, and approved, a Triangulated Irregular Network (TIN) model of the bathymetric surface was created. The TIN model was used to compute a stage-capacity rating and a stage-area rating for the reservoir according to methods outlined in Wilson and Richards (2006). Both ratings were extended to the maximum capacity of the reservoir, which is the elevation of the spillway at 3,339.88 ft. The ratings are computed at stage increments of 1 ft and are provided in appendix A.

Area and capacity ratings also were computed at 0.01-ft stage increments using the Aquatic Informatics Graphical Rating and Shift Application Tool (GRSAT) software, which is used for many calculations provided in this report. Elevations and corresponding surface area or capacity values from the TIN model were used as input points for the GRSAT ratings. Each rating was computed in log space and extended over the range of conditions observed. The 0.01-ft rating tables were used for computational purposes only and were not provided in this report because the bathymetric survey and the TIN model are accurate only to the nearest foot.

Reference points used to establish the reservoir stage datum at the reservoir stage gage were surveyed using RTK GPS in October 2011. The surveyed elevations were referenced to the North American Vertical Datum of 1988 (NAVD 88) for each reference point and mini-piezometer. This allowed the reservoir stage record to be referenced to the same vertical datum. Previously, the reservoir stage record was referenced to an arbitrary vertical datum and the new survey improved the accuracy of the existing stage datum of the reservoir. The base station was set up over NGS benchmark R-84 (fig. 2) during the 2011 survey, and the spillway elevation served as a quality-assurance check to ensure that bathymetric survey data agreed with the new survey data. The base station was set up for more than 4 hours during the October 2011 survey because the longer duration base station data collection period has been shown to drastically reduce the error associated with survey data, especially when it exceeds 4 hours (Soler and others, 2006). Increased vertical accuracy was imperative because the gage-height record is reported to within 0.01 ft; elevations obtained for the NGS benchmark and the dam face during the 2011 survey were within 0.05 ft of survey results from 2009. Each point was surveyed with a roving GPS receiver on a 2-m survey rod equipped with a bipod and each point was occupied for 180 epochs to maximize vertical accuracy.

The overall vertical accuracy of the control points surveyed in October 2011 was 0.024 m, and the horizontal accuracy was 0.021 m. Accuracy was computed using overall root mean square error provided by the OPUS solution and methods described by the Federal Geographic Data Committee (1998).

To determine water volume and surface area during the study, a stage gage was installed on the south end of the reservoir at the deepest point and used in conjunction with the stage-capacity rating and a stage-area rating for water budget calculations. The Indian Creek Reservoir stage gage (USGS station 13211131) has a period of record from March 2010 to August 2010, and from February 2011 to October 2011. The reservoir stage ranged from 4.13 to 0 ft during 2010, and 14.67 to 10.11 ft during 2011. Maximum surface area was 23.4 acres during the 2010 study period and 121 acres during the 2011 study period. In 2010, the maximum reservoir volume was 28.5 acre-ft at the end of March and decreased to desiccation in August. In 2011, reservoir volume increased from 320 acre-ft in late February to 760 acre-ft at the end of April, which was followed by a monthly decrease to a volume of 361 acre-ft by the end of October.

Evaporation

Reservoir evaporation was calculated using the Bowen ratio energy-budget method. The meterologic and hydrologic data used in the energy-budget method was collected with an instrumentation cluster installed on a raft positioned on the reservoir (fig. 2). The raft was initially installed in May 2010, and was operational from June 2010 through the end of August 2010. In March 2011, the raft was reinstalled on the reservoir and continued in operation until the end of the study period in November. The methods described in this report follow methods used for an open water evaporation study of Walker Lake, Nevada (Allander and others, 2009).

The Bowen ratio energy-budget method of estimating evaporation is considered to be one of the most rigorous and accurate methods to determine evaporation (Harbeck and others, 1958; Winter, 1981). The energy-budget equation for open water is as follows (Sturrock and others, 1992; Allander and others, 2009):

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w + Q_b = Q_x \qquad (2)$$

where

Q_s is incoming short-wave radiation,
Q_r is reflected short-wave radiation,
Q_a is incoming long-wave radiation,
Q_{ar} is reflected long-wave radiation,
Q_{bs} is long-wave radiation emitted from the body of water,
Q_v is net energy advected to the reservoir,
Q_e is energy used for evaporation,
Q_h is energy conducted from the water body as sensible heat,
Q_w is energy advected from the water body by the evaporated water,
Q_b is energy transferred from reservoir bed sediments to the reservoir, and
Q_x is change in energy stored in the reservoir, or called heat-storage energy flux.

All of these energy terms are in watts per square meter (W/m^2). The solar radiation terms Q_s, Q_r, Q_a, and the sum of Q_{ar}, and Q_{bs} were measured quantities using precision pyrgeometers (long-wave radiation) and pyranometers (short-wave radiation) suspended over the water, the values of which were used to calculate net radiation Q_n:

$$Q_n = Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} \qquad (3)$$

Net energy advected (Q_v) into Indian Creek Reservoir comes from the surface-water inflows from Indian Creek, groundwater inflows, and precipitation. Energy advected away from the reservoir occurs through evaporation because there is no surface-water outflow. Net energy advected into the reservoir is calculated as follows:

$$Q_v = cp\sum F_x(T_x - T_b) \quad (4)$$

where

- c is the specific heat of water (4,190 J/kg),
- ρ is the density of evaporated water (1,000 kg/m^3),
- F_x is the flux of inflow component (m/s),
- T_x is temperature of inflowing water (°C), and
- T_b is an arbitrary base temperature (0°C).

There are three primary sources of energy advection to the reservoir: surface water, precipitation directly on the reservoir, and groundwater. Of these sources, surface-water inflow is considered significant, and the others are low to negligible contributors. Heat advection into the reservoir due to precipitation was calculated for each energy-budget period, where the temperature of the precipitation was assumed the same as the mean air temperature for the energy-budget period. Results from the calculation indicate that heat advection owing to precipitation was fairly negligible when values for all but two energy-budget periods were less than 1 W/m^2, and for two other periods values were less than 2 W/m^2. Although the resulting values were small, they were summed with the surface-water heat advection results by energy-budget period for a net heat advection value. Heat advection due to groundwater is assumed negligible. This assumption is based on a hypothetical exercise using real and estimated values to calculate heat advection from groundwater inflow. For example, the reservoir at a maximum capacity, with a surface area of 217 acres, would need to receive 357 acre-ft of groundwater inflow during the year at 15°C to gain 1 W/m^2. Because the 357 acre-ft groundwater inflow is three times the net groundwater inflow of 99.6 acre-ft in 2011 (snowpack snow-water equivalent was 155 percent of average), heat advection from groundwater inflow probably is negligible. Heat advection between the reservoir sediment (Q_b) and the water also is assumed to be negligible and usually is not measured (Winter, 1981; Rosenberry and others, 2007; Allander and others, 2009).

The Q_e, Q_h, and Q_w terms in equation (2) were a function of evaporation rate (E) and were not directly measured. These terms are all related to E as follows:

$$Q_e = pEL, \quad (5)$$

$$Q_h = RQ_e, \quad (6)$$

$$Q_w = cpE(T_e - T_b), \quad (7)$$

where

- E is the energy-budget evaporation rate (m/s),
- L is the latent heat of vaporization of water (2,450,000 [J/kg]/°C),
- R is the Bowen ratio (dimensionless), and
- T_e is the temperature of the evaporated water (taken as the surface temperature, T_0, °C).

Heat storage in the reservoir (Q_x) is computed using the following equation (Allander and others, 2009):

$$Q_x = \frac{c_w d_e \Delta T}{t}, \quad (8)$$

where

- Q_x is heat storage energy flux (W/m^2),
- C_w is the volumetric heat capacity of water, a constant (4.187 M [J/m^3]/°C),
- d_e is the mean reservoir depth (m),
- ΔT is the change in volume-weighted temperature (°C), and
- t is the time span of the energy-budget period (seconds).

The mean reservoir depth (d_e) at the end of each energy-budget period was determined by dividing the total reservoir volume by the reservoir surface area. The change in volume-weighted temperature was calculated by determining the thermal profile of the reservoir using a precision thermistor chain continuously suspended in the water column, and measuring temperatures from the sediment surface to the water surface in 1-ft increments. The temperature of each 1-ft horizontal layer was multiplied by the water layer volume, and their products were summed. A volume-weighted temperature was then computed by dividing that sum by the total reservoir volume. Vertical profile temperature data for energy-budget periods 13 and 14 were not available because of equipment failure. The mean reservoir temperature was computed using the mean surface-water and reservoir-bottom temperatures for the respective energy-budget periods, and was based on the assumption that the reservoir was well mixed. Additionally, a data gap occurred in the reservoir-stage gage record from July 28 to August 4, 2010. A linear interpolation was used for the data gap to estimate daily mean stage values based on a linear regression model for the reservoir stage. This method was determined to be sufficient for this short data gap because water-budget components were stable from July 23 to August 9, 2010 (including the 5 days before and after the data gap) with no surface-water inflow, only 0.03 in. of precipitation was recorded at the Mountain Home RAWS, and seepage estimates from the meters indicated negligible loss. The 2009 bathymetric survey provided the total reservoir volume, volumes by layer, and surface area by stage elevation needed for the calculations (appendix A). A summary of terms used to calculate the heat-storage energy flux is provided in table 1. The heat-storage energy flux ranged from a minimum of -50.8 W/m^2 during energy-budget period 41, October 7–13, 2011, to a maximum of 41.8 W/m^2 during energy-budget period 19, May 6–12, 2011.

Table 1. Heat storage energy flux and other computation terms for seasonal energy budget periods, Indian Creek Reservoir, Ada County, Idaho, June 2010–November 2011.

[All periods start at 0000 hours and end at 2359 hours on the corresponding end dates. Reservoir stage, volume, and surface area are from observation made on the end date for each budget period. Reservoir stage in feet above National Geodetic Vertical Datum of 1929. Reservoir surface area interpolated from 2009 bathymetric survey stage-area relation table. **Abbreviations:** ft, foot; acre-ft, acre-foot; *T*, volume weighted reservoir temperature, in degrees Celsius (°C); **Δ***T*, change in volume weighted reservoir temperature, in degrees Celsius (°C); d_e, mean reservoir depth (reservoir volume/reservoir area) in meters (m); J/m^2, joules per square meter; Q_x, heat-storage energy flux, in watts per square meter (W/m^2); e, estimate; –, data not available]

