

Prepared in cooperation with Town of Breckenridge, Colorado

Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado



Scientific Investigations Report 2006–5265

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By John G. Elliott, Stephen J. Char, Samuel M. Linhart, V. Cory Stephens, and
Gregory B. O'Neill

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Cover photograph: Goose Pasture Tarn and the 10-Mile Range, Summit County, Colorado. Photograph by Jon F. Nania, USGS, August 26, 2004.

Contents

Abstract.....	1
Introduction.....	1
Purpose and Scope	3
Previous Investigations.....	3
Acknowledgments	4
Study Area.....	5
Geographic Setting.....	5
Precipitation and Streamflow	5
Methods.....	8
Aerial Photography.....	8
Sediment Transport Measurements	8
Bathymetric Surveying.....	8
Seismic Surveying	11
Lacustrine Sediment Coring and Analysis.....	12
Topographic Surveying and Sediment Probing	12
Sedimentation in Goose Pasture Tarn.....	13
Aerial Photography Interpretation, 1968 to 2005	13
Sediment Transport into Goose Pasture Tarn, 2004 and 2005	13
Bathymetric and Seismic Surveys of Goose Pasture Tarn	14
Reservoir Area and Capacity	16
Sediment Volume in Goose Pasture Tarn	31
Lacustrine Sediment Particle Size	32
Lacustrine Sediment Chemistry	34
Summary and Conclusions.....	42
References Cited.....	44

Figures

1. Map of Goose Pasture Tarn study area in Summit County, Colorado.....	2
2. Map of Goose Pasture Tarn showing principal tributaries and stream gages	6
3. Hydrographs of annual peak discharges from streamflow-gaging stations 09046490 Blue River at Blue River, 1984–2005, and 09046600 Blue River near Dillon, 1958–2005.....	7
4. Hydrographs of daily mean discharges from Blue River at Blue River and Blue River near Dillon, Colorado.....	7
5. Map of Goose Pasture Tarn showing locations of topographic surveys, sediment probing, sediment coring, and seismic and bathymetric profiles	9
6. Aerial photographs of Goose Pasture Tarn on September 9, 1968, September 23, 1975, September 13, 1983, September 23, 2001, and July 13, 2005.....	10
7. Graph showing exposed delta areas calculated from aerial photographs	14
8. Map showing reservoir-bed topography and estimated thickness of accumulated sediment in Goose Pasture Tarn since 1965	17
9. Graph showing reservoir stage and water-surface area	30
10. Graph showing reservoir stage and capacity.....	31
11. Graphs showing cumulative sediment-size distribution of cores extracted from Goose Pasture Tarn	33

12. Graphs showing cumulative sediment-size distribution of surficial sediment excavated from delta areas35

Tables

- Summary of discharge and sediment-transport measurements made at U.S. Geological Survey streamflow-gaging stations 392547106023400 Blue River above Pennsylvania Creek, and 09046400 Indiana Creek above the mouth at Blue River, Colorado15
- Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado18
- Results of sediment-core particle-size and trace-constituent analysis of sample cores from Goose Pasture Tarn near Breckenridge, Colorado.....37

Conversion Factors, Abbreviations, and Datums

Multiply	by	To obtain
Length		
inch	2.54	centimeter (cm)
millimeter (mm)	0.03937	inch
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m ²)
square mile (mi ²)	2.590	square kilometer (km ²)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m ³)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m ³ /yr)
Mass		
gram (g)	0.03527	ounce (oz)
pound (lb)	453.6	gram (g)
ton, short	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	megagram (Mg/d)
Force		
kilograms per square meter (kg/m ²)	0.2048	pounds per square foot (lb/ft ²)
newtons per square meter (N/m ²)	0.02088	pounds per square foot (lb/ft ²)
newtons per cubic meter (N/m ³)	0.006365	pounds per cubic foot (lb/ft ³)

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).

Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

By John G. Elliott, Stephen J. Char, Samuel M. Linhart, V. Cory Stephens, and Gregory B. O'Neill

Abstract

Goose Pasture Tarn, a 771-acre-foot reservoir in Summit County, Colorado, is the principal domestic water-storage facility for the Town of Breckenridge and collects runoff from approximately 42 square miles of the upper Blue River watershed. In the 40 years since the reservoir was constructed, deltaic deposits have accumulated at the mouths of two perennial streams that provide most of the inflow and sediment to the reservoir. The Blue River is a low-gradient braided channel and transports gravel- to silt-size sediment. Indiana Creek is a steep-gradient channel that transports boulder- to silt-size sediment. Both deltas are composed predominantly of gravel, sand, and silt, but silt has been deposited throughout the reservoir. In 2004, the U.S. Geological Survey, in cooperation with the Town of Breckenridge, began a study to determine the volume of accumulated sediment in Goose Pasture Tarn, the long-term sedimentation rate for the reservoir, and the particle-size and chemical characteristics of the sediment.

Exposed delta deposits occupied 0.91 acre and had an estimated volume of 0.6 acre-foot in 2005. Aerial photographic analysis indicated both the Blue River and Indiana Creek deltas grew rapidly during time intervals that included larger-than-average annual flood peaks on the Blue River. Sediment-transport relations could not be developed for the Blue River or Indiana Creek because of minimal streamflow and infrequently observed sediment transport during the study; however, suspended-sediment loads ranged from 0.02 to 1.60 tons per day in the Blue River and from 0.06 to 1.55 tons per day in Indiana Creek. Bedload as a percentage of total load ranged from 9 to 27 percent.

New reservoir stage-area and stage-capacity relations were developed from bathymetric and topographic surveys of the reservoir bed. The original 1965 reservoir bed topography and the accumulated sediment thickness were estimated from a seismic survey and manual probing. The surface area of Goose Pasture Tarn in 2005 was 66.4 acres, and the reservoir capacity was 771.1 acre-feet at a full-pool elevation of 9,886.4 feet. The 1965 surface area was 67.1 acres, and the reservoir capacity was 818.0 acre-feet, indicating that the reservoir surface area has decreased by 0.7 acre, or about 1.1 percent, and the

reservoir capacity has decreased by 46.9 acre-feet, or about 5.7 percent over a 40-year period.

Sediment thickness determined with seismic profiling ranged from 0 to 4.0 feet and averaged 0.7 foot, with lesser thicknesses in the deeper parts of the reservoir and greater thicknesses near the deltas. Probe-determined sediment thickness ranged from 1.0 to 4.4 feet and averaged 2.8 feet near the Blue River delta and ranged from 0.3 to 6.0 feet and averaged 3.6 feet near the Indiana Creek delta. Approximately 47.5 acre-feet of sediment has accumulated in Goose Pasture Tarn and in the Blue River and Indiana Creek deltas, or an average of 1.19 acre-feet per year.

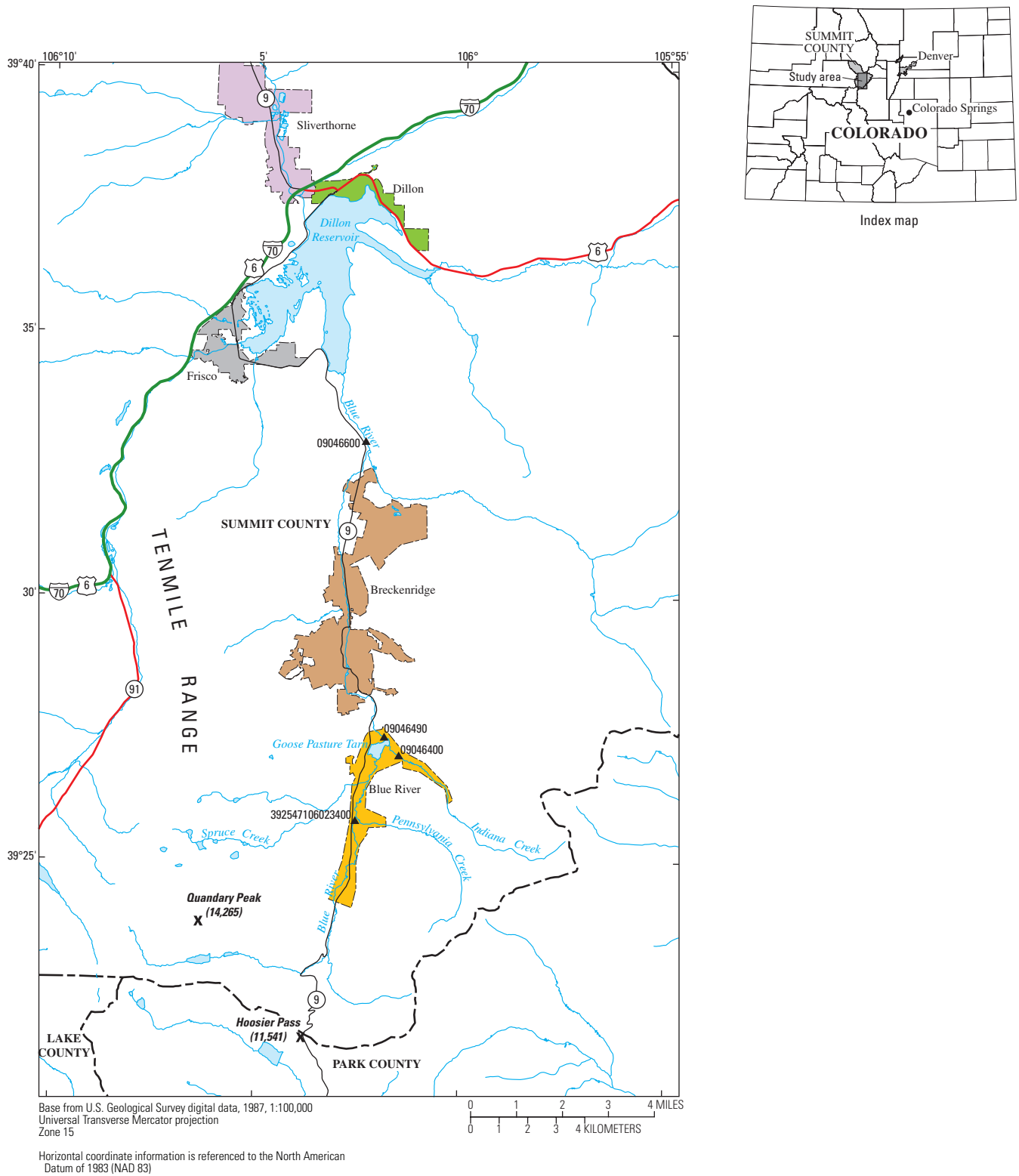
Sediment cores from several locations in the reservoir showed stratification, which is indicative of different depositional dates or mechanisms. Metal and trace-constituent levels from the cores were compared with three standards. Silver, cadmium, europium, lead, and zinc were present in greater concentrations than Southern Rocky Mountain background levels in four sediment cores, and cadmium, lead, and zinc levels also were equal to or exceeded the Threshold Effect Concentration standards. Lead exceeded the Probable Effect Concentration standard in silt from the Blue River delta and deep water near the north shore. Tin was present in greater concentrations than Southern Rocky Mountain background levels in deep water near the east shore, and chromium and copper levels were equal to or exceeded the Threshold Effect Concentration standards in these cores.

Introduction

Goose Pasture Tarn, in Summit County, Colorado, is the principal domestic water-storage facility for the Town of Breckenridge and collects runoff from 42.4 mi² of the upper Blue River watershed (fig. 1). Goose Pasture Tarn is a 771-acre-ft reservoir that was created in 1965 when a dam was constructed on the Blue River approximately 1.4 mi south of Breckenridge. The Town of Breckenridge is concerned about the possible decrease in long-term reservoir-storage capacity from sedimentation and the resulting need to monitor sedimentation processes.

Two perennial streams provide most of the inflow and sediment to Goose Pasture Tarn. The Blue River is the

2 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado



EXPLANATION

09046400 ▲ Streamflow-gaging station—Number is site identification number

Figure 1. Goose Pasture Tarn study area in Summit County, Colorado.

largest inflowing stream and drains approximately 85 percent of the watershed upstream from the reservoir. The Blue River becomes a braided channel and enters Goose Pasture Tarn through a large, low-relief wetland. Bed material at the inflow is coarse gravel to silt-size sediment. Indiana Creek is the other principal tributary entering Goose Pasture Tarn. Indiana Creek has a steeper gradient than the Blue River and drains approximately 15 percent of the watershed. Bed material in Indiana Creek is boulder to silt-size sediment.

Potential economic losses and diminished storage capacity caused by sedimentation have been recognized for many years (Brown, 1948). The distribution of sediment in a reservoir, as well as the total sediment volume, may shorten the useful life of a reservoir. Fluvial sediment transported into a reservoir is deposited in a variety of locations depending on the transported sediment-particle size, reservoir shape, water-surface elevation, ratio of reservoir capacity to inflow, wave action, and reservoir operation (Porterfield and Dunnam, 1964). Larger and heavier sediment particles—cobble, gravel, and sand—tend to be deposited near the inflow in the typically observed delta topset and foreset beds (Lane, 1953). Finer sediments held in suspension—some sand, silt, and clay—can travel farther into the reservoir and be deposited as bottomset beds over a wide area. Density currents, or gravity flow, can reentrain some of the finer sediment deposits and transport them close to the dam.