Energy-budget period	Start date	End date	Days in period	Reservoir stage (ft)	Reservoir volume (acre-ft)	Reservoir surface area (acre)	*T* (°C)	Δ*T* (°C)	d_e (m)	Change in heat storage (×10^4 J/m^2)	Q_x(W/m^2)
0	06-04-10	06-10-10	7	3,314.73	26.3	19.3	17.4	–	0.439	–	–
1	06-11-10	06-17-10	7	3,314.53	22.4	17.3	19.2	1.8	0.398	315	5.20
2	06-18-10	06-24-10	7	3,314.32	19.1	15.3	19.6	0.3	0.384	50	0.83
3	06-25-10	07-01-10	7	3,314.11	16.0	13.4	21.6	2.1	0.365	324	5.36
4	07-02-10	07-08-10	7	3,313.84	12.7	11.4	19.0	-2.6	0.342	-383	-6.33
5	07-09-10	07-15-10	7	3,313.56	9.83	9.52	22.6	3.6	0.318	496	8.20
6	07-16-10	07-22-10	7	3,313.21	7.02	7.42	22.4	-0.2	0.289	-21.9	-0.36
7	07-23-10	07-29-10	7	3,312.88	5.24	5.73	22.7	0.2	0.491	39.4	0.65
8	07-30-10	08-05-10	7	3,312.57	3.09	4.54	22.6	-0.0	0.207	-5.86	-0.10
9	08-06-10	08-12-10	7	3,312.23	1.77	3.29	20.8	-1.9	0.164	-147	-2.42
10	08-13-10	08-19-10	7	3,311.85	0.91	2.06	20.3	-0.5	0.135	-30.7	-0.51
11	03-09-11	03-15-11	7	3,321.13	320	73.2	5.4	–	1.330	–	–
12	03-16-11	03-22-11	7	3,321.22	327	74.2	6.2	0.9	1.340	484	8.01
13	03-23-11	03-29-11	7	3,321.97	386	82.2	[1]5.9	-0.3	1.360	-189	-3.13
14	03-30-11	04-07-11	9	3,324.07	581	104.0	[1]8.3	2.7	1.540	1,480	19.0
15	04-08-11	04-14-11	7	3,324.65	644	111.0	8.9	0.3	1.750	388	6.41
16	04-15-11	04-21-11	7	3,325.12	697	116.0	10.5	1.6	1.770	1,190	19.7
17	04-22-11	04-28-11	7	3,325.63	757	121.0	10.2	-0.3	1.910	-226	-3.73
18	04-29-11	05-05-11	7	3,325.59	752	121.0	10.1	-0.1	1.900	-90.4	-1.50
19	05-06-11	05-12-11	7	3,325.63	757	121.0	13.3	3.2	1.910	2,530	41.8
20	05-13-11	05-19-11	7	3,325.54	746	120.0	14.8	1.6	1.890	1,240	20.6
21	05-20-11	05-26-11	7	3,325.42	732	119.0	14.7	-0.1	1.870	-101	-1.67
22	05-27-11	06-02-11	7	3,325.32	720	118.0	13.2	-1.5	1.860	-1,140	-18.9
23	06-03-11	06-09-11	7	3,325.26	713	118.0	15.6	2.3	1.850	1,800	29.7
24	06-10-11	06-16-11	7	3,325.09	693	116.0	16.8	1.2	1.820	951	15.7
25	06-17-11	06-23-11	7	3,324.93	675	114.0	17.9	1.1	1.800	858	14.2
26	06-24-11	06-30-11	7	3,324.71	650	112.0	19.1	1.2	1.770	898	14.8
27	07-01-11	07-07-11	7	3,324.51	628	109.0	20.8	1.7	1.750	1,230	20.4
28	07-08-11	07-14-11	7	3,324.29	604	107.0	21.2	0.4	1.730	304	5.03
29	07-15-11	07-21-11	7	3,324.05	579	104.0	21.4	0.2	1.700	112	1.86
30	07-22-11	07-28-11	7	3,323.80	553	101.0	21.3	-0.1	1.660	-75	-1.23
31	07-29-11	08-04-11	7	3,323.58	531	98.8	22.5	1.2	1.650	826	13.7
32	08-05-11	08-11-11	7	3,323.35	509	96.4	22.5	0.0	1.610	0.810	0.01
33	08-12-11	08-18-11	7	3,323.12	487	93.9	21.1	-1.4	1.590	-933	-15.4
34	08-19-11	08-25-11	7	3,322.90	467	91.6	21.0	-0.1	1.550	-50.2	-0.83
35	08-26-11	09-01-11	7	3,322.67	446	89.3	21.2	0.2	1.520	125	2.06
36	09-02-11	09-08-11	7	3,322.48	429	87.4	18.5	-2.7	1.500	-1,700	-28.1
37	09-09-11	09-15-11	7	3,322.32	415	85.6	20.0	1.5	1.480	917	15.2
38	09-16-11	09-22-11	7	3,322.16	402	84.1	18.4	-1.6	1.450	-991	-16.4
39	09-23-11	09-29-11	7	3,322.00	388	82.4	18.1	-0.3	1.440	-167	-2.75
40	09-30-11	10-06-11	7	3,321.92	382	81.6	17.1	-1.0	1.420	-616	-10.2
41	10-07-11	10-13-11	7	3,321.87	378	81.1	11.9	-5.2	1.420	-3,070	-50.8
42	10-14-11	10-20-11	7	3,321.81	373	80.5	12.7	0.8	1.410	495	8.19
43	10-21-11	10-27-11	7	3,321.71	365	79.4	11.0	-1.7	1.400	-997	-16.5
44	10-28-11	11-03-11	7	3,321.66	361	78.8	8.0	-3.1	1.380	-1,790	-29.6
45	11-04-11	11-10-11	7	3,321.66	361	78.8	3.9	-4.1	1.360	-2,340	-38.7
46	11-11-11	11-17-11	7	3,321.66	361	78.8	3.8	-0.1	1.360	-38.7	-0.64

[1]Volume weighted reservoir temperature calculated from average of surface and bottom temperatures, based on the assumption that the reservoir was well mixed with no temperature stratification; the mean temperature represents the entire water column.

Substituting appropriate terms from the previous equations, the following equation is used to determine evaporation in this study:

$$E = \frac{Q_n + Q_v - Q_x}{p[L(1+R) + cT_o]}, \tag{9}$$

The Bowen ratio, R, is a unitless value for the ratio of sensible heat flux (Q_h) to latent heat flux (Q_e) at the air-water interface. It is computed from field-measured data as follows:

$$R = \frac{c_b P(T_1 - T_2)}{e_1 - e_2}, \tag{10}$$

where

c_b is an empirical constant (0.00061°C^{-1}),

P is the atmospheric pressure at Indian Creek Reservoir (89900 Pa),

$T_1 - T_2$ is the air temperature difference (°C) at the reservoir surface and 1.5 m above the reservoir surface, and

$e_1 - e_2$ is the vapor pressure difference (Pa) between the reservoir surface and 1.5 m above the reservoir surface.

Temperature and humidity were measured directly at 1.5 m above the water surface; the temperature of the water surface was measured using a precision thermistor suspended in the top 1 cm of the reservoir water. Vapor pressures were calculated using temperature and humidity data, and calculations assumed vapor at the air-water boundary layer was 100 percent saturated. The typical temperature humidity sensor height for calculating the Bowen ratio is 2 m, except in circumstances where the fetch is short, as is the case on Indian Creek Reservoir. When the fetch is short, the air moving from one surface type to another (land to water) has insufficient time to reflect the changes in latent and sensible heat, and, in turn, can create higher uncertainty (Stannard and others, 2004). Heilman and others (1989) determined that in situations where the fetch was short and the Bowen ratio was small, a fetch-to-height ratio of as little as 20-to-1 could be used compared to the typical 100-to-1 ratio. Stannard and others (2004) also determined that fetch-induced errors are reduced by placing the lower sensor at the water surface when using the Bowen ratio energy-budget method over short fetches. Meteorological data were collected every 10 seconds and averaged for 15-minute intervals for 96 values during each 24-hour period. Energy-budget and subsequent-water budget calculations were computed for periods of not less than 1 week because of increased error in the Qx values (energy storage in the reservoir) for shorter intervals (Winter, 1981; Swancar and others, 2000).

Evaporation Rates

Evaporation rate estimates were made during two study periods, March–August 2010, and March–November 2011, for Indian Creek Reservoir for 47 energy-budget periods with duration of at least 7 days. A summary of the evaporation rates by energy-budget period and the energy-budget components used to compute them are listed in table 2. The maximum evaporation rate was 9.2 mm/d during energy-budget period 6, July 16–22, 2010; the minimum evaporation rate was 0.8 mm/d during energy-budget period 46, November 11–17, 2011. Evaporation rates during the study were highest in July and lowest during the early spring and late autumn periods. A correlation of evaporation in relation to available energy was statistically significant with a coefficient of determination (R^2) value of 0.92 (fig. 3), and Spearman's rank correlation coefficient of 0.94. Energy-budget period 14, March 30–April 7, 2011, had significant heat flux because of surface-water inflow. These large fluctuations are typical when short energy-budget periods are calculated, but tend to average out when energy-budget periods of 2 weeks or longer are used (Tanny and others, 2008). The evaporation rate distribution (fig. 4) indicates that the highest evaporation rates tend to occur in June and July of each year. Evaporation rates from the energy-budget periods form the basis for estimating monthly evaporation.

To estimate monthly evaporation, the daily mean evaporation rate from the energy-budget period was applied to the applicable day of the month and the results were summed for total evaporation in inches for each month. The discharge volumes from evaporation were calculated by multiplying the monthly evaporation total by the monthly mean surface area. During the study, the surface area of the reservoir varied from totally desiccated in August 2010, to a maximum of 120 acres in May and June 2011. For April and May 2010, direct measurements to calculate evaporation were not available, so the daily mean evaporation rates from April and May 2011 were used to estimate evaporation. The estimates seem reasonable because seepage meters that were placed on the reservoir during these months measured reservoir gains from groundwater of 0.014 to 0.29 acre-ft/d (mean of 0.15 acre- ft/d), and the water-budget calculations indicate groundwater seepage to the reservoir in April and May at 0.16 and 0.10 acre-ft/d, respectively.

Evaporation estimates during this study indicate that evaporation from the reservoir exceeds the average annual precipitation. In 2011, estimated evaporation from the reservoir during the study period was 50.2 in, with a total discharge from evaporation of 428 acre-ft. The annual precipitation average for Boise is 11.8 in.(National Weather Service, 2012) and for Mountain Home is 10.0 in. (Western

Table 2. Summary of energy-budget components and calculated evaporation rates for seasonal energy-budget periods, Indian Creek Reservoir, Ada County, Idaho, seasonally June 2010–November 2011.

[All periods start at 0000 hours and end at 2359 hours on indicated dates; all units are daily mean values and are in watts per square meter (W/m^2) unless otherwise noted. Q_n: net radiation. Q_v: net energy advected to the lake. Q_x: heat storage energy flux; measured independently and therefore did not need to be estimated. ***R***: Bowen ratio. T_0: water-surface temperature, in degrees Celsius, (°C). ***E***: energy budget period evaporation rate, in millimeters per day (mm/d). **Total *E***: total evaporation during energy budget period, in inches (in.). –, insufficient data to calculate]

Energy-budget period	Start date	End date	Days in period	Q_n	Q_v	Q_x	*R* (unitless)	T_0 (°C)	*E* (mm/d)	Total *E* (in.)
0	06-04-10	06-10-10	7	134	1	–	0.17	18.2	4.0	1.1
1	06-11-10	06-17-10	7	246	0	5	0.15	17.7	7.2	2.0
2	06-18-10	06-24-10	7	238	0	1	0.08	19.4	7.5	2.1
3	06-25-10	07-01-10	7	226	0	5	0.00	21.7	7.5	2.1
4	07-02-10	07-08-10	7	254	0	-6	0.06	19.5	8.4	2.3
5	07-09-10	07-15-10	7	247	0	8	0.00	22.0	8.1	2.2
6	07-16-10	07-22-10	7	253	0	0	-0.06	22.2	9.2	2.5
7	07-23-10	07-29-10	7	208	0	1	-0.03	23.0	7.3	2.0
8	07-30-10	08-05-10	7	219	0	0	-0.06	22.9	7.9	2.2
9	08-06-10	08-12-10	7	175	0	-2	-0.08	19.6	6.6	1.8
10	08-13-10	08-19-10	7	205	0	-1	-0.09	20.1	7.6	2.1
11	03-09-11	03-15-11	7	64	0	–	-0.10	5.3	2.5	0.7
12	03-16-11	03-22-11	7	64	0	8	0.24	6.1	1.6	0.4
13	03-23-11	03-29-11	7	89	37	-3	0.34	6.4	3.4	0.9
14	03-30-11	04-07-11	9	115	220	19	0.25	9.1	8.8	3.1
15	04-08-11	04-14-11	7	125	66	6	0.36	8.8	4.7	1.3
16	04-15-11	04-21-11	7	131	50	20	0.30	10.4	4.3	1.2
17	04-22-11	04-28-11	7	149	57	-4	0.35	10.1	5.4	1.5
18	04-29-11	05-05-11	7	192	8	-1	0.25	10.1	5.6	1.6
19	05-06-11	05-12-11	7	192	19	42	0.14	13.6	5.1	1.4
20	05-13-11	05-19-11	7	161	2	21	0.21	14.9	4.1	1.1
21	05-20-11	05-26-11	7	206	1	-2	0.19	14.6	6.0	1.7
22	05-27-11	06-02-11	7	154	1	-19	0.29	13.1	4.7	1.3
23	06-03-11	06-09-11	7	191	1	30	0.16	16.4	4.8	1.3
24	06-10-11	06-16-11	7	223	0	16	0.15	17.0	6.2	1.7
25	06-17-11	06-23-11	7	232	1	14	0.02	18.8	7.3	2.0
26	06-24-11	06-30-11	7	244	0	15	0.03	19.3	7.6	2.1
27	07-01-11	07-07-11	7	242	0	20	-0.03	21.5	7.7	2.1
28	07-08-11	07-14-11	7	241	0	5	0.02	21.7	7.9	2.2
29	07-15-11	07-21-11	7	242	0	2	0.00	21.6	8.2	2.3
30	07-22-11	07-28-11	7	248	0	-1	-0.02	21.7	8.6	2.4
31	07-29-11	08-04-11	7	201	0	14	-0.09	22.8	7.0	1.9
32	08-05-11	08-11-11	7	210	0	0	-0.02	22.7	7.3	2.0
33	08-12-11	08-18-11	7	190	0	-15	-0.04	21.4	7.2	2.0
34	08-19-11	08-25-11	7	205	0	-1	-0.14	20.5	8.1	2.2
35	08-26-11	09-01-11	7	159	0	2	-0.12	19.5	6.1	1.7
36	09-02-11	09-08-11	7	155	0	-28	-0.12	17.4	7.1	1.9
37	09-09-11	09-15-11	7	133	0	15	-0.12	19.6	4.6	1.3
38	09-16-11	09-22-11	7	124	0	-16	0.06	18.3	4.6	1.3
39	09-23-11	09-29-11	7	108	0	-3	-0.05	18.3	4.0	1.1
40	09-30-11	10-06-11	7	50	2	-10	0.04	17.2	2.0	0.6
41	10-07-11	10-13-11	7	58	1	-51	0.14	11.8	3.3	0.9
42	10-14-11	10-20-11	7	46	1	8	0.16	12.7	1.2	0.3
43	10-21-11	10-27-11	7	23	0	-16	0.30	10.9	1.1	0.3
44	10-28-11	11-03-11	7	27	0	-30	0.11	7.9	1.8	0.5
45	11-04-11	11-10-11	7	16	0	-39	0.53	3.7	1.3	0.3
46	11-11-11	11-17-11	7	25	0	-1	0.11	3.7	0.8	0.2

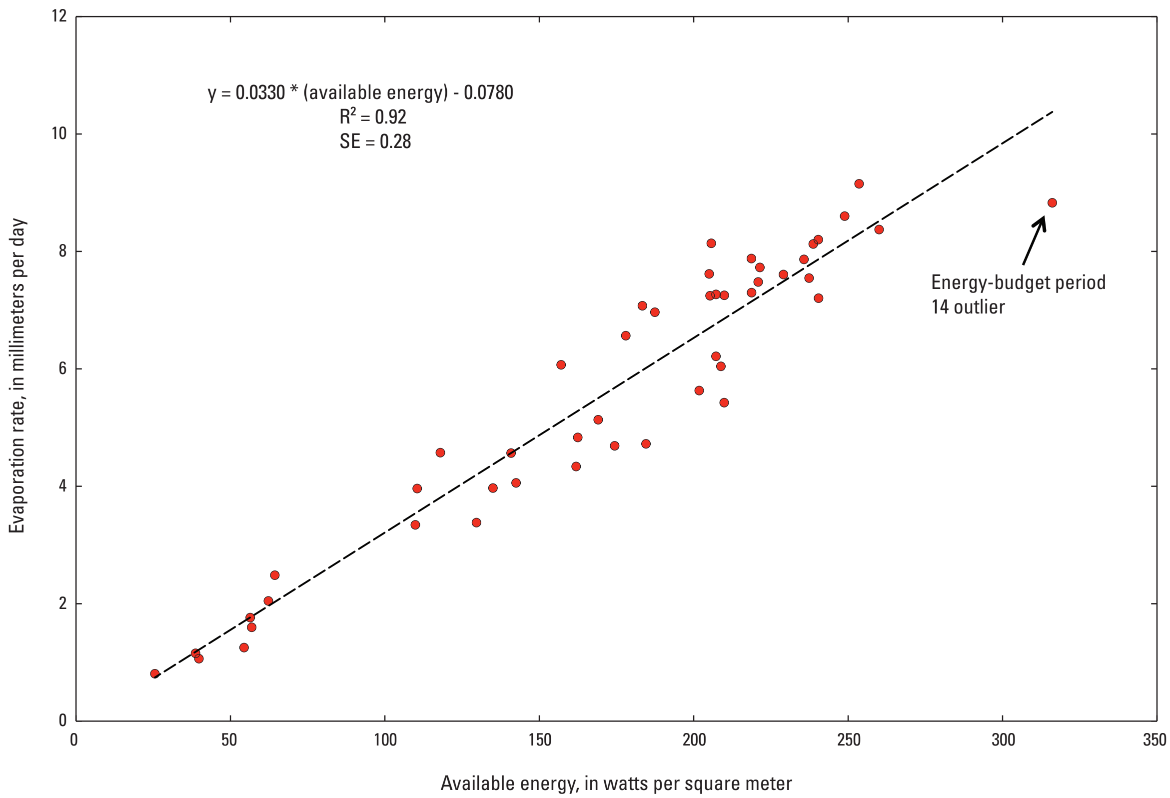


Figure 3. Relation between available energy and evaporation rates for Indian Creek Reservoir, Ada County, Idaho, 2010–11.

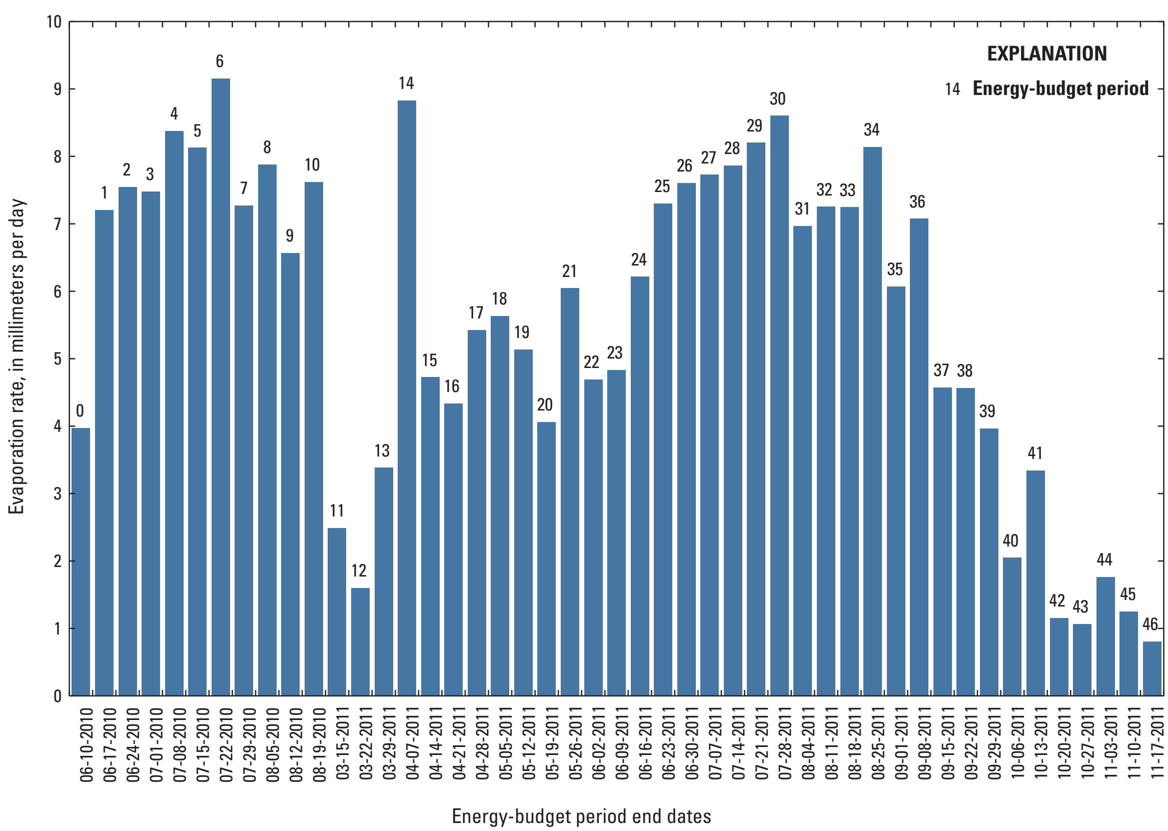


Figure 4. Evaporation rates for energy-budget periods, Indian Creek Reservoir, Ada County, Idaho, 2010–11.

Regional Climate Center, 2012a; precipitation for Mountain Home RAWS in 2010 was 10.1 in., and in 2011 was 10.4 in., indicating that local precipitation during the study was close to normal in both years (Western Regional Climate Center, 2012b). Therefore, surface-water and groundwater contributions to the reservoir are essential for it to maintain observed water levels. The monthly mean (March–October) estimates of reservoir characteristics for 2010 and 2011 are shown in table 3. Monthly evaporation estimates were lowest in March (2.8 in.) and October (2.3 in.), and were highest during June (mean of 7.6 in.) and July (mean of 9.9 in.). Mean reservoir surface area varied during the first study year, with a mean reservoir surface area of 22.2 acres in April 2010, which then decreased until the reservoir desiccated in August 2010. The mean reservoir surface area in 2011 ranged from a minimum of 74.8 acres in March to a maximum of 120 acres in May.

A correlation of the net energy at the reservoir (as compared to total energy measured at the Mountain Home RAWS over the two seasons) was done as a quality-assurance evaluation of the solar radiation equipment placed on Indian Creek Reservoir. The results were statistically significant, with an R^2 of 0.96 (fig. 5), and a Spearman's rank correlation coefficient of 0.98.

Evaporation Uncertainty

Although the Bowen ratio energy-budget method is considered the most accurate method to estimate evaporation, it is not without limits and uncertainty. Winter (1981) did a comparison of uncertainty from other energy-budget studies and determined that monthly uncertainty was about 10 percent in the summer. Gunaji (1967) determined that energy-budget periods with a duration of about 2 weeks had a computed error of 4.4–27.8 percent, with a mean study error of 10.5 percent. Uncertainty also is introduced by the accuracy of the bathymetric survey, a short fetch, and other instrumentation used to calculate volume and discharge.