Exposed and submerged deltaic sedimentary deposits are visible in Goose Pasture Tarn at both inflow areas. Sediment deposited by the Blue River is relatively fine (gravel, sand, and silt), whereas sediment deposited by Indiana Creek is coarser (gravel and cobbles) near the inflow but becomes sand and silt distally into the reservoir in the direction of the dam. The downstream reaches of Indiana Creek are bordered by flood and debris-flow deposits, indicating some episodic coarse-sediment delivery in addition to the finer sediment transported by perennial streamflow. A flood caused by heavy rain on snow cover in June 1995 may have supplied a large amount of sediment to the reservoir from Indiana Creek (Gary Roberts, Town of Breckenridge, oral commun., July 1, 2003).

Two potential actions by the Town of Breckenridge could entrain the accumulated lacustrine sediments and possibly affect the quality of drinking water. First, intermittent spillway modifications and repairs require lowering the reservoir water surface by approximately 4 ft (Gary Roberts, Town of Breckenridge, oral commun., January 2004). Pool lowering could be accompanied by downcutting into, and erosion of, the Blue River and Indiana Creek deltaic deposits that are normally underwater when the reservoir is at full pool. Second, reservoir dredging to increase storage capacity also could entrain sediment now stored in the reservoir. Quantification of the postreservoir sediment volume and long-term sedimentation rates in Goose Pasture Tarn is needed to enable the Town of Breckenridge to determine whether dredging is necessary. Chemical analysis of lacustrine sediments also is needed to identify the presence of constituents with the potential to degrade the municipal water supply if disturbed and give

the Town of Breckenridge information needed to facilitate appropriate mitigation action. In 2004, the U.S. Geological Survey, in cooperation with the Town of Breckenridge, began a study to determine the volume of accumulated sediment in Goose Pasture Tarn, the long-term sedimentation rate for the reservoir, and the particle-size and chemical characteristics of the sediment.

Purpose and Scope

The purpose of this report is to present findings of a collaborative study of sedimentation in Goose Pasture Tarn between the U.S. Geological Survey (USGS) and the Town of Breckenridge. This report includes an estimation of prereservoir (prior to 1965) valley topography and postreservoir-bottom topography determined by interpretation of existing maps, reservoir design plans, and bathymetric survey data of Goose Pasture Tarn. Dates and extent of episodic sedimentation events or progressive deltaic deposition and reservoir infilling from 1965 through 2005 were determined by acquisition and interpretation of aerial photography of Goose Pasture Tarn. Information not previously available on water supply, timing, and magnitude of runoff into Goose Pasture Tarn are provided from installation and seasonal operation of new streamflow-gaging stations on the Blue River and Indiana Creek upstream from Goose Pasture Tarn. Suspended- and bedload-sediment transport discharges were measured at the gaging stations when water-discharge measurements were made. The base of postreservoir sediment deposits was identified from marker strata such as buried soil horizons and inundated wetland vegetation. The thickness and area of post-reservoir deltaic and lacustrine deposition were determined by sediment coring, bathymetry, seismic profiling, and surveying submerged and exposed deltaic deposits. An estimate of the accumulated sediment volume and long-term rate of sediment deposition in Goose Pasture Tarn is provided. The report concludes with a description of sediment-particle size, silt and clay content, and trace-element chemistry determined by collection and analysis of reservoir-sediment cores.

Previous Investigations

Quantification of the accumulated sediment volume in Goose Pasture Tarn requires identification of the preinundation reservoir-bed topography by sediment coring or seismic profiling or from an original land-surface map. A map produced in May 1964 (Ketchum, Konkel, Ryan, and Fleming Consulting Engineers, Inc., 1964, *in* Resource Engineering, Inc., 2002) shows the proposed dam and inundated area on topography delineated with 10-ft contour lines. Although the 10-ft contour lines do not provide the resolution needed to determine original reservoir-bed topography for comparison, a reservoir-capacity curve and annotation on the 1964 map indicated that the reservoir's projected capacity would be 912 acre-ft at the spillway elevation. In 1987, the 1965 surface area of the

4 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

reservoir at full pool (or spillway elevation) was estimated to be 78 acres (Tipton and Kalmbach Consulting Engineers, Inc., 1987, *in* Resource Engineering, Inc., 2002).

Several postreservoir studies that estimated surface area and capacity of Goose Pasture Tarn at various times were summarized by Tipton and Kalmbach Consulting Engineers, Inc. (1987, *in* Resource Engineering, Inc., 2002) and Resource Engineering, Inc. (2002). The reservoir depth and surface area were calculated from 49 bathymetric measurements as part of an aquatic weed evaluation in 1982 (Lewis and others, 1982, *in* Resource Engineering, Inc., 2002). The surface area was 65.4 acres, and the reservoir capacity was estimated to be 798.7 acre-ft at full pool in 1982.

A topographic map of Goose Pasture Tarn that was based on aerial photography flown in October 1983 was used to compute a surface area of 66.2 acres and the incremental volume of water at elevations greater than the existing spillway for a hypothetical dam-enlargement project (Tipton and Kalmbach Consulting Engineers, Inc., 1987, *in* Resource Engineering, Inc., 2002). The Tipton and Kalmbach report also presented area and capacity values for stages below the spillway elevation but did not indicate how these values were derived; however, the earlier estimates by Lewis and others (1982, *in* Resource Engineering, Inc., 2002) probably were used. The 1983 full-pool capacity was reported as 796.8 acre-ft. The Tipton and Kalmbach report expressed a skeptical opinion of the 1964 (Ketchum, Konkel, Ryan, and Fleming Consulting Engineers, Inc., 1964, *in* Resource Engineering, Inc., 2002) area and volume calculations on the basis of a comparison of the 1964 study with the 1982 (Lewis and others) and 1983 (Tipton and Kalmbach Consulting Engineers, Inc., 1987) estimated values. However, only 49 depth measurements were made in 1982, and no rationale was given for the 1983 capacity estimates below spillway elevation, so the 1982 and 1983 estimates may not be appropriate for comparative purposes. Also, it appears that the potential decrease in area and capacity from deltaic sedimentation after 1964, some of which is visible in aerial photographs taken in 1975 and 1983, was not considered in the estimation process.

A 1991 study of reservoir depth was done by WRC Engineers (Resource Engineering, Inc., 2002, *in* Resource Engineering, Inc., 2002) and was based on 159 survey points. The 1991 study determined the surface area to be 67.2 acres and estimated the reservoir capacity to be 891.4 acre-ft when filled to the spillway elevation (Resource Engineering, Inc., 2002). Resource Engineering, Inc., performed a bathymetric study of Goose Pasture Tarn in 2002 by using sonar and ground-penetrating radar. The 2002 study was based on 13,300 points and resulted in a 1-ft contour map of the reservoir bottom that was used to develop elevation-area and elevation-capacity relations. The 2002 reservoir surface area was 67.3 acres, and the reservoir capacity was estimated to be 795.7 acre-ft. None

of the earlier Goose Pasture Tarn studies made estimates of the area and thickness of sediment deposited since 1965 or of the sediment supply rate into the reservoir.

Earlier studies of Goose Pasture Tarn capacity noted the dense growth of aquatic weeds in the reservoir which may have added to some of the inconsistencies in capacity estimates. Lewis and others (1982, *in* Resource Engineering, Inc., 2002) identified *Elodea sp.* as the primary plant in the reservoir, with approximately 28 percent of the reservoir bed supporting dense *Elodea* growth. Low turbidity in the reservoir allowed sufficient light to support macrophyte growth to depths of 22 to 25 ft. The 2002 reservoir-bed sonar measurements in shallow areas of Goose Pasture Tarn may be unreliable because of dense *Elodea* growth requiring additional depth measurements using ground-penetrating radar (Resource Engineering, Inc., 2002).

No studies of Goose Pasture Tarn sediment chemistry are known to exist; however, sediment cores were collected from Dillon Reservoir, about 8 mi downstream from Goose Pasture Tarn, in 1997 to determine the effects of urban development and mining on water quality in the Blue River watershed (Greve and others, 2001). Sediments in Dillon Reservoir, constructed in 1963, revealed some effect of nearby urban development but were found to be relatively low in pesticides, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons. Concentrations of arsenic, cadmium, chromium, copper, lead, and zinc in sediment samples exceeded freshwater sediment-quality guidelines established by the Canadian Council of Ministers of the Environment (Canadian Council of Ministers of the Environment, 1999) and varied with sediment age, likely indicating a mining contribution (Greve and others, 2001).

Acknowledgments

The authors are grateful for the collaboration with the Town of Breckenridge and the cooperation of the residents surrounding Goose Pasture Tarn. Gary Roberts, Water System Supervisor, Town of Breckenridge, provided essential information on the reservoir's history and operations as well as logistical support for onsite sampling. Jon Nania and Cory Stephens, USGS, assisted with bathymetric and seismic measurements and lacustrine sediment coring. Paul Kinzel, Aaron Burman, George Ingersoll, and Mike Stevens, USGS, assisted with topographic surveys and deltaic sediment probing. Sediment-size analyses were performed by the USGS Iowa Sediment Laboratory and by Heather Sproule Eppler, USGS. Sediment-chemistry analyses were performed by the USGS Geologic Discipline Geochemistry Analytical Laboratory. Discharge and sediment measurements at streamflow-gaging stations on the Blue River and Indiana Creek were made by Andrea Fleming, USGS.

Study Area

Geographic Setting

Goose Pasture Tarn is a manmade reservoir on the Blue River located in a glaciated, mountain valley in Summit County, Colorado, approximately 1.4 mi south of the Town of Breckenridge. The reservoir elevation at the spillway is 9,886.4 ft. The Blue River watershed upstream from the reservoir has a drainage area of approximately 42 mi². The watershed is bounded on the west by peaks of the Tenmile Range with summits greater than 13,000 ft, including Quandary Peak (14,265 ft), and is bounded on the east by 12,000- and 13,000-ft summits of the Continental Divide (figs. 1, 2). The mountains above approximately 11,500 ft are vegetated by alpine tundra, and below that elevation, they are vegetated by subalpine coniferous forest. The Blue River upstream from Goose Pasture Tarn has a relatively low gradient and meanders through wetlands, beaver dams, and willow stands (fig. 2). Tributary streams to the Blue River are relatively steep and bouldery.

Mountains in the Tenmile Range are composed mostly of Precambrian biotitic gneiss, schist, and migmatite with some areas of Tertiary and Cretaceous intrusive rocks and Pennsylvanian sedimentary rocks. The mountains on the eastern side of the Blue River watershed are a mixture of Permian and Pennsylvanian sedimentary formations, Cretaceous and Jurassic sedimentary formations, and Tertiary and Cretaceous intrusives (Tweto, 1979). Mineral concentrations in these formations supported mining in the 19th century; however, more mining prospects were located in watersheds north of and downstream from tributaries draining into Goose Pasture Tarn.

Precipitation and Streamflow

Annual precipitation in the Blue River watershed is recorded at Dillon, Colorado, elevation 9,060 ft, approximately 8 mi north of Goose Pasture Tarn (fig. 1). The mean annual precipitation at Dillon is 16.0 inches, with relatively greater amounts occurring as snow in March, April, and May and as summer monsoonal rainfall in July, August, and September. The mean annual total snowfall at Dillon is 127.5 inches, and the greatest monthly accumulation of 22.2 inches occurs in March (Desert Research Institute, Western Regional Climate Center, <http://www.wrcc.dri.edu/index.html>, accessed December 2, 2005). A Natural Resources Conservation Service (NRCS) SNOTEL site is located on Hoosier Pass, approximately 6 mi south of Goose Pasture Tarn, at an elevation of 11,550 ft. The mean annual precipitation at Hoosier Pass, including the winter snow/water equivalent, is 28.8 inches, or approximately 80 percent greater than the mean annual precipitation at Dillon (U.S. Department of Agriculture Natural Resources Conservation Service, <http://www.wcc.nrcs.usda>.

gov/snotel/Colorado/colorado.html, accessed December 2, 2005).

Streamflow from six headwater tributaries of the Blue River upstream from Goose Pasture Tarn is regulated and diverted through the Hoosier Pass tunnel and eventually is delivered to the city of Colorado Springs (Crowfoot and others, 2002). These transmountain diversions have attenuated the Blue River annual flood peaks and decreased the total annual runoff flowing into Goose Pasture Tarn to varying degrees since the reservoir was constructed in 1964. Annual peak discharge on the Blue River at Goose Pasture Tarn is reflected by discharge measured at streamflow-gaging station 09046490, Blue River at Blue River, Colorado, 350 ft downstream from the Goose Pasture Tarn dam spillway and operating continuously since October 1983 (fig. 1). The reservoir is operated in such a way that it is normally full or nearly full, and spring snowmelt runoff generally flows into and through the reservoir with a short residence time (Gary Roberts, Town of Breckenridge, oral commun., July 1, 2003); however, the reservoir effect on instantaneous flood-peak discharge is unknown.

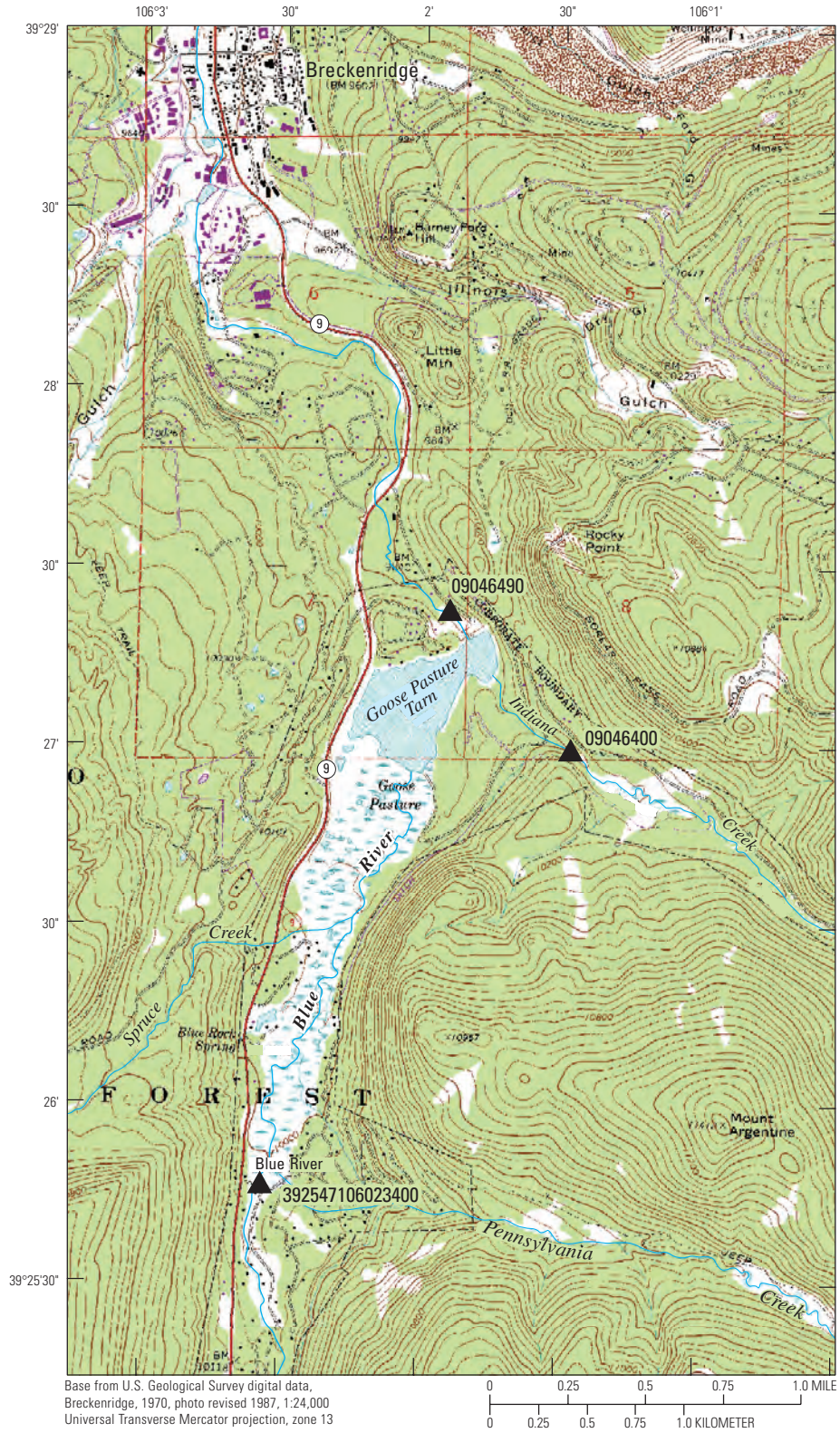
Annual instantaneous peak discharges downstream from the dam ranged from 72 ft³/s on July 20, 2004, to 681 ft³/s on June 18, 1995 (fig. 3). The second-highest recorded peak discharge was 506 ft³/s on July 1, 1984. The peak of daily mean discharges occurs, on average, on June 22 with a mean value of 126 ft³/s (fig. 4). Mean annual runoff downstream from Goose Pasture Tarn is 24,350 acre-ft.

Blue River streamflow also has been recorded since October 1957, 0.3 mi upstream from Dillon Reservoir, approximately 8 mi downstream from Goose Pasture Tarn, at station 09046600, Blue River near Dillon, Colorado (fig. 1). Annual instantaneous peak discharge at station 09046600, where the drainage area is 121 mi², ranged from 30 ft³/s on August 1, 1961, to 1,390 ft³/s on June 18, 1995 (fig. 3). Other large peak discharges were 1,250 ft³/s (June 17, 1965), 1,210 ft³/s (June 26, 1983), and 1,050 ft³/s (May 25, 1984). The peak of daily mean discharges occurs, on average, on June 18 with a mean value of 359 ft³/s (fig. 4). Mean annual runoff is 76,800 acre-ft, adjusted for diversions to the Hoosier Pass tunnel (Crowfoot and others, 2002).

The largest recorded flood peaks at streamflow-gaging stations on the Blue River below Goose Pasture Tarn and near Dillon occurred in years when the mountain snowpack contained a high water content late in the spring. The snow/water equivalents at the Hoosier Pass SNOTEL site were 22.0 inches on April 1, 1965 (no later measurements recorded in 1965); 10.8 inches on June 1, 1983; 20.5 inches on May 1, 1984; 26.9 inches on June 1, 1995; and 4.0 inches on May 1, 2002 (U.S. Department of Agriculture, 2005). Of significance to this study was the observation that the 1,390-ft³/s flood on June 18, 1995, delivered a large amount of sediment to Goose Pasture Tarn from both the Blue River and Indiana Creek (Gary Roberts, Town of Breckenridge, oral commun., July 1, 2003).

New streamflow-gaging stations were established in 2004 and 2005 on the Blue River and Indiana Creek upstream from

6 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado



EXPLANATION

09046400 ▲ Streamflow-gaging station—Number is site identification number

Figure 2. Goose Pasture Tarn showing principal tributaries and stream gages.

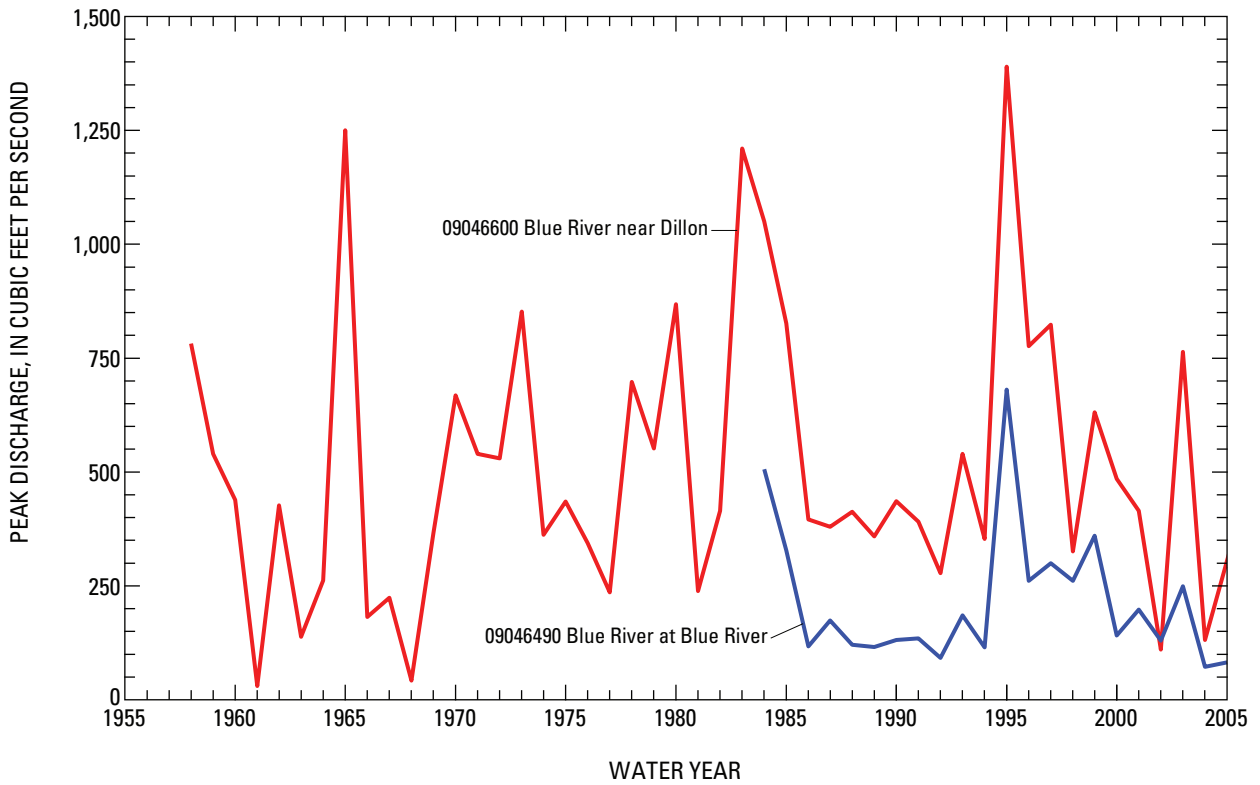


Figure 3. Annual peak discharges from streamflow-gaging stations 09046490 Blue River at Blue River, 1984–2005, and 09046600 Blue River near Dillon, 1958–2005.

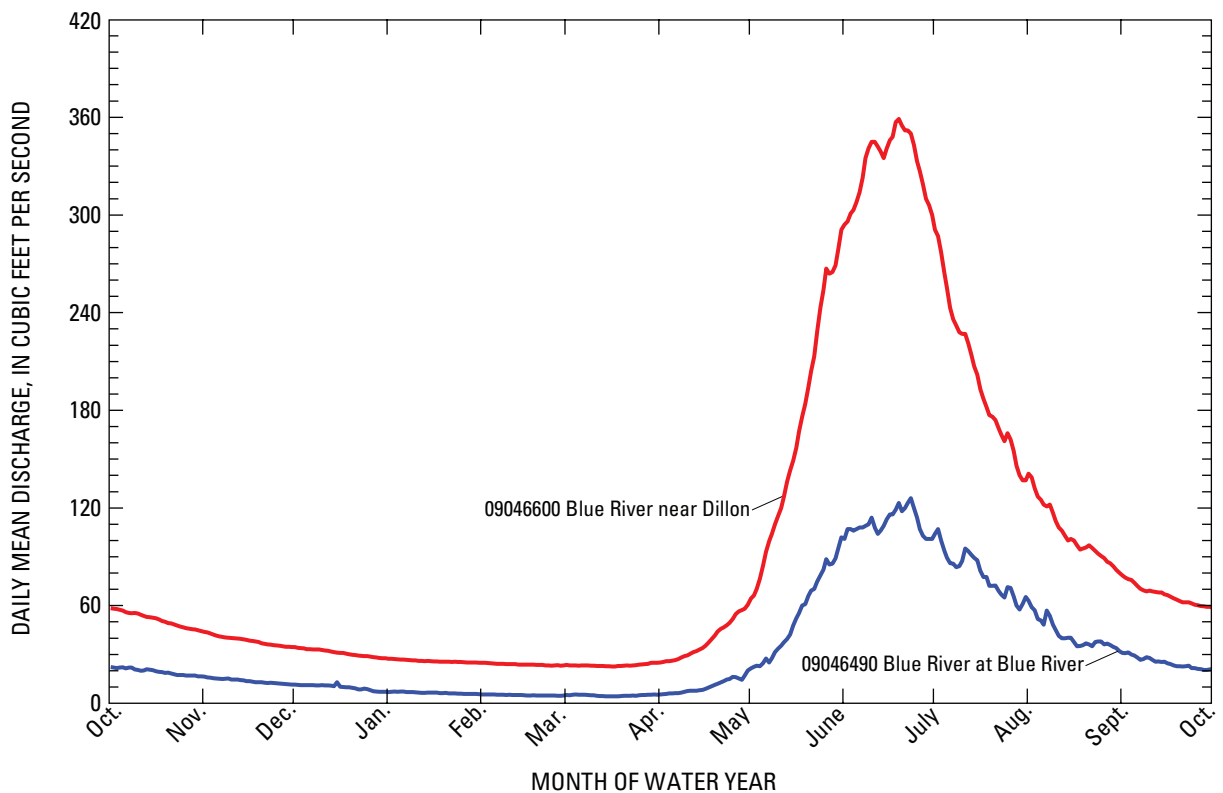


Figure 4. Daily mean discharges from Blue River at Blue River and Blue River near Dillon, Colorado.

Goose Pasture Tarn for the purpose of this study; these are station 392547106023400, Blue River above Pennsylvania Creek, and station 09046400, Indiana Creek above the mouth at Blue River, Colorado (fig. 1).