Finally, the reservoir is partially covered in emergent hydrophytes that vary in their areal coverage, depending on the time of year and the depth of water. Information on how much vegetation affects evaporation varies by plant species, area coverage, plant density, and other factors (Mitsch and Gosselink, 2007).

Table 3. Monthly mean evaporation, area, volume, and evaporative losses from Indian Creek Reservoir, Ada County, Idaho, 2010–11.

[**Evaporation:** Monthly evaporation estimated from evaporation rates in the energy-budget periods. The 2009 Indian Creek Reservoir bathymetric survey provided the data for computing the stage-area and stage-volume relation. **Volume evaporated:** Determined by multiplying monthly mean evaporation by monthly mean reservoir area. –, not estimated]

Year	March	April	May	June	July	August	September	October
Evaporation, in inches								
2010	–	[1]6.9	[1]6.2	7.7	10	–	–	–
2011	2.8	6.9	6.2	7.5	9.8	8.8	5.9	2.3
Mean reservoir area, in acres								
2010	–	22.2	19.0	17.5	9.6	–	–	–
2011	74.8	111	120	116	106	94.7	85.6	81.0
Mean reservoir volume, in acre-feet								
2010	–	31.4	25.5	22.8	9.8	–	–	–
2011	332	641	746	692	595	494	413	374
Volume evaporated, in acre-feet								
2010	–	12.2	9.8	11.2	7.7	–	–	–
2011	17.5	63.3	62.4	72.6	86.0	69.2	42.0	15.4

[1]Monthly evaporation rate estimated using 2011 daily mean evaporation for respective months.

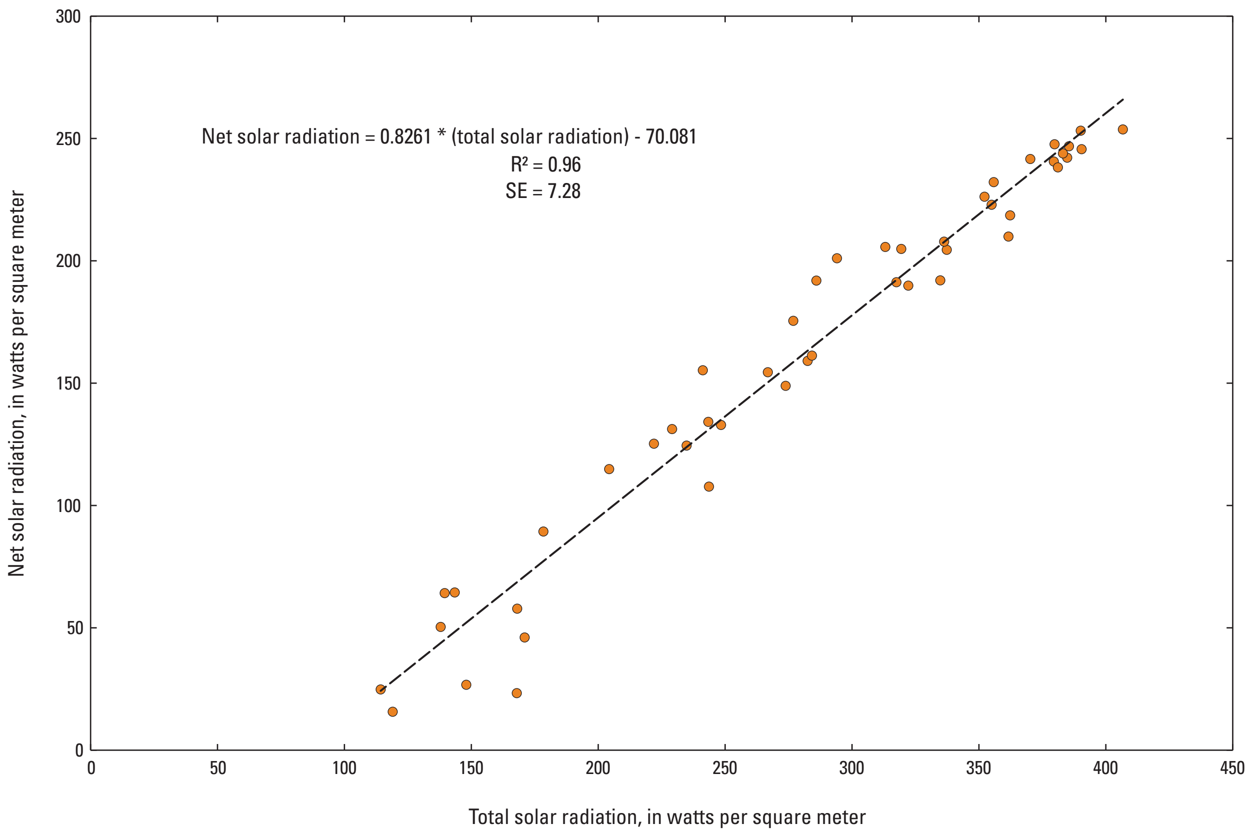


Figure 5. Relation between total solar radiation at Mountain Home Remote Automated Weather Station (RAWS) and net solar radiation at Indian Creek Reservoir, Ada County, Idaho, 2010–11.

Seepage Meter Method

Seepage meters are commonly used to observe and to measure exchange of water between surface water (lakes, reservoirs, and streams) and groundwater at a point location. For this study, the seepage meter method used two seepage meters constructed of rigid plastic 55-gal drums cut in half (fig. 6), and deployed according to methods described in Rosenberry and LaBaugh (2008). Seepage meter bags were attached to the drums and were used to measure actual seepage that occurs in the area of sediment covered by the drum, during a specific period. With the seepage meter method, it was assumed that the measured seepage occurred in 5–20 percent of the reservoir surface area. This assumption was made because seepage rates commonly decrease significantly with distance from shore (McBride and Pfannkuch, 1975). The seepage meter method also assumed that all subsurface flow is isotropic and occurs in the vertical direction.

The bag used to estimate seepage into or out of the reservoir was attached using a brass ball valve, two barb fittings, vinyl tubing, and hose clamps. The smallest inside diameter of tubes and fittings used in the seepage meter construction was 6.35 mm. Two-liter, thin-walled bags were used to measure volume change over time during a seepage measurement. The seepage bags had a nominal thickness of 0.025 mm. The bag thickness and minimum inside diameter of the seepage meter were selected to minimize potential measurement error.

A total of 23 seepage measurements were collected in 553 days. The first seepage measurement was made on April 23, 2010, and the last seepage measurement was made on October 28, 2011. For each measurement, the bag was filled with about 1,000 mL of water and the bag and water were weighed. The bag was deployed during a known period,

Figure 6. Seepage meter constructed from a 55-gallon plastic drum, connection hose, and measurement chamber used for bag deployment, Indian Creek Reservoir, Ada County, Idaho

retrieved, and weighed again. The weight difference in grams was equivalent to volume change in milliliters (equation 11). An increase in weight indicated a seepage gain to the reservoir from perched groundwater, and a weight loss indicated seepage loss from reservoir to perched groundwater or underlying sediments.

$$Q = \frac{w_2 - w_1}{t} \qquad (11)$$

where

- Q is seepage through seepage chamber (mL/d; positive values represent reservoir gains from groundwater inflow),
- w_1 is initial weight of seepage bag (gram [g]),
- w_2 is final weight of seepage bag (g),
- 1 g of water is 1 mL of water, and
- t is time in days.

Generally, seepage meters were placed in two locations and moved as the reservoir stage increased or decreased. One seepage meter was placed at the base of the rock face north of the reservoir stage gage. The other seepage meter was placed at the south-central edge of the reservoir east of the control tower (fig 2). During the first year of measurements, the reservoir was relatively low and seepage meters were deployed at the reservoir edge and then moved inward toward the center of the reservoir pool as it became smaller. During February of the second year, the reservoir stage was 7 ft higher than the peak stage from the prior year. One seepage meter was deployed in February 2011 on the northwest side of the reservoir. Placing the seepage meter was difficult because the reservoir was frozen and finding a suitable location free of basalt riprap to deploy the meter was a trial-and-error process. A second meter was deployed at the southern edge of the thawed reservoir in March 2011. Between late March and late April 2011, the reservoir stage rose more than 4 ft and both seepage meters became inaccessible and were not used for measurements thereafter. Two new meters were deployed in accessible locations in May 2011.

Seepage measurements were evaluated for potential errors prior to being used to estimate seepage into or out of the reservoir. Two types of errors were observed during the study that prevented use of some seepage measurements. Both sources of error were related to seepage bag condition upon retrieval. If the seepage bag was leaking or contained air bubbles, the seepage measurement was omitted from the dataset. Seepage meters have many additional sources of error and those are discussed in the section “Sources of Error.”

Segmented Darcy Method

The segmented Darcy method utilizes a combination of water-level measurements in the reservoir and in adjacent near-shore wells to calculate water-table gradients between the wells and the reservoir; the Darcy equation was used to calculate groundwater inflow to and outflow from the reservoir within discrete segments of the reservoir shoreline (Rosenberry and LaBaugh, 2008). With this method, the length of the shoreline segment, *m*, is multiplied by the effective thickness of the aquifer, *b*, to determine the area, *A*, of a vertical plane at the shoreline through which water passes to enter or leave the surface-water body. The reservoir-bed sediment thickness was assumed to be 10 ft, or the thickness of the clay layer observed in the nearby shallow well and correlated to the bottom of the reservoir. The Darcy equation commonly is used to calculate the flow of water that passes through the vertical plane associated with each segment. Flows to or from the surface-water body for each segment are summed to calculate net flow for the entire surface-water body and are computed using the following equation:

$$Q = KA((h_1 - h_2)/L) \qquad (12)$$

where

- Q is flow through a vertical plane that extends beneath the shoreline of a surface-water body in (ft^3/d);
- K is the vertical hydraulic conductivity (ft/d);
- A is the area of the plane through which all water must pass, depending on the direction of flow [shoreline length (m) × effective thickness of the aquifer (*b*)] (ft^2);
- h_1 is the hydraulic head in the well of interest (ft);
- h_2 is the surface-water stage (ft); and
- L is distance from the well to the shoreline (ft).

Three mini-piezometers were installed in the reservoir bed sediment in May 2011 to provide information for the segmented-Darcy calculations. The mini-piezometers were used to: (1) calculate the hydraulic gradient in reservoir sediments; (2) use Darcy’s law to back-calculate hydraulic conductivity at the locations of the seepage meter measurements; and (3) calculate seepage gains and losses for the reservoir using the segmented-Darcy approach. Mini-piezometers were completed at depths of 1.2–1.3 ft in the reservoir-bed sediments. Each mini-piezometer was constructed of 1-in. galvanized pipe with 1/8-in. holes drilled in the bottom 6 in. of the pipe. The bottom of the pipe was then crimped and filled with coarse sand before driving it into the reservoir-bed sediments. One mini-piezometer was installed near the inflow at the highway and was used for observing the groundwater, one was installed next to the south seepage meter, and one was installed next to the northwest seepage meter (fig. 2). The elevations of the mini-piezometers were surveyed utilizing high-precision RTK GPS, as previously described in the “Change in Reservoir Storage” section of this report. Hydraulic gradients between perched groundwater and the reservoir were calculated for three field visits between June 15 and August 19, 2011, using water levels in each mini-piezometer and reservoir stage and the depth of the mini-piezometer below the reservoir-bed surface.