Methods

Three approaches were taken to derive estimates of reservoir sedimentation rate and reservoir capacity; photogrammetric, sedimentologic, and seismic methods were used in this study. Deltaic deposition at the inflow of the two streams entering Goose Pasture Tarn (the Blue River and Indiana Creek) was determined from a combination of aerial photographic interpretation and onsite observations (Elliott and Gyetvai, 1999). The mass and rate of sediment supplied to Goose Pasture Tarn from these two tributaries was estimated with suspended- and bedload-sediment transport measurements. The storage capacity of the reservoir was determined from a bathymetric survey of the reservoir-bed topography. The postreservoir volume of sediment in Goose Pasture Tarn was determined by sediment coring and seismic profile interpretation.

Sediment samples were collected from cores extracted from the reservoir bed, from pits dug in the deltaic deposits, and from streamflow. Sediment concentrations and particle-size distributions were determined by the USGS Iowa Sediment Laboratory using accepted procedures. The chemical composition of sediment in Goose Pasture Tarn was determined by the USGS Geologic Discipline Geochemistry Analytical Laboratory. The locations of topographic surveys, sediment probing, sediment coring, and seismic and bathymetric profiles are plotted on a map of Goose Pasture Tarn (fig. 5).

Aerial Photography

Aerial photographs of Goose Pasture Tarn were used to assess the development of exposed delta deposits since the reservoir was constructed. Hardcopies of USGS photographs taken on September 19, 1968, September 23, 1975, and September 13, 1983, were scanned into digital format for geographic information system (GIS) analysis (fig. 6A through 6C). Additional digital aerial imagery, rectified to known coordinates of ground features visible in the photograph (georectified), was collected by USGS on September 23, 2001, and obtained from the Microsoft Terraserver Web site (<http://terraserver-usa.com/>) (fig. 6D). Digital aerial imagery collected July 13, 2005, in the form of digital orthophoto quadrangles (DOQs), was obtained from the U.S. Department of Agriculture National Aerial Imagery Program (USDA NAIP) (fig. 6E). The DOQs previously were rectified to known coordinates.

Digital versions of the scanned aerial photographs from 1968, 1975, and 1983 were registered to the 2005 USDA NAIP data, and shorelines and delta boundaries depicted

on each photograph were delineated and analyzed in a GIS. Registration was accomplished with GIS georeferencing tools (Environmental Systems Research Institute, Inc., 2004a) that were used to match features from the unregistered scanned photograph with the same features on the 2005 DOQ and then perform an affine rectification. Shoreline and delta boundaries then were traced into digital vector polygon data by using the georectified photography. Area calculations then were performed on the polygon data with XTools Pro (Data East LLC, 2003–2004).

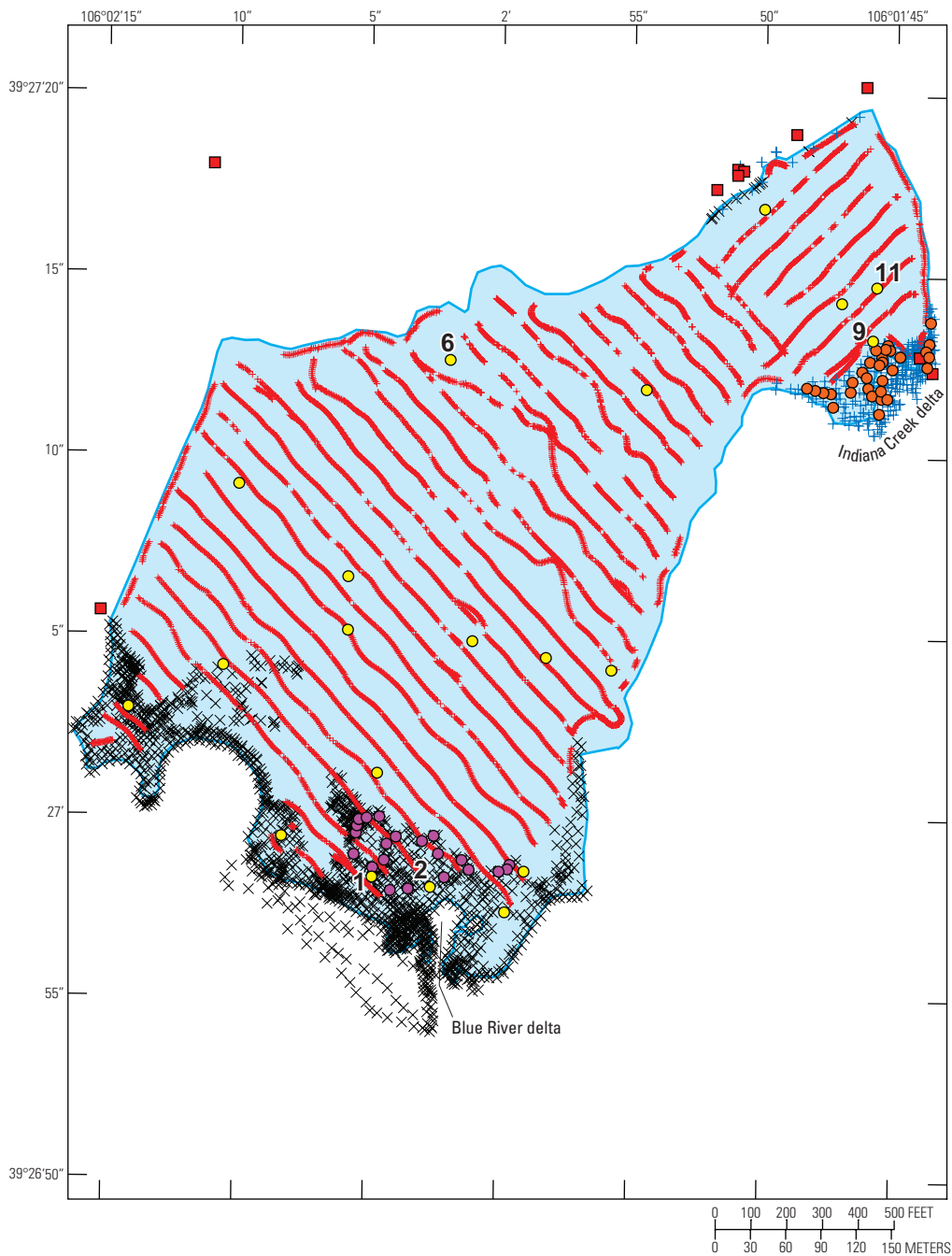
Sediment Transport Measurements

Sediment discharge measurements were made to determine suspended- and bedload-transport relations (sediment discharge compared to water discharge) at the new stream-flow-gaging stations on the two channels entering Goose Pasture Tarn—station 392547106023400 Blue River above Pennsylvania Creek and station 09046400 Indiana Creek above the mouth at Blue River (fig. 2). Water discharge measurements also were made in conjunction with the sediment measurements (Carter and Davidian, 1968). Because of relatively little snowmelt runoff in 2004 and 2005 (fig. 3) and transmountain diversions from the Blue River headwater tributaries, all water-discharge, suspended-sediment, and bedload measurements were made by wading the streams. Suspended sediment was collected with a DH-48 hand-held sampler, and bedload was collected with a 3-inch, hand-held Helley-Smith bedload sampler (Guy and Norman, 1970; Edwards and Glysson, 1999).

Sediment loads, or sediment discharges, were calculated at the two sampling sites by using instantaneous measurements of streamflow, suspended-sediment concentration, and bedload. Sediment loads, in tons per day, were computed for two modes of transport (suspended load and bedload) as well as for the total sediment load (suspended load plus bedload) if both modes had been sampled. Suspended-sediment load (tons per day) was calculated using the method of Porterfield (1972, p. 43) as the product of water discharge (cubic feet per second), suspended-sediment concentration (milligrams per liter), and a coefficient of 0.0027. Bedload (tons per day) was calculated using the method of Edwards and Glysson (1999, p. 80) as the product of the channel width (feet), the mass of the bedload sample (grams), and a units conversion factor of 0.381 (for a 3-inch sampler orifice), divided by the length of time the Helley-Smith sampler was in contact with the streambed (seconds).

Bathymetric Surveying

Bathymetry data were collected on August 23–24, 2004, and on June 8, 2005. Bathymetric mapping was accomplished using boat-mounted global positioning system (GPS) equipment, echo depth-sounding equipment, and computer software. The GPS allowed for accuracies of about 3.3 ft (approximately 1 m) in the horizontal direction. The echo sounder emits



EXPLANATION










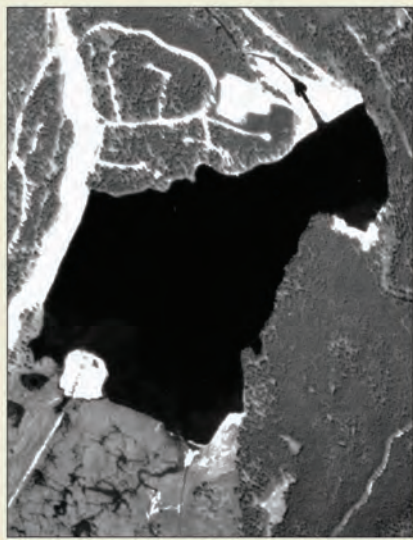
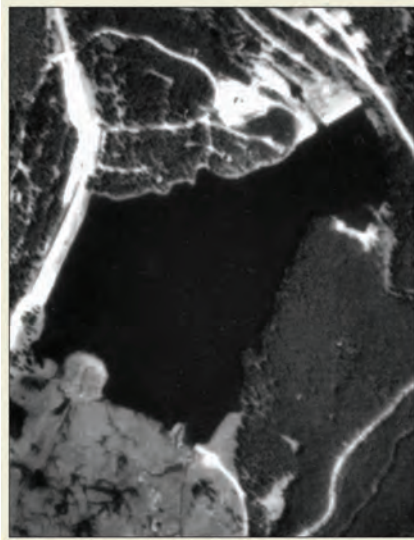
- | | |
|--|--|
|  Water's edge, full pool, 2004 |  Probed sediment thickness, Blue River delta |
|  Seismic and bathymetric transect |  Cored sediment thickness, Goose Pasture Tarn |
|  Surveyed topography, total station method |  Reference mark |
|  Surveyed topography, real-time kinetic method |  Selected core number shown in table 3 |
|  Probed sediment thickness, Indiana Creek delta | |

Figure 5. Goose Pasture Tarn showing locations of topographic surveys, sediment probing, seismic coring, and seismic and bathymetric profiles.

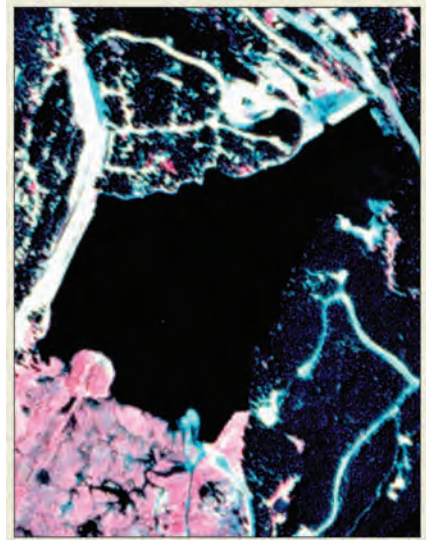
(A) September 9, 1968



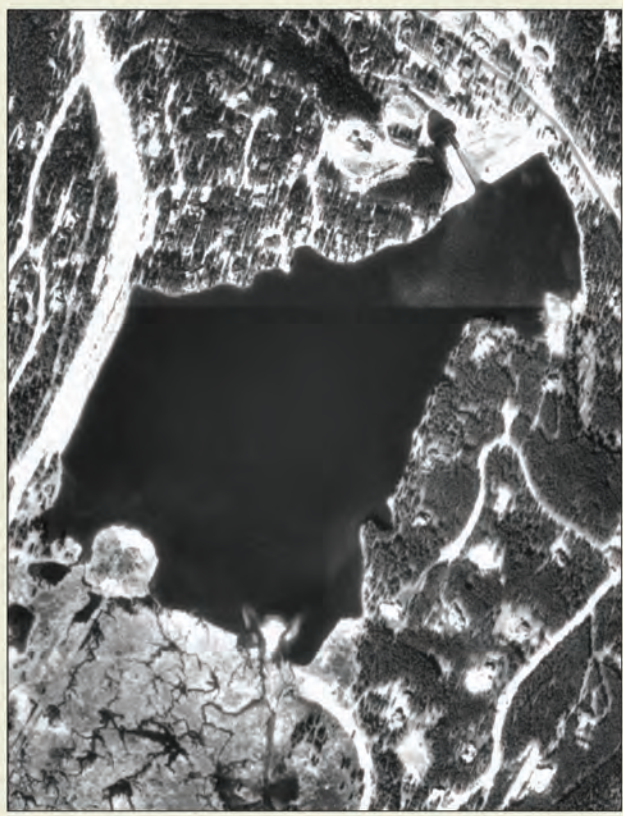
(B) September 23, 1975



(C) September 13, 1983



(D) September 23, 2001



(E) July 13, 2005

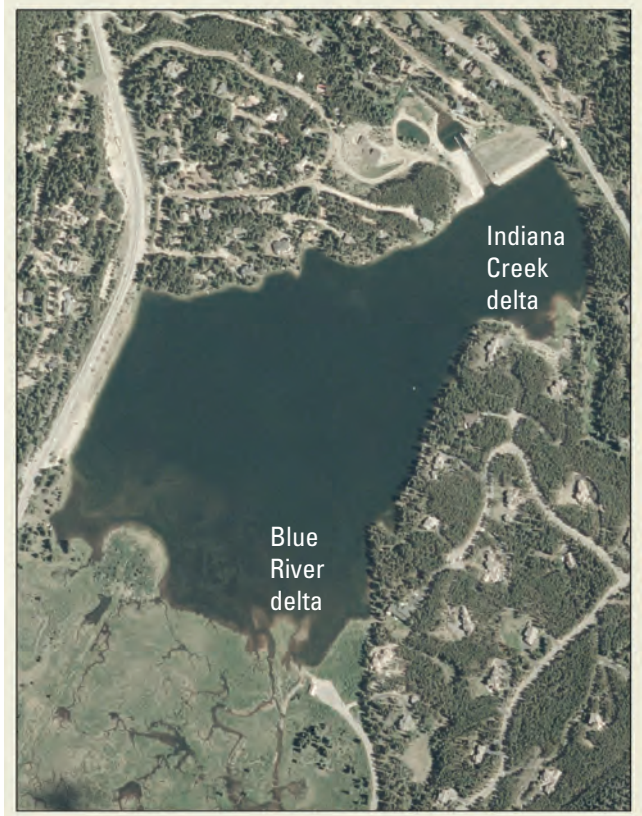


Figure 6. Aerial photographs of Goose Pasture Tarn on (A) September 9, 1968, (B) September 23, 1975, (C) September 13, 1983, (D) September 23, 2001, and (E) July 13, 2005 (Source: U.S. Geological Survey digital aerial imagery and U.S. Department of Agriculture National Aerial Imagery Program).

pulses of sound that are reflected off the reservoir bottom and then received by a transducer. The echo sounder transmitted at a frequency of 200 kilohertz (kHz), and the initial return, or reflection, was interpreted by the hydrographic software, Hypack Max (Coastal Oceanographics, Inc., 2002), as the lake bottom. Water depths were determined by the echo sounder software on the basis of speed of sound in water compensated for temperature (U.S. Army Corps of Engineers, 1994, chapter 9).

A bar check, or instrument calibration, on the echo sounder was performed at the beginning of each day of data collection following established protocols (U.S. Army Corps of Engineers, 1994, chapter 9). This was done to ensure that the echo sounder was calibrated correctly and measuring the correct depths. The bar check involves suspending a 2-ft-diameter flat aluminum plate directly below the echo sounder. The suspension line is marked in 5-ft increments. An initial calibration was made at 5 ft by entering the speed of sound in water and then adjusting the offset of the transducer in the computer software. The offset is the draft of the transducer below the reservoir surface. The aluminum plate then was lowered in 5-ft increments (depending on the range of depths expected to be encountered on the day of data collection), and adjustments in the speed of sound were made until depth readings and the depth of the aluminum plate agreed to within ± 0.1 ft.

Using the echo sounder, the bathymetry data were collected along planned transect lines spaced approximately 75 ft apart. Individual data-collection locations along a transect line generally were 5 to 10 ft apart (fig. 5). Bathymetry data also were collected, using the echo sounder, while driving the boat around the perimeter of the reservoir. Raw depth soundings were recorded in the hydrographic software, Hypack Max (Coastal Oceanographics, Inc., 2002). The echo-sounding equipment gives depth estimates of limited reliability in water less than 3.3 ft deep. Therefore, in shallow areas of the reservoir and near the tributary inflow locations, depths were determined from a topographic survey made in May 2004 when the reservoir water surface was drawn down approximately 3.8 ft. Full-pool water depths in these shallow areas were derived by subtracting the surveyed bed elevation from the reference surface elevation (9,886.4 ft) and merging these survey-derived depths with the bathymetrically derived depths elsewhere in the reservoir.

The reference water-surface elevation on the day of bathymetric data collection was determined by measuring down to the water surface from a reference mark at the dam spillway with a known elevation. The elevation of the reference mark was determined using GPS surveying equipment, and the real-time kinetic (RTK) survey was submitted to the National Geodetic Survey's Online Positioning Users Service (OPUS) Web site for processing (<http://www.ngs.noaa.gov/OPUS/>). Shore-point locations also were collected to define the water's edge of the reservoir. These locations were collected by touching the bow of the boat to the shoreline at

various intervals along the shoreline and recording the position using a bow-mounted GPS antenna.

Postprocessing of the bathymetry data was performed in the Hypack Max software and involved removing obvious spikes, editing extraneous points within the shore-point files, and applying tide corrections to convert unprocessed sounding depths to elevation. The processed bathymetry data then were exported to tabular XYZ format for input into the GIS to produce point data from which a three-dimensional surface of the reservoir-bottom elevations could be generated. When integrated with topographically collected point data (described in a subsequent section), the three-dimensional surface was generated using a Natural Neighbors interpolation algorithm (Environmental Systems Research Institute, Inc., 2004b).

Seismic Surveying

Seismic digital records were collected at the same time the bathymetry data were collected to estimate the original reservoir bottom. Seismic profiling was accomplished using boat-mounted GPS equipment, subbottom profiling equipment, and computer software. The broad-spectrum subbottom profiler emits pulses of sound at different frequencies that are reflected off subbottom materials of different densities. The subbottom profiler consists of five transducers integrated into one transducer array. The subbottom profiler transmitted at frequencies of 200, 48, 24, 12, and 4 kHz (kilohertz). Lower frequencies are capable of penetrating increasingly denser materials. The 200-kHz signal used in seismic interpretation was the same 200-kHz signal used by the hydrographic software, Hypack Max (Coastal Oceanographics, Inc., 2002) to compute water depth.

Seismic profiles were collected along the same planned transect lines, generated in Hypack Max (Coastal Oceanographics, Inc., 2002), that were used for collection of the bathymetric data (fig. 5). The software SDIDepth (Specialty Devices, Inc., 2003) continuously recorded the seismic digital record. Seismic profiles also were collected while driving the boat once around the perimeter of the reservoir. The distance of the boat from shore during the perimeter run varied, depending upon the depths, due to the 3.3-ft depth limitations of the data-collection equipment.

Sediment cores were collected for thickness calibration at various points around the reservoir to aid in interpretation of the seismic record during postprocessing and are discussed in greater detail in the "Lacustrine Sediment Coring and Analysis" section of this report. Twenty sediment-calibration cores with corresponding position data were collected at Goose Pasture Tarn (fig. 5). Upon collection of the core samples, physical measurements of the observed layer(s) were recorded. The original reservoir bottom was determined by inspecting the core for a layer of grasses, twigs, color, and (or) hardness changes, and texture change below a layer of sediment. The original reservoir-bed material was typically of the same kind of material as the material on the dry landscape surrounding

the reservoir. In some cases, upon inspection of the core, a clear physical transition or marker indicating the original reservoir bottom was not visible. In those cases, it was assumed that depth to refusal, the point at which the core tubing would no longer penetrate the reservoir bed, indicated the depth to the original reservoir bed.

Sediment thickness data were generated using the Depthpic software (Specialty Devices, Inc., 2003). Initial postprocessing involved removing obvious spikes and anomalies from bathymetry data stored in Depthpic. An estimation of sediment thickness then was obtained by interpretation of the seismic digital record (in Depthpic) using the different frequencies. A digital representation of the sediment-calibration cores (measured lengths of the observed layers) was imported and superimposed onto the seismic digital record. Frequency settings were adjusted to best match the amount of wave penetration into the subbottom compared with the superimposed core data. Sediment thickness then was estimated by manually digitizing (in Depthpic) the portion of digital record thought to be the best representation of the bottom of the sediment layer. After digitization of each transect, data were exported in XYZ format (easting, northing, and sediment thickness) with all units in feet. Depthpic subtracts the water depth (depth to water—substrate interface) from the digitized subbottom depth to obtain sediment thickness. The XYZ files then were imported into the GIS to produce point data from which a three-dimensional surface representing sediment thickness could be generated. When integrated with topographically collected sediment-probe point data (described in fuller detail in the “Topographic Surveying and Sediment Probing” section), the three-dimensional sediment-thickness surface was generated using a Natural Neighbors interpolation algorithm (Environmental Systems Research Institute, Inc., 2004b).

Lacustrine Sediment Coring and Analysis

Sediment in Goose Pasture Tarn was collected in cores to identify the former land surface before inundation (the original reservoir bed), to determine postinundation sediment thickness, to calibrate the seismic digital record, and to collect sediment samples for grain-size and chemical composition analysis. Sediment cores were collected and evaluated with acceptable USGS methods (Greve and others, 2001; Mau, 2002; Linhart and Nania, 2003).

Twenty sediment cores were collected with a vibrating corer (Specialty Devices, Inc., 2003) at various locations in the reservoir in 2004 and 2005 (fig. 5). The 24-lb (submerged weight) coring head and core barrel (a 2.56-inch-inside-diameter, clear, butyrate tube) were lowered slowly from a boat scaffold to the reservoir bed. A 24-volt battery system created a vibrating frequency of 5,000 to 7,000 cycles per minute, and the weighted core barrel was allowed to penetrate through the lacustrine sediment and into the original reservoir-bed material causing minimal disturbance and compaction. The core barrel then was raised and capped below the water

surface to prevent sample loss. The original bed material was identified onsite through the transparent core barrel, usually defined by a stratigraphic concentration of sticks, organic matter, or gleyed (bluish-gray) soil or sediment. Lacustrine sediment thickness above the bed marker was recorded along with position coordinates.

Some core sediments were collected and saved for later particle-size analysis at the USGS Iowa Sediment Laboratory in Iowa City, Iowa, and chemical analysis at the USGS Geologic Discipline Geochemistry Analytical Laboratory in Denver, Colorado. Sediment-size analysis consisted of wet-sieving coarser materials (down to 0.125-mm particle size) and pipet analysis of finer materials (down to 0.002-mm particle size) to determine the particle-size distribution of sediment in the cores (Guy, 1969). Chemical analysis to identify the presence and relative abundance of 48 metal and other constituents was performed by the total-digestion method on the finer materials (less than 2-mm particle diameter) in the sediment and not on the larger gravel and rock fragments found in some sediment cores. The objective was to identify chemical constituents that were transported with finer sediments and likely to be reentrained when disturbed if the reservoir is drawn down or if sediment is dredged from the reservoir.

Topographic Surveying and Sediment Probing

Shallow-water areas of Goose Pasture Tarn, less than approximately 3.3 ft deep, presented difficult conditions for accurate bathymetric water-depth and seismic sediment-thickness estimations. Determining accurate sediment thickness in shallow areas near the inflow of the Blue River and Indiana Creek was critical to the study because these deltaic sediments were believed to account for a substantial amount of the total sediment in the reservoir. Seismic thickness estimates were augmented in the two delta areas by topographic surveys of the delta surface and by manually probing the deltaic deposits with a graduated rod at a time when the water-surface elevation of the reservoir was drawn down several feet (fig. 5).

Surveys of the exposed delta surfaces in May 2004 were used to accurately portray the reservoir-bed topography in deltaic areas inundated by shallow water at normal, or full-pool, elevation. These surveys also included deltaic deposits sub-aerially exposed at full-pool elevation. The Indiana Creek delta was surveyed on May 14, 2004, with a Topcon total station. The Topcon total station and several vertical- and horizontal-reference control points were located on the Goose Pasture Dam (fig. 5). The Blue River delta was surveyed on May 21, 2004, with a Trimble RTK surveying instrument. The RTK base station was set up over the same reference point on the Goose Pasture Dam. The RTK survey was submitted to the National Geodetic Survey's Online Positioning Users Service (OPUS) Web site for processing (<http://www.ngs.noaa.gov/OPUS/>). Data from both surveys were rectified to the OPUS solution, as were all bathymetric and seismic data. The coordinate system was UTM Zone 13, horizontal datum

NAD 83 (meters), vertical datum NAVD 88, Geoid 03, ellipsoid WGS 84. Data from the bathymetric and seismic profiles were converted to meters to merge with the topographic survey data and overlaid on the 2005 aerial photograph as a visual check for position verification. All location, depth, and sediment-thickness data subsequently were converted back to feet for this report.

Deltaic sediments were manually probed with a graduated steel rod while the topographic survey was being made, and the estimated thickness and location coordinates were recorded (fig. 5). Most of the deltaic sediments were in the sand-size range (0.0625 to 2.0 mm diameter) and could be penetrated easily with the steel rod. The base of the deltaic deposits usually consisted of a layer of coarse stream gravel or cobbles. Two exploratory pits were dug to confirm the thickness estimates by probing. The pit thickness and probed thickness were within 0.1 ft of each other at both locations, with the probe-determined thicknesses being overstated by 0.1 ft.