A triangular irregular network (TIN) model for reservoir bathymetry was used to compute A and L in equation 12. The shoreline length varied during the study and contours generated using the TIN model were used to adjust the shoreline lengths and distance from each mini-piezometer to the shoreline based on the reservoir stage. The survey points used to generate the TIN model are attached to this report as a geographic information system (GIS) shapefile with methods presented and described within the metadata. All survey points used to generate the TIN model had a vertical accuracy of 1 ft.

Hydraulic conductivity was estimated based on literature values for the observed sediment matrix, which was organic clay to silt. Freeze and Cherry (1979) present a range from 0.13 ft/d for silt to 1.34×10^{-5} ft/d for organic clay. Hydraulic conductivity also was calculated using gradient from head differences between the reservoir and the mini-piezometers as described in equation 13. Hydraulic conductivity was estimated based on the observed sediment matrix, which was organic clay to silt. Measured seepage rates were used to calculate the hydraulic gradient at two mini-piezometers for three specific dates between June 15 and August 19, 2011 (equation 13):

$$K = \frac{q}{i} \tag{13}$$

where

K is hydraulic conductivity (ft/d);
q is the seepage rate (ft/d); and
i is hydraulic gradient (dimensionless) where i is the head difference between the reservoir and the mini-piezometer divided by the vertical distance between the reservoir bed and the middle of the screened interval (0.9–1.1 ft).

The segmented-Darcy approach assumes several conditions:

1. All water that exchanges with a surface-water body passes horizontally through a vertical plane positioned at the shoreline that extends to a finite depth (b) beneath the surface of the surface-water body. At depths greater than b, groundwater flows beneath the surface-water body and does not exchange with the surface-water body;
2. The direction of waterflow is horizontal and perpendicular to the shoreline as flow enters or leaves the vertical plane defining the shoreline of the surface-water body;
3. The hydraulic gradient between the well and the surface-water body is uniform; and
4. The aquifer is homogeneous and isotropic within the segment.

Reservoir Seepage

Conceptual Model of Reservoir Seepage

A conceptual understanding of the reservoir, its sources of inflow, and groundwater in the study area is necessary to provide context for the estimates of seepage made during this study. Surface-water inflow from Indian Creek enters the reservoir from the northeast through an existing channel that was modified in the late 1960s to construct Interstate 84 (fig. 2). As a result of highway construction, surface-water has spread out and created a small alluvial plain on the north side of the highway. Hyporheic flow (subsurface streamflow through adjacent stream and bank sediments) likely enters the reservoir through the alluvium north of the highway during and shortly after runoff events in the intermittent channel. The former channel of Indian Creek extends several hundred yards toward the center of the reservoir. An additional intermittent drainage to the northwest also may have provided surface-water inflow, but because the drainage basin is small, it was not considered a significant contributor during the periods of the study.

IDWR has measured water levels in a shallow well completed at 160 ft below land surface and located 600 ft south of the reservoir spillway (IDWR well log tag number D-0020068). Water levels in this well are understood to represent the water table in the local aquifer. The reservoir desiccates at 3,311 ft and water levels in the shallow well ranged between 3,180 and 3,172 ft during this study. The driller's log for well D-0020068 shows a clay layer between 3,310 and 3,300 ft, which is well correlated to the clay layer at the maximum depth of the reservoir at 3,311 ft. The well log also documents that the water-table elevation was about 3,270 ft when the well was drilled in November 2000, indicating that the water table has declined about 100 ft. The water table measured in well D-0020068 was about 40 ft deeper than the maximum depth of the reservoir in 2000, and was between 131 and 139 ft deeper than the maximum depth of the reservoir during the study. If the lithology reported in this well extends below the reservoir, the reservoir likely is underlain by at least 10 ft of clay and an unsaturated zone of about 130 ft exists below the bottom of the reservoir. The well log for well D-0020068 describes a more permeable 9-ft layer of gravel above the clay lithology. Following a period when the reservoir is dry (as it was in the year prior to the study and in August 2010), the clay layer below the bottom of the reservoir likely acts as a water sink and as the reservoir fills the clay becomes saturated. During wet years such as 2011, perched groundwater likely accumulates over this impermeable clay layer. Seepage measurements may reflect gains from perched groundwater or losses to unsaturated near-shore or reservoir-bottom sediments. However, these gains and losses do not mean significant gains or losses to the local aquifer. Transient subsurface flow (that is, flow to unsaturated reservoir sediments) has been shown to cause erroneously large estimates of seepage loss in wetland environments (Gerla, 1992). Plant transpiration also may account for some observed seepage losses during peak plant growth in the summer. Figure 7 shows the attenuated, delayed response in the local aquifer recharge in relation to large changes in reservoir elevation. This response is likely due to groundwater percolation from areas outside of the reservoir, and not seepage from the reservoir itself.

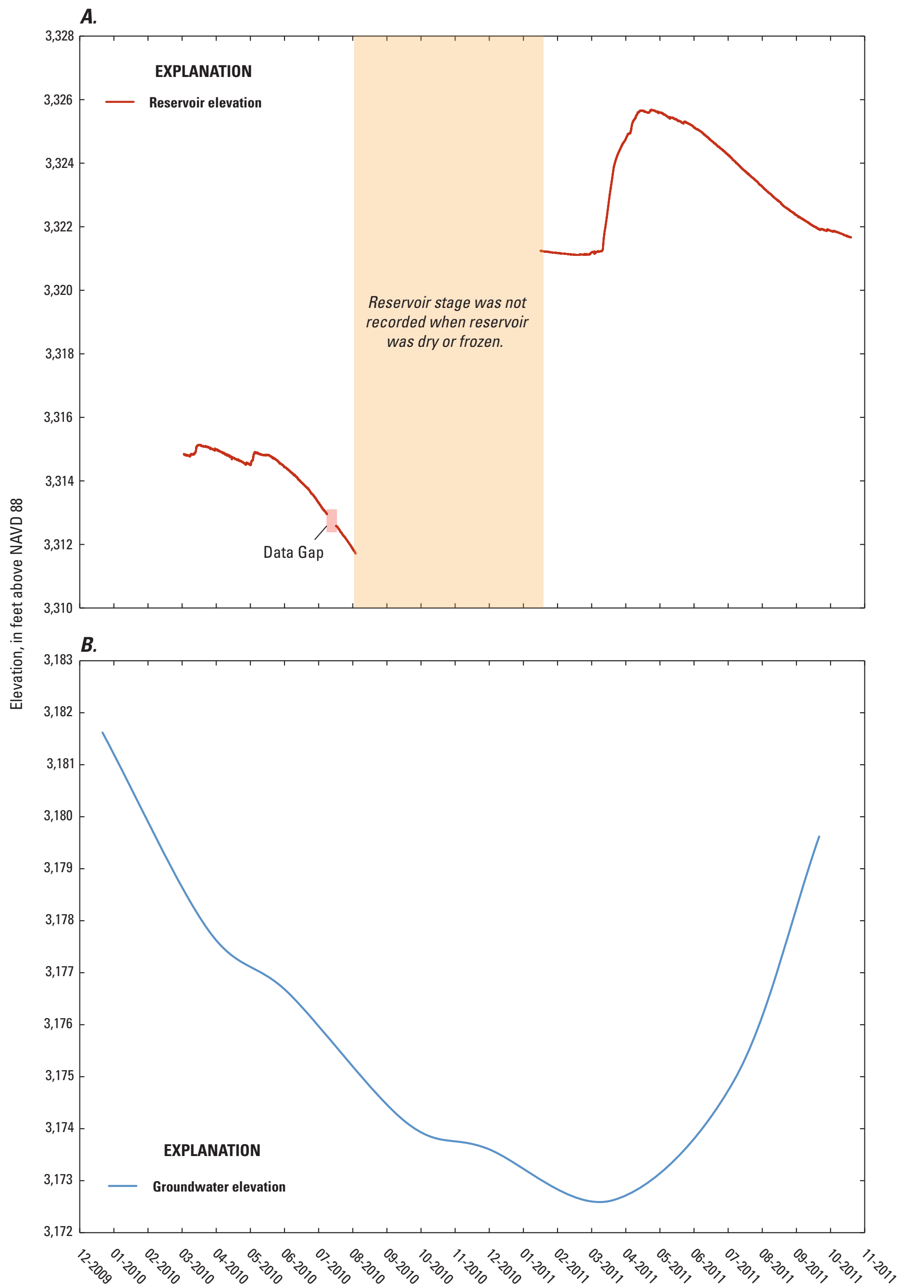


Figure 7. Comparison of groundwater elevations in shallow well D-0020068 to reservoir elevation, for Indian Creek Reservoir, Ada County, Idaho. *(A)* Reservoir elevation; and *(B)* groundwater elevation.

Reservoir Seepage Results

Water-budget derived estimates of seepage followed a predictable pattern, with the reservoir gaining water from seepage during the wetter months of March–May; the reservoir consistently lost water to groundwater seepage during the drier months of June–October (table 4). The reservoir desiccated in August 2010, so there are no monthly evaporation or water-budget estimates for August–October 2010.

A summary of Indian Creek's monthly water budget is presented in table 5. Groundwater gains contributed 71.2 percent (4.8 acre-ft) of the reservoir inflows (precipitation, surface water inflows, and groundwater seepage gains) in April 2010, and 47.7 percent (3.0 acre-ft) in May 2010. Groundwater gains contributed 29.4 percent (37.5 acre-ft) of the reservoir inflows in March 2011, and 15.1 percent (59.4 acre-ft) in April 2011, and diminished to less than less than 1 percent (0.2 acre-ft) by May 2011. Groundwater losses constituted 12.6 percent (-1.6 acre-ft) of the total reservoir outflow (evaporation and groundwater seepage losses) in June 2010, increasing to 31.2 percent (-3.5 acre-ft) of reservoir outflows in July 2010. Reservoir losses to groundwater in June 2011 were 12.5 percent (-10.4 acre-ft), and increased incrementally each month to 59.1 percent (-22.3 acre-ft) by October 2011, although actual monthly volume losses from the reservoir remained relatively stable from July through October (ranging from -20.1 to -26.8 acre-ft per month). Overall reservoir losses to groundwater are less significant relative to losses from evaporation.

Direct seepage measurements and the seepage calculated using the segmented-Darcy method provide seepage estimates on specific dates when the measurements were made. Results for each seepage measurement and each reservoir seepage estimation method are shown in table 6 and figure 8. Seepage estimation methods are described as (1) estimated seepage describes a direct application of the seepage rate measured at each meter to a percentage of the reservoir-bed surface area at the time of the measurement, and (2) segmented-Darcy method describes the segmented approach using head differences and distances along the shoreline between mini-piezometers. The net reservoir seepage from water budget calculations also is provided in table 6 as a comparison. Mini-piezometer water levels, vertical hydraulic gradients, and calculated hydraulic conductivities used in the segmented-Darcy method (Rosenberry and LaBaugh, 2008, p. 22) are listed in table 7.

Losses estimated using measured seepage in 2010 and 2011 might have been overestimated because of unsaturated flow conditions, whereas measured gains likely indicate interaction with perched groundwater (fig. 8). Direct seepage measurement results did not show significant gains or losses to the reservoir and likely did not exceed measurement uncertainty for this method. That a seepage loss was measured on June 15, 2011, in the northwest seepage meter while the water level in the mini-piezometer was greater than the reservoir stage elevation indicates that such small seepage rates do not always exceed measurement uncertainty (table 6). Quantification of measurement uncertainty was beyond the scope of this project. Qualitatively, direct seepage measurement results indicate that Indian Creek Reservoir most likely was gaining water in April and May of 2010 and 2011. In 2010, which was a much drier year than 2011, the reservoir began losing water to reservoir-bed sediments on June 9, although measurements in 2011 did not indicate water loss conditions until August 19.

Although seepage estimates made using the seepage meter method were all less than one-third of an acre-foot per day, seepage estimates made using the segmented-Darcy method between May and August 2011 were essentially zero (table 6). This method comparison suggests that minimum estimated seepage using measured flux greater than 5 percent of the reservoir surface area is still an overestimate of seepage in Indian Creek Reservoir. Vertical hydraulic conductivity calculated at the seepage meters ranged from 9.79×10^{-4} to 6.37×10^{-2} ft/d, which is within the range of hydraulic conductivities for silt and clay provided in Freeze and Cherry (1979).

Reservoir seepage measured using seepage meters and the segmented-Darcy approach was generally negligible relative to magnitude of losses from evaporation from Indian Creek Reservoir during this study. Seepage measurements and water levels in mini-piezometers provided insights to conditions within reservoir-bed sediments rather than the local aquifer, which was 131–139 ft below the bottom of the reservoir during this study. Estimated water gains are likely from seasonally perched groundwater, whereas estimated water losses are likely to unsaturated near-shore sediments or the 10-ft-thick clay layer underlying the reservoir. Given the error associated with methods used to estimate seepage in this study and the relatively small fluxes measured with seepage meters, seepage to the vertically distant local aquifer beneath Indian Creek Reservoir is likely negligible.

An evaluation of the lithologic log in a nearby shallow well shows that the thickness of the fine-grained reservoir-bed sediments likely is a factor in the low seepage estimates. The lowest point in the reservoir bottom was measured at 3,311 ft when the reservoir desiccated in August 2010. A clay layer was observed in the lithologic log of the nearby shallow well (Idaho Department of Water Resources Well D-020068) at elevations of 3,300–3,010 ft. The potential existence of a 10-ft-thick clay layer below the reservoir supports the low seepage estimates from the reservoir.

Table 4. Water budget by energy-budget period for Indian Creek Reservoir, Ada County, Idaho, 2010–11.

[Reservoir volume calculated from measured reservoir stage, and 2009 bathymetric survey. Evaporation was calculated using the energy-budget method. Precipitation for 2010 obtained from Mountain Home Remote Automated Weather Station (RAWS), and in 2011 from the IDARNG1 RG2 RAWS; surface-water inflow was measured at the mouth of the Indian Creek inlet. Negative groundwater seepage values indicate a reservoir loss, positive values indicate a reservoir gain. All units are in acre-feet, unless otherwise noted. **Abbreviations:** acre-ft/d, acre-foot per day; –, not estimated]

Energy-budget period	Start date	End date	Number of days	Mean reservoir volume	Change in reservoir volume	Surface area at end period (acres)	Total evaporation for period	Total precipitation	Net surface water inflow for period	Calculated net groundwater seepage	Calculated net groundwater seepage rate (acre-ft/d)
	–	06-03-10	–	27.7	–	–	–	–	–	–	–
0	06-04-10	06-10-10	7	26.3	-1.4	19	1.76	0.48	0.0	-0.1	-0.01
1	06-11-10	06-17-10	7	22.4	-3.9	17	2.86	0.00	0.0	-1.0	-0.14
2	06-18-10	06-24-10	7	19.1	-3.3	15	2.65	0.00	0.0	-0.7	-0.09
3	06-25-10	07-01-10	7	16.0	-3.1	13	2.30	0.01	0.0	-0.8	-0.11
4	07-02-10	07-08-10	7	12.7	-3.3	11	2.18	0.00	0.0	-1.1	-0.16
5	07-09-10	07-15-10	7	9.8	-2.9	10	1.78	0.02	0.0	-1.1	-0.16
6	07-16-10	07-22-10	7	7.0	-2.8	7	1.56	0.00	0.0	-1.2	-0.18
7	07-23-10	07-29-10	7	5.2	-1.8	6	0.96	0.00	0.0	-0.8	-0.12
8	07-30-10	08-05-10	7	3.1	-2.2	5	0.82	0.00	0.0	-1.3	-0.19
9	08-06-10	08-12-10	7	1.8	-1.3	3	0.50	0.01	0.0	-0.8	-0.12
10	08-13-10	08-19-10	7	0.9	-0.9	2	0.36	0.00	0.0	-0.5	-0.07
	–	03-08-11	–	320	–	–	–	–	–	–	–
11	03-09-11	03-15-11	7	321	0.7	73	4.18	1.10	0.0	3.8	0.54
12	03-16-11	03-22-11	7	327	6.7	74	2.72	3.34	0.0	6.1	0.87
13	03-23-11	03-29-11	7	386	58.5	82	6.38	4.45	43.6	16.8	2.40
14	03-30-11	04-07-11	9	581	195.3	104	27.14	3.04	192	27.4	3.04
15	04-08-11	04-14-11	7	644	62.5	111	12.04	0.09	62.7	11.8	1.68
16	04-15-11	04-21-11	7	697	53.4	116	11.58	6.98	43.0	15.0	2.14
17	04-22-11	04-28-11	7	757	60.5	121	15.09	2.42	53.0	20.2	2.88
18	04-29-11	05-05-11	7	753	-4.9	121	15.61	0.10	7.5	3.1	0.44
19	05-06-11	05-12-11	7	757	4.9	121	14.28	4.94	11.7	2.5	0.36
20	05-13-11	05-19-11	7	747	-10.9	120	11.20	2.30	0.9	-2.9	-0.41
21	05-20-11	05-26-11	7	732	-14.4	119	16.53	2.78	0.6	-1.2	-0.18
22	05-27-11	06-02-11	7	720	-11.8	118	12.73	2.76	0.5	-2.3	-0.33
23	06-03-11	06-09-11	7	713	-7.1	118	13.05	3.72	0.4	1.8	0.26
24	06-10-11	06-16-11	7	693	-19.8	116	16.55	0.10	0.3	-3.7	-0.52
25	06-17-11	06-23-11	7	675	-18.3	114	19.16	2.29	0.2	-1.6	-0.23
26	06-24-11	06-30-11	7	650	-24.9	112	19.51	0.00	0.0	-5.4	-0.77
27	07-01-11	07-07-11	7	628	-22.1	109	19.40	0.55	0.0	-3.3	-0.46
28	07-08-11	07-14-11	7	604	-23.8	107	19.27	0.36	0.0	-4.9	-0.70
29	07-15-11	07-21-11	7	579	-25.4	104	19.59	0.09	0.0	-5.9	-0.84
30	07-22-11	07-28-11	7	553	-25.6	101	19.99	0.00	0.0	-5.6	-0.80
31	07-29-11	08-04-11	7	531	-22.0	99	15.81	0.08	0.0	-6.3	-0.90
32	08-05-11	08-11-11	7	509	-22.4	96	16.05	0.00	0.0	-6.3	-0.91
33	08-12-11	08-18-11	7	487	-21.9	94	15.63	0.00	0.0	-6.3	-0.90
34	08-19-11	08-25-11	7	467	-20.4	92	17.12	0.00	0.0	-3.3	-0.47
35	08-26-11	09-01-11	7	446	-20.8	89	12.44	0.07	0.0	-8.4	-1.20
36	09-02-11	09-08-11	7	429	-16.8	87	14.19	0.00	0.0	-2.6	-0.37
37	09-09-11	09-15-11	7	415	-13.9	86	8.99	0.36	0.0	-5.3	-0.75
38	09-16-11	09-22-11	7	402	-13.6	84	8.82	0.00	0.0	-4.8	-0.68
39	09-23-11	09-29-11	7	388	-13.3	82	7.50	0.00	0.0	-5.8	-0.83
40	09-30-11	10-06-11	7	382	-6.6	82	3.84	4.08	0.0	-6.8	-0.98
41	10-07-11	10-13-11	7	378	-4.0	81	6.23	4.46	0.0	-2.2	-0.32
42	10-14-11	10-20-11	7	373	-4.9	80	2.14	2.82	0.0	-5.6	-0.80
43	10-21-11	10-27-11	7	365	-7.9	79	1.94	0.00	0.0	-6.0	-0.85
44	10-28-11	11-03-11	7	361	-4.0	79	3.19	0.66	0.0	-1.5	-0.21
45	11-04-11	11-10-11	7	361	0.0	79	2.27	0.39	0.0	1.9	0.27
46	11-11-11	11-17-11	7	361	0.0	79	1.46	0.85	0.0	0.6	0.09

Table 5. Monthly water budget for Indian Creek Reservoir, Ada County, Idaho, 2010–11.

[Reservoir volume is calculated from measured reservoir stage at the end of the period, and 2009 bathymetric survey. Evaporation was calculated using the energy-budget method. Precipitation for 2010 obtained from Mountain Home Remote Automated Weather Station (RAWS) and for 2011 from the IDARNG1 RG2 RAWS station; surface-water inflow was measured at the mouth of the Indian Creek inlet. Negative groundwater seepage values indicate a reservoir loss, positive values indicate a reservoir gain. All values in acre-feet, unless otherwise noted. **Abbreviations:** acre-ft/d, acre-feet per day; –, not estimated]

Start date	End date	Reservoir volume	Change in reservoir volume	Total evaporation	Total precipi-tation	Surface-water inflow	Calculated net groundwater seepage	Calculated net groundwater seepage rate (acre-ft/d)	Groundwater reservoir inflow (percent)	Groundwater reservoir outflow (percent)
03-01-10	03-30-10	28.5	–	–	–	–	–	–	–	–
04-01-10	04-30-10	28.3	-0.2	[1]6.9	1.9	0	4.8	0.16	71.2	–
05-01-10	05-30-10	28.3	0.0	[1]6.2	3.3	0	3.0	0.10	47.7	–
06-01-10	06-30-10	16.4	-11.8	11.2	1.0	0	-1.6	-0.06	–	12.6
07-01-10	07-31-10	5.24	-11.2	7.7	0.0	0	-3.5	-0.12	–	31.2
–	02-28-11	320	–	–	–	–	–	–		–
03-01-11	03-31-11	430	110	17.5	12.5	77	37.5	1.25	29.4	–
04-01-11	04-30-11	760	330	63.3	11.8	322	59.4	2.05	15.1	–
05-01-11	05-31-11	725	-34.8	62.4	11.7	16	0.2	0.01	0.8	–
06-01-11	06-30-11	650	-74.8	72.6	7.1	1	-10.4	-0.36	–	12.5
07-01-11	07-31-11	545	-105	86.0	1.1	0	-20.1	-0.67	–	18.9
08-01-11	08-31-11	449	-95.9	69.2	0.1	0	-26.8	-0.89	–	27.9
09-01-11	09-30-11	386	-62.8	42.0	0.4	0	-21.2	-0.73	–	33.6
10-01-11	10-31-11	361	-25.7	15.4	12.0	0	-22.3	-0.74	–	59.1

[1]Total evaporation estimated using 2011 daily mean evaporation rate for respective months.

Table 6. Measured and estimated seepages and comparisons using various methods, Indian Creek Reservoir, Ada County, Idaho, 2010–11.