Sedimentation in Goose Pasture Tarn

Aerial Photography Interpretation, 1968 to 2005

Aerial photographs from 5 years were used to assess the accumulation of deltaic sediment from the Blue River and Indiana Creek to Goose Pasture Tarn. The Blue River enters Goose Pasture Tarn at the southernmost part of the reservoir, and Indiana Creek enters from the south in the eastern part of the reservoir (fig. 2). Deltas formed by both streams are visible in figures 6B through 6E. Contrary to its appearance, the large, round landform in the southwestern part of the reservoir is not a delta; apparently, it is a construction relict from the creation of the reservoir. The exposed areas of deltaic deposits in each photograph were delineated and areas computed with GIS. Delta areas estimated from aerial photographs include only the visible, exposed part of the delta and not the submerged deposits, which could not be viewed except in very shallow, clear water (fig. 6E). The accuracy of delta delineation and area calculations was limited by the quality of the enlarged photographs, shadows cast by nearby trees, and partial transparency of water in the reservoir. All photographs were taken at full-pool conditions (water-surface elevation 9,886.4 ft), and the water's edge was assumed to be a consistent elevation marker.

A reference shoreline was determined from the September 9, 1968, aerial photograph (fig. 6A), the first taken after the reservoir was filled in 1965. Peak discharge recorded at the streamflow-gaging station near Dillon was relatively low in 1966, 1967, and 1968 (fig. 3), and it appears that little sediment had accumulated in deltas during these first few years. Shorelines and the delta margins in subsequent years' photographs (figs. 6B–6E) were compared to the 1968

reference shoreline to identify depositional areas, and incremental growth or erosion of the deltas was estimated.

Delta areas increased in the 40-year period after construction of the Goose Pasture Dam. The Blue River delta was 0.37 acre, and the Indiana Creek delta was 0.54 acre by 2005. The Blue River delta experienced a rapid increase in area between the 1968 and 1975 photographs and between the 1975 and 1983 photographs (fig. 7). Large floods in 1973, 1980, and 1983, recorded at the streamflow-gaging station near Dillon (fig. 3) (USGS surface water data for Colorado, <http://waterdata.usgs.gov/co/nwis/sw>), could have contributed to delta accumulation between photograph dates. Little sediment accumulation was visible after 1983, and the decrease in delta area between 1983 and 2001 could be due to erosion of earlier deltaic sediment by wave action.

The Indiana Creek delta also showed rapid growth between 1968 and 1975 and between 1975 and 1983, and some growth between 1983 and 2001. The flood peak of 1995 was the highest discharge on record at the streamflow-gaging station near Dillon (fig. 3), and local observers reported that a large amount of coarse sediment was deposited on the Indiana Creek fan during the June 1995 flood, which was caused by heavy rain on snow cover (Gary Roberts, Town of Breckenridge, oral commun., July 1, 2003). The decrease in delta area between 2001 and 2005 could be due to erosion by wave action.

Sediment Transport into Goose Pasture Tarn, 2004 and 2005

Streamflow in the Blue River and Indiana Creek was low in 2004 and 2005 because of relatively little snowmelt runoff in 2004 and transmountain diversions from the Blue River headwater tributaries both years (fig. 3). Consequently, sediment entrainment and transport in the two streams was not great, and little sediment was delivered to the reservoir. Suspended-sediment measurements were made intermittently on the Blue River and Indiana Creek from the spring, before the seasonal runoff began, through mid- to late summer, after the runoff peak. Bedload measurements were made less frequently because, many times, no bedload movement was observed when suspended-sediment measurements were being made. Suspended-sediment samples were collected at both sites in 2004, but because of small sediment volume in the samples, they were not analyzed for concentration. Attempts also were made to collect bedload in 2004, but material was in transport on only one occasion.

Suspended-sediment and bedload measurements were repeated in 2005 with similar results; low streamflow discharges, low suspended-sediment concentrations, and little or no bedload transport resulted in very small sediment loads. Peak discharges were 81 ft³/s on the Blue River above Pennsylvania Creek and 43 ft³/s on Indiana Creek above the mouth. Streamflow ranged from 3.7 to 49.3 ft³/s in the Blue River and from 2.5 to 32.0 ft³/s in Indiana Creek when sediment

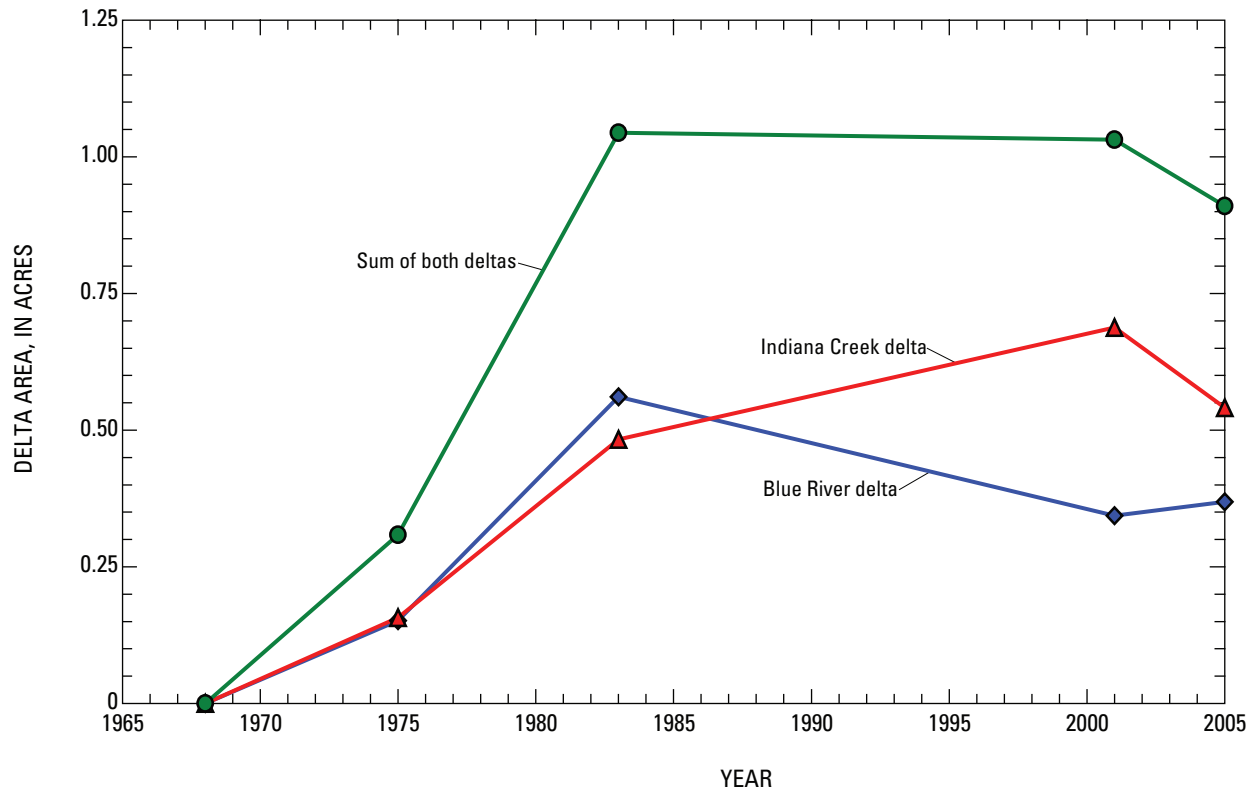


Figure 7. Exposed delta areas calculated from aerial photographs.

measurements were made in 2005 (table 1). Suspended-sediment concentrations ranged from 1 to 12 mg/L in the Blue River and 4 to 19 mg/L in Indiana Creek in 2005. Suspended-sediment loads ranged from 0.02 to 1.60 ton/d in the Blue River and from 0.06 to 1.55 ton/d in Indiana Creek in 2005. The composition of the suspended sediment collected in the two streams was mostly in the sand-size range (0.0625 to 2.0 mm diameter); however, no determination was made of the percentage of suspended sediment finer than 0.0625 mm (silt- and clay-size material) because collected suspended-sediment volumes were too small for size analysis.

One bedload measurement was made on the Blue River, and four bedload measurements were made on Indiana Creek in 2005. No bedload movement was observed on other days when suspended-sediment measurements were made in 2005. Bedload was 0.26 ton/d in the Blue River on July 25, 2005, and ranged from 0.004 to 0.07 ton/d in Indiana Creek on the 4 days it was measured. The material being transported as bedload on these 5 days was mostly sand-size material (0.0625 to 2.0 mm diameter), with a few small gravel particles.

Total sediment load is the sum of suspended-sediment load and bedload and was calculated on days when both modes of sediment transport were observed. Bedload as a percentage of total sediment load ranged from 9 to 27 percent during the relatively low streamflows for which measurements were made. Bedload is expected to be a greater percentage of total sediment load during flood discharges when the coarse gravel, cobbles, and boulders in the streambed are entrained

by the greater shear stresses associated with deeper and faster runoff.

Sediment-transport relations and sediment budgets could not be computed for suspended sediment and bedload sediment in the Blue River and Indiana Creek because of the minimal streamflow during the duration of this study and infrequently observed sediment transport. Derivation of sediment-transport relations requires that sediment-load data be collected over a wide range of streamflows, including normal peak-flow discharges that were not observed in 2004 and 2005. Sediment budget calculation requires sediment-transport relations and long-term streamflow discharge records, which are not available for the Blue River and Indiana Creek upstream from Goose Pasture Tarn.

Bathymetric and Seismic Surveys of Goose Pasture Tarn

Bathymetric and seismic surveys of Goose Pasture Tarn were done in August 2004 and June 2005. Because of the dense growth of an aquatic plant, *Elodea sp.*, in shallow areas in late summer, the reservoir-bed surface in approximately one-third of Goose Pasture Tarn could not be identified reliably in the 2004 bathymetric survey. Lewis and others (1982) and Resource Engineering, Inc. (2002) also noted the dense growth of this aquatic plant in similar areas of Goose Pasture Tarn. A second set of bathymetric and seismic surveys in the

Table 1. Summary of discharge and sediment-transport measurements made at U.S. Geological Survey streamflow-gaging stations 392547106023400 Blue River above Pennsylvania Creek, and 09046400 Indiana Creek above the mouth at Blue River, Colorado.

Sample date (dd mm yy)	Gage height (ft)	Discharge (ft ³ /s)	Channel width (ft)	Maximum depth (ft)	Suspended- sediment concentration ¹ (mg/L)	Suspended- load ² (ton/d)	Bedload ³ (ton/d)	Total sediment load (ton/d)	Bedload percentage of total (%)	Remarks
392547106023400 Blue River above Pennsylvania Creek										
6 May 04	nd ⁴	11.3	15.4	0.92	nd	nd	0	--	--	No bedload catch. Turbidity: very clear
20 May 04	nd ⁴	4.89	14.5	.46	nd	nd	0	--	--	No bedload catch. Turbidity: clear
1 June 04	nd ⁴	4.28	14.3	.48	nd	nd	.03	--	--	Bedload collected.
3 Aug 04	nd ⁴	10.4	14.9	.54	nd	nd	0	--	--	No bedload catch.
26 April 05	3.50	3.7	10.8	.70	2	0.02	nd	--	--	
23 May 05	3.90	15.7	18.0	1.10	5	.19	nd	--	--	
2 June 05	3.84	12.7	18.2	1.00	1	.03	nd	--	--	
13 June 05	3.81	11.2	18.0	nd	2	.06	nd	--	--	
21 June 05	3.98	10.6	18.1	1.00	2	.06	nd	--	--	
25 July 05	4.27	49.3	18.3	1.40	12	1.60	.26	1.86	14	
09046400 Indiana Creek above the mouth at Blue River, Colorado										
7 May 04	nd ⁴	5.50	9.5	.89	nd	nd	nd	--	--	No bedload sample attempted.
20 May 04	nd ⁴	8.21	9.3	.80	nd	nd	0	--	--	No bedload catch. Turbidity: clear
2 June 04	nd ⁴	7.20	9.3	.78	nd	nd	0	--	--	No bedload catch. Turbidity: clear
26 April 05	7.40	2.5	9.0	.60	9	.06	nd	--	--	
23 May 05	8.21	30.2	9.4	2.1	19	1.55	nd	--	--	
26 May 05	8.25	32.0	9.5	2.0	15	1.25	nd	--	--	
2 June 05	8.09	20.7	10.1	1.9	5	.28	.03	.31	9.4	
13 June 05	7.98	17.4	10.0	na	4	.16	.06	.23	27	
21 June 05	7.97	16.0	9.0	1.0	5	.19	.07	.27	27	
1 July 05	7.83	10.1	9.6	1.0	nd	nd	0	--	--	No reported concentration from laboratory.

¹Some suspended-sediment samples not analyzed due to imperceptible sediment in sample bottle.

²Suspended-sediment load, $Q_{\text{susp}} = Q \times C \times 0.0027$, where Q equals discharge in cubic feet per second and C equals suspended-sediment concentration in milligrams per liter.

³Bedload, $Q_{\text{bedload}} = 0.381 \times (\text{channel width}/\text{total sampling time}) \times (\text{collected sediment mass})$.

⁴Gage not installed in 2004; therefore, no gage heights recorded.

shallow areas was made in early June 2005 before the seasonal *Elodea sp.* growth covered the reservoir bed. The 2004 data from shallow areas were not used in the analysis, and the 2005 data were substituted and merged with 2004 data from deeper, vegetation-free areas. Little change to the reservoir-bed topography likely occurred between August 2004 and June 2005 because very little fluvial sediment was transported into Goose Pasture Tarn during this time (table 1).

Bathymetric- and seismic-survey transect lines were spaced roughly 75 ft apart, whereas data points on these transects were spaced at roughly 5- to 10-ft intervals (fig. 5). In very shallow delta areas of the reservoir at full pool, elevation data from topographic surveys were substituted for bathymetric data because the reliability of the bathymetric data can be questionable at water depths of less than about 3.3 ft. The topographic surveys of delta surfaces were done in May 2004 when the reservoir water surface was drawn down approximately 3.7 ft for dam maintenance work. The contemporary reservoir-bed surface area was mapped using a total of 5,421 elevation points after the 2004 and 2005 bathymetric surveys and 2004 topographic surveys were merged.

Data from the bathymetric and topographic surveys were combined into a single GIS point dataset. Where bathymetric data overlapped topographic data, the bathymetric data were removed in this process. The contemporary (2005) reservoir-bed surface then was created from the points in the GIS using a Natural Neighbors interpolation algorithm (Environmental Systems Research Institute, Inc., 2004b). The contemporary reservoir-bed surface was used in a GIS cut/fill (Environmental Systems Research Institute, Inc., 2004c) analysis to define (1) the stage-area and stage-capacity relation discussed in a subsequent section of this report and (2) the topography of accumulated lacustrine sediment on the reservoir bed (fig. 8).

The deepest areas of the reservoir were near the west end of the Goose Pasture Tarn dam and westward from that location, and north of the Indiana Creek delta, possibly representing the former drainages of the Blue River and Indiana Creek before the dam was constructed. The maximum water depth at full-pool conditions was 35.8 ft, and the mean water depth was 13.5 ft. Other than nearshore areas, the shallowest water at full pool was west of the Indiana Creek delta and in most of the southwestern end of the reservoir. These shallow areas probably represent prereservoir low-relief land surfaces and postreservoir sediment-accumulation areas (fig. 8).

Seismic data, based on 7,341 points, were calibrated with the lacustrine sediment cores and were used to estimate (1) the original reservoir-bed surface, that is, the land surface that existed when the reservoir was filled in 1965, and (2) the thickness and volume of accumulated, postreservoir sediment. The presedimentation, original reservoir-bed surface was identified from seismic profiles and mapped as a continuous surface in GIS by using a Natural Neighbors interpolation algorithm (Environmental Systems Research Institute, Inc., 2004b). The original reservoir-bed surface was used to estimate the original (1965) reservoir stage-area and stage-capacity relations. These relations are discussed in a

subsequent section of the report, “Reservoir Area and Capacity.” Probe-determined sediment thicknesses from a low-water topographic survey of the Blue River and Indiana Creek deltas were merged with seismically determined, reservoir-sediment thicknesses into a single GIS thickness dataset. The probed sediment data gave reliable estimates of sediment thickness in areas too shallow for seismic interpretation and in areas assumed to have the greatest evidence of postreservoir sediment accumulation (fig. 5).

The greatest sediment accumulations revealed in the thickness dataset were located near the inflows of the Blue River and Indiana Creek. These areas are visible in the aerial photographs (fig. 6) and to the observer at normal and drawn-down water levels. Sediment thickness determined with seismic profiling ranged from 0 to 4.0 ft and averaged 0.7 ft, with lesser thicknesses in the deeper parts of Goose Pasture Tarn and greater thicknesses near the deltas. Sediment thickness determined with a probe ranged from 1.0 to 4.4 ft and averaged 2.8 ft near the Blue River delta and from 0.3 to 6.0 ft and averaged 3.6 ft near the Indiana Creek delta. Sediment accumulation and volumetric estimates are discussed in a subsequent section of the report, “Sediment Volume in Goose Pasture Tarn.”

Reservoir Area and Capacity

The 2005 reservoir capacity of Goose Pasture Tarn was determined from bathymetric measurements, and the reservoir surface area was surveyed with GPS while bathymetric measurements were being made. At a full-pool elevation of 9,886.4 ft, the surface area of Goose Pasture Tarn in 2005 was 66.4 acres and the capacity, or volume, was 771.1 acre-ft (table 2).

The original area and capacity of Goose Pasture Tarn in 1965 were estimated in this study from 2005 seismic profiling in the reservoir and manual probing of exposed delta deposits that, together, identified the prereservoir land surface. It was assumed that the 1965 dam had the same configuration as in 2005 and that the reservoir was filled to a water-surface elevation of 9,886.4 ft. At full-pool elevation, the 1965 surface area was 67.1 acres, and the reservoir capacity was 818.0 acre-ft (table 2). On the basis of the 2005 survey and the estimate of the original reservoir-bed topography, the full-pool reservoir surface area has decreased by 0.7 acre, or about 1.1 percent. The magnitude of estimated reservoir surface-area decrease is reasonable considering the sum of delta surface areas created since 1965 was 0.9 acre in 2005 (fig. 7). Reservoir capacity, or volume, decreased by 46.9 acre-ft, or about 5.7 percent over the same 40-year period. Plots of reservoir surface area/water-surface elevation and capacity/water-surface elevation are shown in figures 9 and 10.

Reservoir water-surface area and capacity estimates from a 2002 survey (Resource Engineering, Inc., 2002) also are presented for comparison in table 2 and figures 9 and 10. Water-surface area from this study and the 2002 Resource

18 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach’s 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,886.4	66.4	771.1	67.1	818.0	-0.7	-1.1	-46.9	-5.7	67.3	795.7
9,886.3	66.1	764.5	66.9	811.3	-8	-1.2	-46.8	-5.8	67.0	789.0
9,886.2	65.8	757.9	66.7	804.6	-8	-1.2	-46.7	-5.8	66.7	782.2
9,886.1	65.6	751.3	66.5	797.9	-9	-1.3	-46.6	-5.8	66.5	775.5
9,886.0	65.4	744.7	66.3	791.3	-9	-1.4	-46.6	-5.9	66.2	768.8
9,885.9	65.2	738.2	66.2	784.7	-1.0	-1.5	-46.5	-5.9	65.9	762.2
9,885.8	65.0	731.7	66.0	778.1	-1.0	-1.5	-46.4	-6.0	65.6	755.6
9,885.7	64.8	725.2	65.8	771.5	-1.1	-1.6	-46.3	-6.0	65.3	749.0
9,885.6	64.6	718.7	65.6	764.9	-1.1	-1.6	-46.2	-6.0	65.0	742.4
9,885.5	64.4	712.3	65.4	758.3	-1.1	-1.6	-46.1	-6.1	64.8	735.9
9,885.4	64.2	705.9	65.2	751.8	-1.0	-1.6	-45.9	-6.1	64.5	729.4
9,885.3	64.0	699.5	65.0	745.3	-1.0	-1.6	-45.8	-6.2	64.2	722.9
9,885.2	63.8	693.1	64.9	738.8	-1.0	-1.6	-45.7	-6.2	63.9	716.5
9,885.1	63.6	686.7	64.7	732.3	-1.0	-1.6	-45.6	-6.2	63.7	710.1
9,885.0	63.5	680.3	64.5	725.9	-1.1	-1.6	-45.5	-6.3	63.4	703.7
9,884.9	63.3	674.0	64.4	719.4	-1.1	-1.7	-45.4	-6.3	63.1	697.4
9,884.8	63.1	667.7	64.2	713.0	-1.1	-1.7	-45.3	-6.4	62.8	691.1
9,884.7	62.9	661.4	64.0	706.6	-1.1	-1.8	-45.2	-6.4	62.6	684.7
9,884.6	62.7	655.1	63.9	700.2	-1.2	-1.9	-45.1	-6.4	62.3	678.5
9,884.5	62.5	648.8	63.7	693.8	-1.2	-1.9	-45.0	-6.5	62.0	672.3
9,884.4	62.3	642.6	63.6	687.4	-1.3	-2.1	-44.8	-6.5	61.7	666.1
9,884.3	62.0	636.4	63.4	681.1	-1.4	-2.2	-44.7	-6.6	61.4	660.0
9,884.2	61.6	630.2	63.2	674.8	-1.6	-2.5	-44.6	-6.6	61.1	653.8
9,884.1	61.2	624.1	63.0	668.5	-1.8	-2.9	-44.4	-6.6	60.8	647.8
9,884.0	60.7	618.0	62.8	662.2	-2.1	-3.3	-44.2	-6.7	60.5	641.7
9,883.9	60.1	611.9	62.6	655.9	-2.5	-4.0	-44.0	-6.7	60.2	635.7
9,883.8	59.3	606.0	62.3	649.6	-3.1	-4.9	-43.7	-6.7	59.9	629.8
9,883.7	58.3	600.1	62.0	643.4	-3.7	-6.0	-43.3	-6.7	59.5	623.8
9,883.6	57.5	594.3	61.7	637.2	-4.2	-6.7	-43.0	-6.7	59.2	617.9
9,883.5	56.7	588.6	61.2	631.1	-4.6	-7.4	-42.5	-6.7	58.8	612.0

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,883.4	55.8	583.0	60.7	625.0	-4.8	-8.0	-42.0	-6.7	58.4	606.2
9,883.3	55.0	577.4	60.0	619.0	-5.1	-8.4	-41.5	-6.7	57.9	600.4
9,883.2	54.1	572.0	59.3	613.0	-5.2	-8.8	-41.0	-6.7	57.5	594.6
9,883.1	53.1	566.6	58.5	607.1	-5.3	-9.1	-40.5	-6.7	57.0	588.9
9,883.0	52.2	561.3	57.7	601.3	-5.5	-9.5	-40.0	-6.6	56.5	583.2
9,882.9	51.2	556.2	56.9	595.6	-5.7	-10.0	-39.4	-6.6	56.0	577.5
9,882.8	50.2	551.1	56.1	589.9	-5.9	-10.5	-38.8	-6.6	55.5	572.0
9,882.7	49.2	546.1	55.3	584.4	-6.1	-11.1	-38.2	-6.5	54.9	566.4
9,882.6	48.2	541.3	54.5	578.9	-6.3	-11.5	-37.6	-6.5	54.4	560.9
9,882.5	47.7	536.5	53.7	573.4	-6.0	-11.1	-37.0	-6.5	53.9	555.5
9,882.4	47.4	531.7	52.8	568.1	-5.4	-10.2	-36.4	-6.4	53.4	550.1
9,882.3	47.1	527.0	52.0	562.9	-4.9	-9.4	-35.9	-6.4	52.9	544.8
9,882.2	46.9	522.3	51.3	557.7	-4.5	-8.7	-35.4	-6.4	52.4	539.6
9,882.1	46.6	517.6	50.7	552.6	-4.2	-8.3	-35.0	-6.3	51.9	534.4
9,882.0	46.3	513.0	50.3	547.6	-4.0	-7.9	-34.6	-6.3	51.5	529.2
9,881.9	46.1	508.3	49.8	542.6	-3.7	-7.4	-34.2	-6.3	51.0	524.2
9,881.8	45.9	503.7	49.4	537.6	-3.5	-7.1	-33.9	-6.3	50.6	519.2
9,881.7	45.7	499.2	49.0	532.7	-3.4	-6.8	-33.5	-6.3	50.2	514.1
9,881.6	45.4	494.6	48.6	527.8	-3.2	-6.6	-33.2	-6.3	49.9	509.2
9,881.5	45.2	490.1	48.3	522.9	-3.1	-6.3	-32.9	-6.3	49.5	504.2
9,881.4	44.9	485.6	47.9	518.1	-2.9	-6.1	-32.6	-6.3	49.2	499.3
9,881.3	44.7	481.1	47.6	513.4	-2.8	-6.0	-32.3	-6.3	49.0	494.4
9,881.2	44.5	476.6	47.3	508.6	-2.8	-5.9	-32.0	-6.3	48.7	489.5
9,881.1	44.3	472.2	47.0	503.9	-2.7	-5.7	-31.7	-6.3	48.5	484.6
9,881.0	44.1	467.8	46.7	499.2	-2.6	-5.5	-31.5	-6.3	48.3	479.7
9,880.9	43.9	463.4	46.4	494.6	-2.4	-5.3	-31.2	-6.3	48.1	474.9
9,880.8	43.7	459.0	46.0	490.0	-2.3	-4.9	-31.0	-6.3	48.0	470.1
9,880.7	43.6	454.6	45.7	485.4	-2.1	-4.6	-30.8	-6.3	47.8	465.3
9,880.6	43.4	450.3	45.3	480.8	-1.9	-4.3	-30.6	-6.4	47.5	460.6
9,880.5	43.2	445.9	45.0	476.3	-1.8	-4.0	-30.4	-6.4	47.3	455.8