[**Direct measurement:** Seepage rates were measured at northwest and south seepage meters. **Estimated and calculated seepage rates:** Estimated gain/loss to/from reservoir using seepage measurements and a range of reservoir surface-area percentages applicable to measured seepage flux. **Estimated overall seepage and hydraulic conductivities using segmented Darcy method:** Seepage estimated using the segmented-Darcy method. Seepage rates were measured from two seepage meters located on the southern edge and the northwestern edge of the reservoir. Overall gain or overall loss indicates that one seepage meter measured a gain and the other measured a loss. Net gain or loss was used in the calculations.. **Abbreviations:** acre-ft/d, acre-foot per day; ft/d, foot per day; K, hydraulic conductivity; E, exponent; na, not available]

Direct measurement			
Date	Seepage rate (ft/d)	Date	Seepage rate (ft/d)
Northwest seepage meter		South seepage meter	
04-23-10	1.32^{-02}	04-23-10	6.75^{-02}
06-09-10	-3.53^{-02}	06-09-10	-2.13^{-02}
07-16-10	-2.27^{-02}	03-11-11	-1.78^{-05}
02-04-11	3.29^{-03}	05-04-11	3.21^{-03}
03-11-11	-8.08^{-04}	05-25-11	4.75^{-03}
05-03-11	-1.12^{-04}	06-15-11	2.66^{-03}
06-15-11	-9.12^{-04}	07-12-11	8.98^{-04}
07-12-11	5.40^{-04}	07-15-11	-1.21^{-04}
08-19-11	1.05^{-03}	08-19-11	-9.39^{-03}
09-28-11	1.96^{-04}	10-04-11	7.73^{-04}
		10-28-11	6.37^{-04}

Table 6. Measured and estimated seepages and comparisons using various methods, Indian Creek Reservoir, Ada County, Idaho, 2010–11. —Continued

[**Direct measurement:** Seepage rates were measured at northwest and south seepage meters. **Estimated and calculated seepage rates:** Estimated gain/loss to/from reservoir using seepage measurements and a range of reservoir surface-area percentages applicable to measured seepage flux. **Estimated overall seepage and hydraulic conductivities using segmented Darcy method:** Seepage estimated using the segmented-Darcy method. Seepage rates were measured from two seepage meters located on the southern edge and the northwestern edge of the reservoir. Overall gain or overall loss indicates that one seepage meter measured a gain and the other measured a loss. Net gain or loss was used in the calculations. **Abbreviations:** acre-ft/d, acre-foot per day; ft/d, foot per day; K, hydraulic conductivity; E, exponent; na, not available]

Estimated seepage rate using seepage flux and reservoir surface area					Calculated seepage rate using the water budget method	
Date	Condition	Total (acre-ft/d)	20 percent (acre-ft/d)	5 percent (acre-ft/d)	Water budget period	Seepage rate (acre-ft/d)
04-23-10	Gain	1.47	0.29	0.01	na	na
06-09-10	Loss	-0.69	-0.14	-0.02	June 4–10, 2010	-0.01
07-16-10	Loss	-0.40	-0.08	-0.02	July 9–22, 2010	-0.16
02-04-11	Gain	0.24	0.05	0.01	na	na
03-11-11	Loss	-0.06	-0.01	-0.00	March 9–15, 2011	0.54
05-03-11	Overall gain	0.38	0.08	0.02	April 29–May 5, 2011	0.44
05-25-11	Gain	0.57	0.11	0.03	May 20–26, 2011	-0.17
06-15-11	Overall gain	0.20	0.04	0.01	June 10–16, 2011	-0.52
07-12-11	Gain	0.10	0.02	0.00	July 8–14, 2011	-0.70
07-15-11	Loss	-0.01	-0.00	-0.00	July 15–21, 2011	-0.84
08-19-11	Overall loss	-0.78	-0.16	-0.04	August 19–25, 2011	-0.47
09-28-11	Gain	0.02	0.00	0.00	September 23–29, 2011	-0.83
10-04-11	Gain	0.06	0.01	0.00	September 30–October 6, 2011	-0.98
10-28-11	Gain	0.05	0.01	0.00	October 28–November 3, 2011	-0.21

Estimated overall seepage using segmented-Darcy method		Hydraulic conductivities used for segmented-Darcy method	
Date	Median seepage (acre-ft/d)	Hydraulic conductivity (ft/d)	Source
05-25-11	5.68^{-05}	2.52^{-02}	Calculated at south meter 06-15-11
05-27-11	1.01^{-05}	2.12^{-03}	Calculated at northwest meter 06-15-11
06-15-11	1.41^{-04}	9.79^{-04}	Calculated at northwest meter 07-12-11
07-12-11	1.57^{-04}	6.37^{-02}	Calculated at south meter 08-19-11
07-15-11	1.42^{-04}	2.08^{-03}	Calculated at northwest meter 08-19-11
08-19-11	5.15^{-04}	1.339^{-01}	Freeze and Cherry, 1979. Typical K for silt.
		1.339^{-05}	Freeze and Cherry, 1979. Typical K for clay.

Table 7. Mini-piezometer water levels, vertical hydraulic gradients, and calculated hydraulic conductivities, Indian Creek Reservoir, Ada County, Idaho, 2011.

[Segmented-Darcy method used for calculations (Rosenberry and LaBaugh (2008, p. 22). Elevations are referenced to North American Vertical datum of 1988 (NAVD 88). **Abbreviations:** ft, foot; ft, foot; ft/d, foot per day; ft^3/d, cubic foot per day; E, exponent; na, not available]

Piezometer	Date	Time	Groundwater elevation at piezometer (ft NAVD 88)	Reservoir elevation (ft NAVD 88)	Head difference (ft)	Depth to middle of screen from ground surface (ft)	Vertical hydraulic gradient	Seepage (ft^3/d)	Seepage rate (ft/d)	Hydraulic conductivity (ft/d)
South	6-15-11	1034	3,325.25	3,325.15	0.10	0.95	1.05^{-01}	7.33^{-03}	2.66^{-03}	2.52^{-02}
Northwest	6-15-11	1100	3,325.61	3,325.15	0.46	1.07	4.30^{-01}	-2.52^{-03}	-9.12^{-04}	2.12^{-03}
South	7-12-11	0900	3,324.37	3,324.37	0.00	0.95	0.00^{+00}	2.48^{-03}	8.98^{-04}	na
Northwest	7-12-11	1020	3,324.96	3,324.37	0.59	1.07	5.51^{-01}	1.49^{-03}	5.40^{-04}	9.79^{-04}
South	8-19-11	1030	3,322.99	3,323.13	-0.14	0.95	-1.47^{-01}	-2.59^{-02}	-9.39^{-03}	6.37^{-02}
Northwest	8-19-11	1205	3,323.67	3,323.13	0.54	1.07	5.05^{-01}	2.89^{-03}	1.05^{-03}	2.08^{-03}

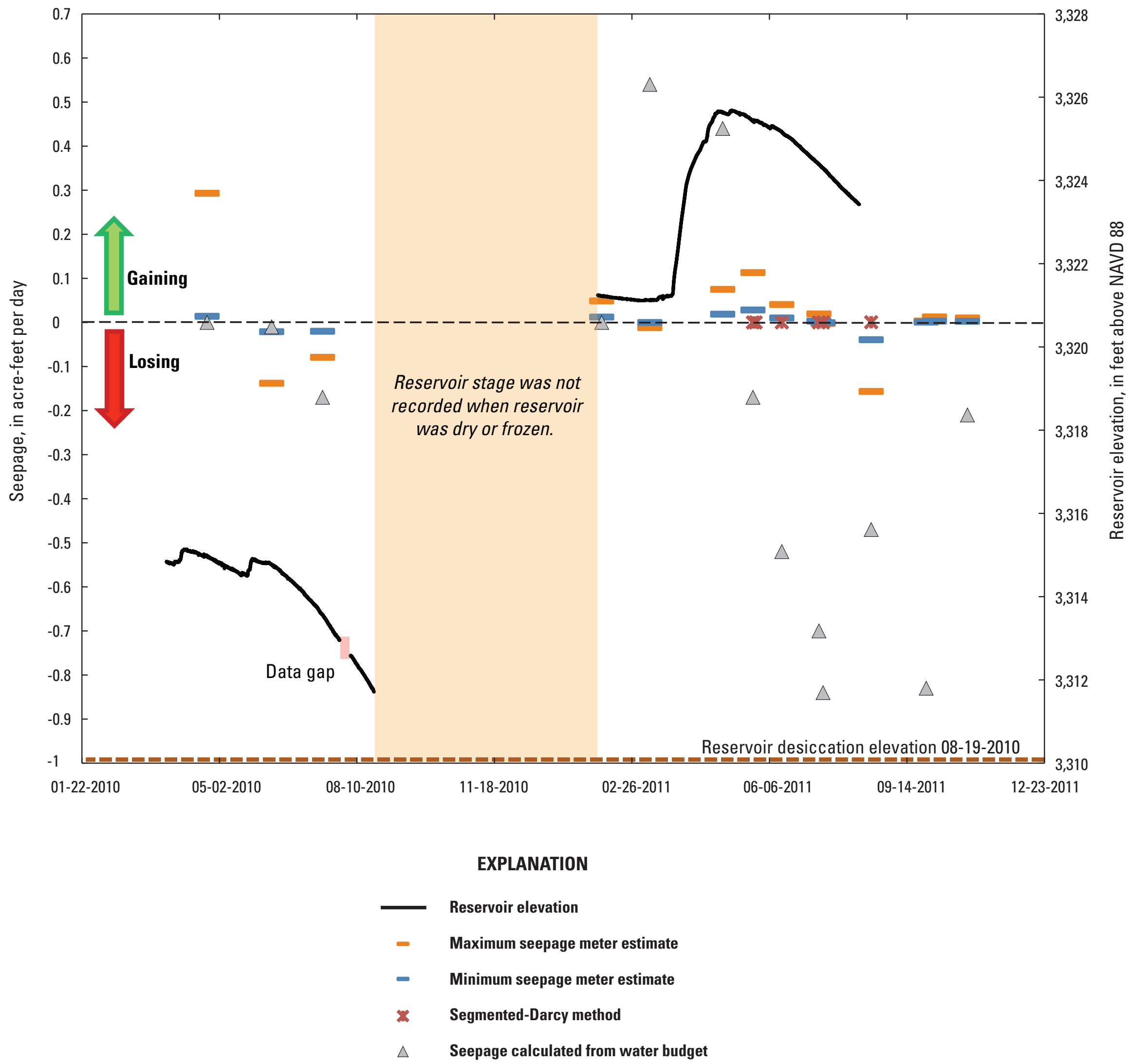


Figure 8. Summary of seepage estimates derived from direct measurements, estimated using the segmented-Darcy method, and those calculated using the reservoir energy-budget for Indian Creek Reservoir, Ada County, Idaho, 2010–11.

Sources of Error

An extended discussion of error sources associated with seepage meter measurements is provided in Rosenberry and LaBaugh (2008). Of those listed, leaks and gas accumulation were the most common. No data affected by these sources of error were used to calculate seepage gain or loss. Determining the heterogeneity of seepage through different locations in the reservoir was beyond the scope of this study. The remaining sources of error were carefully worked around through seepage meter design or general field practices. During the first study year, seepage was measured over short periods; during the second study year, seepage was measured over several hours or days. All measurements displayed negligible groundwater/surface water interaction.

Significant measurement error can be associated with frictional flow loss within the seepage meter, restrictions to flow through the connector between the bag and the chamber, and any resistance to movement of the bag (Rosenberry and LaBaugh, 2008). Coefficients typically are applied to the indicated flux to correct for this problem. Rosenberry and LaBaugh (2008) suggest a seepage meter coefficient between 1 and 1.1 if seepage meters are constructed according to their recommendations. The seepage meters constructed for this study met all the recommendations with the exception that the minimum diameter of tubes and fittings used in construction of the seepage meter was less than 9 mm. The tubes and fittings in the seepage meters constructed for this study had a minimum diameter of 6.35 mm at the bag connection. Because many measurements were made in the same location with each seepage meter, and all seepage rates were less than plus or minus 3 cm/d, applying a coefficient would have negligible effect on results with respect to other sources of error. A review of published experiments in the context of seepage rates measured in Indian Creek Reservoir suggests that no coefficient need be applied to the measurements made during this study. It was beyond the scope of the study to extensively analyze seepage measurement error; two seepage meters are insufficient to provide seepage estimates for an entire reservoir, and only allows for qualitative estimates of overall gain or loss to groundwater from the reservoir. Similarly, bag resistance was not directly measured as part of this study, but Rosenberry and Menheer (2006) list 0.93 as a bag correction factor for the type of bag used in this study.

A comparison of seepage meter results to the appropriate weekly water-budget calculations for net groundwater flux (table 6) are qualitatively similar in that gains and losses to groundwater from the reservoir are small; that they do not always quantitatively align is to be expected for several reasons. The range of uncertainty during short energy-budget periods is higher than the range calculated for long periods. In all but two periods (June and July 2010), net groundwater seepage calculated from the meters was within 10 percent of discharge variability expected from evaporation uncertainty. Alternatively, seepage meters are single points in position around the reservoir and provide results only at the time of the measurement. The evaporation estimates are based on measurements made over a minimum period of a week, and some variability is expected between the estimates. There also may be spatial variability such as heterogeneity of sediment type and permeability, fluctuation owing to evapotranspiration from nearshore vegetation, or topography around the reservoir that allows for more or less groundwater movement than is occurring at the seepage meter location.

Summary

The U.S. Geological Survey, in cooperation with the Idaho Department of Water Resources, conducted an investigation on Indian Creek Reservoir, a small impoundment in east Ada County, Idaho, to quantify groundwater seepage into and out of the reservoir. Data from the study will assist the Idaho Water Resources Department’s Comprehensive Aquifer Management Planning (CAMP) effort to estimate available water resources in Ada County. Three independent methods were utilized to estimate groundwater seepage: (1) the water-budget method; (2) the seepage-meter method; and (3) the segmented Darcy method. Reservoir seepage was quantified during the periods of April through August 2010 and February through November 2011.

With the water-budget method, all measureable sources of inflow to and outflow from the reservoir were quantified, with the exception of groundwater; the water-budget equation was solved for groundwater inflow to or outflow from the reservoir. For the reservoir water budget, surface-water inflow, precipitation falling directly on the reservoir, and change in reservoir storage were measured. Reservoir evaporation was estimated with the Bowen ratio energy-budget method. There is no measureable surface-water outflow from the reservoir.

The seepage-meter method relies on the placement of seepage meters into the bottom sediments of the reservoir for the direct measurement of water flux across the sediment-water interface. Two seepage meters were utilized in the study and a total of 23 discrete seepage measurements were made during the study. Although seepage meters provide objective measurements of seepage, they are representative of single positions in the reservoir, which may not be representative of the reservoir as a whole. Furthermore, seepage-meter measurements are representative of the distinct time at which the measurements are made, whereas, the water-budget estimates of seepage provide continuous estimates of seepage over the study period. As a result of these differences in methodologies, comparisons between water-budget results and seepage-meter measurements are considered semi-quantitative.

The segmented-Darcy method utilizes a combination of water-level measurements in the reservoir and in adjacent near-shore wells to calculate water-table gradients between the wells and the reservoir. The Darcy equation was used to calculate groundwater inflow to and outflow from discrete segments of the reservoir shoreline. During the study, six seepage estimates were made with the segmented-Darcy method. As a result of the discrete nature of these estimates, comparisons of the segmented-Darcy estimates of seepage to the estimates derived from the water-budget and seepage-meter methods are considered semi-quantitative.

The results of the water-budget derived estimates of seepage indicate seepage to be seasonally variable in terms of the direction and magnitude of flow. The reservoir tended to gain water from seepage of groundwater in the wetter months (March-May), while seepage losses to groundwater from the reservoir occurred in the drier months (June-October). Net monthly seepage rates, as computed by the water-budget method, varied greatly. Reservoir gains from seepage ranged from 0.2 to 59.4 acre-feet/month, while reservoir losses to seepage ranged from 1.6 and 26.8 acre-ft/month. An analysis of seepage meter estimates and segmented-Darcy estimates qualitatively supports the seasonal patterns in seepage provided by the water-budget calculations, except that they tended to be much smaller in magnitude. This suggests that actual seepage might be smaller than those estimates made by the water-budget method.

Although the results of all three methods indicate that there is some water loss from the reservoir to groundwater, the seepage losses may be due to rewetting of unsaturated near-shore soils, possible replenishment of a perched aquifer, or both, rather than through percolation to the local aquifer that lies 130 feet below the reservoir. A lithologic log from an adjacent well indicates the existence of a clay lithology that is well correlated to the original reservoir’s base elevation. If the clay lithologic unit extends beneath the reservoir basin

underlying the fine-grain reservoir bed sediments, the clay layer should act as an effective barrier to reservoir seepage to the local aquifer which would explain the low seepage loss estimates calculated in this study.

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References Cited

Allander, K.K., Smith, J.L., and Johnson, M.J., 2009, Evapotranspiration from the lower Walker River basin, west-central Nevada, water years 2005–07: U.S. Geological Survey Scientific Investigations Report 2009-5079, 62 p. (Also available at http://pubs.usgs.gov/sir/2009/5079/.)

Federal Geographic Data Committee, 1998, Geospatial Positioning Accuracy Standards, Part 3: National Standard for Spatial Data Accuracy, Federal Geographic Data Committee, U.S. Geological Survey.

Freeze, A.F., and Cherry, J.A., 1979, Groundwater: Upper Saddle River, New Jersey, Prentice-Hall, 604 p.

Gerla, P., 1992, The relationship of water-table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands: Wetlands, v. 12, no. 2, p. 91–98.

Gunaji, N.N., 1967, Evaporation investigations at Elephant Butte Reservoir in New Mexico: International Association of Scientific Hydrology, Bulletin, v. 12, no. 3, p. 69–90.

Harbeck, G.E., Jr., Kohler, M.A., Koberg, G.E., and others, 1958, Water-loss investigations; Lake Mead studies: U. S. Geological Survey Professional Paper 298, 100 p. (Also available at http://pubs.er.usgs.gov/publication/pp298.)

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets—Foundations for effective water-resource and environmental management: U.S. Geological Survey Circular, 1308 90 p. (Also available at http://pubs.usgs.gov/circ/2007/1308/.)

Heilman, J.L., Brittin, C.L., and Neale, C.M.U., 1989, Fetch requirements for Bowen ratio measurements of latent and sensible heat fluxes: Agricultural and Forest Meteorology, v. 44, no. 3–4, p. 261–273.

McBride, M.S., and Pfannkuch, H.O., 1975, The distribution of seepage within lakebeds: Journal of Research of the U.S. Geological Survey, v. 3, no. 5, p. 505–512.

Mitsch, W.J., and Gosselink, J.G., 2007, Wetlands (4th ed.): Hoboken, New Jersey, Wiley, 582 p.

National Weather Service, 2012, NOWData—NOAA Online Weather Data—Boise temperature records: National Oceanic and Atmospheric Administration, National Weather Service Web site, accessed December 17, 2012, at http://www.wrh.noaa.gov/boi/climo.php.

Natural Resources Conservation Service, Bogus Basin SNOTEL Site: U. S. Department of Agriculture, Natural Resources Conservation Service and National Water and Climate Center Web site, accessed December 17, 2012, at http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=978&state=id.

Rosenberry, D.O., and LaBaugh, J.W., 2008, Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods, book 4, chap. D2, 128 p. (Also available at http://pubs.usgs.gov/tm/04d02/.)

Rosenberry, D.O., and Menheer, M.A., 2006, A system for calibrating seepage meters used to measure flow between ground water and surface water: U.S. Geological Survey Scientific Investigations Report 2006-5053, 21 p. (Also available at http://pubs.usgs.gov/sir/2006/5053/.)

Rosenberry, D.O., Winter, T.C., Buso, D.C., and Likens, G.E., 2007, Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA: Journal of Hydrology, v. 340, no. 3–4, p. 149–166.

Soil Conservation Service, 1950, U.S. Department of Agriculture reservoir sedimentation data summary, Orchard Reservoir: Portland, Oreg., U.S. Department of Agriculture, Soil Conservation Service, Region 7, accessed December 17, 2012, at http://ida.water.usgs.gov/RESSED/datasheets/78-1.pdf.

Soler, T., Michalak, P., Weston, N.D., Snay, R.A., and Foote, R.H., 2006, Accuracy of OPUS solutions for 1- to 4-h observing sessions: GPS Solutions, v. 10, p. 45–55, accessed February 19, 2013, at http://geodesy.noaa.gov/CORS/Articles/OPUSGPSSol.pdf.

Stannard, D.I., Rosenberry, D.O., Winter, T.C., and Parkhurst, R.S., 2004, Estimates of fetch-induced errors in Bowen-ratio energy-budget measurements of evapotranspiration from a prairie wetland, Cottonwood Lake area, North Dakota, USA: Wetlands, v. 24, no. 3, p. 498–513.

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

Swancar, Amy, Lee, T.M., and O'Hare, T.M., 2000, Hydrogeologic setting, water budget, and preliminary analysis of ground-water exchange at Lake Starr, a seepage lake in Polk County, Florida: U.S. Geological Survey Water-Resources Investigations Report 2000-4030, p. 66. (Also available at http://pubs.er.usgs.gov/publication/wri004030.)

Tanny, J., Cohen, S., Assouline, S., Lange, F., Grava, A., Berger, D., Teltch, B., and Parlange, M.B., 2008, Evaporation from a small water reservoir—Direct measurements and estimates: Journal of Hydrology, v. 351, no. 1–2, p. 218–229.

U.S. Census Bureau, 2010, State and County Quick Facts: U.S. Census Bureau Web site, accessed December 17, 2012, at http://quickfacts.census.gov/qfd/states/16/16001.html.

U.S. Geological Survey, 2009, StreamStats for Idaho: U.S. Geological Survey StreamStats Program Web page, accessed December 17, 2012, at http://streamstats.usgs.gov/idaho.html.

Western Regional Climate Center, 2012a, Idaho climate summaries: Western Regional Climate Center Web site, accessed December 17, 2012, at http://www.wrcc.dri.edu/summary/climsmid.html.

Western Regional Climate Center, 2012b, Southern Idaho Remote Automated Weather Stations: Western Regional Climate Center Web site, accessed December 17, 2012, at http://www.raws.dri.edu/sidF.html.

Wilson, G.L., and Richards, J.M., 2006, Procedural documentation and accuracy assessment of bathymetric maps and area capacity tables for small reservoirs: U.S. Geological Survey Scientific Investigations Report 2006-5208, 24 p. (Also available at http://pubs.usgs.gov/sir/2006/5208/.)

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

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Appendixes

Appendix A is a Microsoft® Excel file and appendix B is an ASCII x, y, z and associated metadata. Appendixes are available for viewing or download at http://pubs.er.usgs.gov/publication/sir/2013/5047.

Appendix A. Indian Creek Reservoir Stage, Elevation, Capacity, and Area, Ada County, Idaho, 2011.

Appendix B. Bathymetric Survey of Indian Creek Reservoir, Ada County, Idaho, October 2009.

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