20 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach’s 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,880.4	43.0	441.6	44.7	471.8	-1.7	-3.7	-30.2	-6.4	47.0	451.1
9,880.3	42.8	437.3	44.3	467.4	-1.5	-3.5	-30.0	-6.4	46.7	446.5
9,880.2	42.6	433.1	44.1	463.0	-1.5	-3.3	-29.9	-6.5	46.4	441.8
9,880.1	42.4	428.8	43.8	458.6	-1.4	-3.2	-29.7	-6.5	46.0	437.2
9,880.0	42.2	424.6	43.6	454.2	-1.4	-3.2	-29.6	-6.5	45.6	432.6
9,879.9	42.0	420.4	43.3	449.9	-1.4	-3.1	-29.5	-6.6	45.2	428.0
9,879.8	41.8	416.2	43.1	445.5	-1.3	-3.1	-29.3	-6.6	44.8	423.5
9,879.7	41.6	412.0	42.9	441.2	-1.3	-3.1	-29.2	-6.6	44.4	419.0
9,879.6	41.4	407.9	42.7	437.0	-1.3	-3.0	-29.1	-6.7	44.0	414.6
9,879.5	41.1	403.8	42.4	432.7	-1.3	-3.0	-28.9	-6.7	43.6	410.1
9,879.4	40.9	399.6	42.2	428.5	-1.3	-3.0	-28.8	-6.7	43.2	405.8
9,879.3	40.7	395.6	42.0	424.3	-1.3	-3.0	-28.7	-6.8	42.8	401.5
9,879.2	40.5	391.5	41.7	420.1	-1.3	-3.0	-28.6	-6.8	42.5	397.2
9,879.1	40.2	387.5	41.5	415.9	-1.3	-3.1	-28.4	-6.8	42.1	392.9
9,879.0	40.0	383.5	41.3	411.8	-1.3	-3.1	-28.3	-6.9	41.8	388.7
9,878.9	39.8	379.5	41.1	407.7	-1.3	-3.2	-28.2	-6.9	41.5	384.5
9,878.8	39.5	375.5	40.8	403.6	-1.3	-3.3	-28.1	-7.0	41.2	380.3
9,878.7	39.2	371.6	40.6	399.5	-1.4	-3.4	-27.9	-7.0	40.9	376.2
9,878.6	39.0	367.7	40.4	395.4	-1.4	-3.4	-27.8	-7.0	40.7	372.1
9,878.5	38.7	363.8	40.1	391.4	-1.4	-3.4	-27.6	-7.1	40.4	368.0
9,878.4	38.5	359.9	39.9	387.4	-1.4	-3.4	-27.5	-7.1	40.2	364.0
9,878.3	38.3	356.1	39.6	383.4	-1.4	-3.4	-27.4	-7.1	39.9	360.0
9,878.2	38.0	352.3	39.4	379.5	-1.4	-3.5	-27.2	-7.2	39.7	355.9
9,878.1	37.8	348.5	39.2	375.6	-1.4	-3.5	-27.1	-7.2	39.5	352.0
9,878.0	37.5	344.7	38.9	371.7	-1.4	-3.7	-27.0	-7.3	39.2	348.0
9,877.9	37.2	341.0	38.7	367.8	-1.5	-4.0	-26.8	-7.3	39.0	344.1
9,877.8	36.9	337.3	38.5	363.9	-1.6	-4.2	-26.6	-7.3	38.8	340.2
9,877.7	36.6	333.6	38.2	360.1	-1.6	-4.3	-26.5	-7.4	38.6	336.3
9,877.6	36.3	330.0	37.9	356.3	-1.6	-4.3	-26.3	-7.4	38.3	332.5
9,877.5	36.0	326.3	37.6	352.5	-1.6	-4.3	-26.2	-7.4	38.1	328.7

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,877.4	35.8	322.7	37.3	348.7	-1.5	-4.2	-26.0	-7.5	37.8	324.9
9,877.3	35.5	319.2	37.0	345.0	-1.5	-4.0	-25.8	-7.5	37.5	321.1
9,877.2	35.2	315.7	36.7	341.3	-1.4	-3.9	-25.7	-7.5	37.2	317.4
9,877.1	35.0	312.1	36.4	337.7	-1.4	-3.7	-25.6	-7.6	36.9	313.7
9,877.0	34.7	308.7	36.0	334.1	-1.3	-3.6	-25.4	-7.6	36.6	310.0
9,876.9	34.5	305.2	35.7	330.5	-1.3	-3.6	-25.3	-7.7	36.3	306.4
9,876.8	34.2	301.8	35.5	326.9	-1.3	-3.5	-25.2	-7.7	36.0	302.8
9,876.7	34.0	298.3	35.2	323.4	-1.2	-3.5	-25.0	-7.7	35.7	299.2
9,876.6	33.8	295.0	34.9	319.9	-1.2	-3.4	-24.9	-7.8	35.4	295.6
9,876.5	33.5	291.6	34.7	316.4	-1.1	-3.2	-24.8	-7.8	35.1	292.1
9,876.4	33.3	288.3	34.4	313.0	-1.1	-3.1	-24.7	-7.9	34.8	288.6
9,876.3	33.1	284.9	34.2	309.5	-1.0	-3.1	-24.6	-7.9	34.6	285.2
9,876.2	32.9	281.6	33.9	306.1	-1.0	-3.0	-24.5	-8.0	34.3	281.7
9,876.1	32.7	278.3	33.7	302.7	-1.0	-3.0	-24.4	-8.1	34.1	278.3
9,876.0	32.5	275.1	33.5	299.4	-1.0	-3.0	-24.3	-8.1	33.8	274.9
9,875.9	32.3	271.8	33.3	296.0	-1.0	-2.9	-24.2	-8.2	33.6	271.6
9,875.8	32.1	268.6	33.1	292.7	-9	-2.8	-24.1	-8.2	33.4	268.3
9,875.7	31.9	265.4	32.8	289.4	-9	-2.8	-24.0	-8.3	33.1	264.9
9,875.6	31.7	262.2	32.6	286.2	-9	-2.8	-23.9	-8.4	32.9	261.7
9,875.5	31.5	259.1	32.4	282.9	-9	-2.9	-23.8	-8.4	32.7	258.4
9,875.4	31.3	255.9	32.3	279.7	-9	-2.9	-23.7	-8.5	32.5	255.2
9,875.3	31.1	252.8	32.1	276.4	-1.0	-3.0	-23.6	-8.5	32.3	252.0
9,875.2	30.9	249.7	31.9	273.2	-1.0	-3.0	-23.5	-8.6	32.1	248.7
9,875.1	30.7	246.6	31.7	270.1	-1.0	-3.0	-23.4	-8.7	31.9	245.6
9,875.0	30.5	243.6	31.4	266.9	-9	-3.0	-23.3	-8.7	31.7	242.4
9,874.9	30.3	240.5	31.2	263.8	-1.0	-3.1	-23.2	-8.8	31.5	239.3
9,874.8	30.1	237.5	31.0	260.7	-1.0	-3.2	-23.1	-8.9	31.3	236.2
9,874.7	29.8	234.5	30.8	257.6	-1.0	-3.3	-23.1	-8.9	31.0	233.1
9,874.6	29.6	231.6	30.6	254.5	-1.0	-3.3	-22.9	-9.0	30.8	230.0
9,874.5	29.4	228.6	30.4	251.5	-1.0	-3.4	-22.8	-9.1	30.6	226.9

22 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach’s 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,874.4	29.2	225.7	30.2	248.4	-1.0	-3.4	-22.7	-9.2	30.4	223.9
9,874.3	29.0	222.8	30.0	245.4	-1.0	-3.3	-22.6	-9.2	30.2	220.9
9,874.2	28.8	219.9	29.8	242.4	-1.0	-3.3	-22.5	-9.3	30.0	218.0
9,874.1	28.7	217.0	29.6	239.4	-1.0	-3.3	-22.4	-9.4	29.7	215.0
9,874.0	28.5	214.1	29.4	236.5	-1.0	-3.3	-22.3	-9.5	29.5	212.1
9,873.9	28.3	211.3	29.3	233.6	-1.0	-3.3	-22.3	-9.5	29.3	209.2
9,873.8	28.1	208.5	29.1	230.6	-1.0	-3.4	-22.2	-9.6	29.1	206.3
9,873.7	27.9	205.7	28.9	227.7	-1.0	-3.4	-22.1	-9.7	28.8	203.5
9,873.6	27.7	202.9	28.7	224.9	-1.0	-3.5	-22.0	-9.8	28.6	200.6
9,873.5	27.6	200.1	28.5	222.0	-1.0	-3.5	-21.9	-9.8	28.3	197.8
9,873.4	27.4	197.4	28.4	219.1	-1.0	-3.5	-21.8	-9.9	28.1	195.1
9,873.3	27.2	194.7	28.2	216.3	-1.0	-3.7	-21.7	-10.0	27.8	192.3
9,873.2	27.0	191.9	28.1	213.5	-1.1	-3.8	-21.6	-10.1	27.6	189.5
9,873.1	26.8	189.3	27.9	210.7	-1.1	-4.0	-21.4	-10.2	27.3	186.8
9,873.0	26.6	186.6	27.8	207.9	-1.1	-4.1	-21.3	-10.3	27.0	184.1
9,872.9	26.4	183.9	27.6	205.1	-1.1	-4.2	-21.2	-10.3	26.8	181.5
9,872.8	26.2	181.3	27.4	202.4	-1.2	-4.3	-21.1	-10.4	26.5	178.8
9,872.7	26.0	178.7	27.2	199.7	-1.2	-4.3	-21.0	-10.5	26.2	176.2
9,872.6	25.8	176.1	27.0	197.0	-1.2	-4.5	-20.9	-10.6	26.0	173.6
9,872.5	25.6	173.5	26.8	194.3	-1.3	-4.7	-20.7	-10.7	25.7	171.1
9,872.4	25.4	171.0	26.7	191.6	-1.3	-4.9	-20.6	-10.8	25.5	168.5
9,872.3	25.1	168.5	26.5	188.9	-1.3	-5.1	-20.5	-10.8	25.2	166.0
9,872.2	24.9	166.0	26.3	186.3	-1.4	-5.3	-20.3	-10.9	25.0	163.5
9,872.1	24.6	163.5	26.1	183.7	-1.4	-5.5	-20.2	-11.0	24.8	161.1
9,872.0	24.4	161.0	25.9	181.1	-1.5	-5.9	-20.1	-11.1	24.6	158.7
9,871.9	24.1	158.6	25.7	178.5	-1.6	-6.2	-19.9	-11.1	24.3	156.3
9,871.8	23.8	156.2	25.5	175.9	-1.7	-6.6	-19.7	-11.2	24.1	153.9
9,871.7	23.6	153.8	25.3	173.4	-1.7	-6.7	-19.6	-11.3	23.9	151.5
9,871.6	23.4	151.5	25.1	170.9	-1.7	-6.8	-19.4	-11.4	23.7	149.2
9,871.5	23.2	149.1	24.9	168.4	-1.7	-6.8	-19.2	-11.4	23.5	146.9

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,871.4	23.0	146.8	24.7	165.9	-1.7	-6.9	-19.1	-11.5	23.3	144.6
9,871.3	22.8	144.6	24.4	163.4	-1.7	-6.8	-18.9	-11.6	23.1	142.3
9,871.2	22.6	142.3	24.2	161.0	-1.6	-6.7	-18.7	-11.6	22.9	140.0
9,871.1	22.3	140.0	23.9	158.6	-1.6	-6.7	-18.6	-11.7	22.7	137.8
9,871.0	22.1	137.8	23.7	156.2	-1.6	-6.8	-18.4	-11.8	22.5	135.5
9,870.9	21.9	135.6	23.5	153.9	-1.6	-6.9	-18.2	-11.9	22.3	133.3
9,870.8	21.7	133.4	23.4	151.5	-1.6	-7.0	-18.1	-11.9	22.1	131.1
9,870.7	21.5	131.3	23.2	149.2	-1.6	-7.1	-17.9	-12.0	21.9	129.0
9,870.6	21.4	129.1	23.0	146.9	-1.6	-7.1	-17.7	-12.1	21.7	126.8
9,870.5	21.2	127.0	22.8	144.6	-1.6	-7.1	-17.6	-12.2	21.5	124.6
9,870.4	21.0	124.9	22.6	142.3	-1.6	-7.2	-17.4	-12.2	21.3	122.5
9,870.3	20.7	122.8	22.4	140.1	-1.7	-7.4	-17.3	-12.3	21.1	120.4
9,870.2	20.6	120.7	22.2	137.8	-1.6	-7.4	-17.1	-12.4	20.9	118.3
9,870.1	20.4	118.7	22.0	135.6	-1.6	-7.4	-16.9	-12.5	20.7	116.2
9,870.0	20.2	116.7	21.8	133.4	-1.6	-7.3	-16.8	-12.6	20.5	114.2
9,869.9	20.1	114.7	21.6	131.3	-1.6	-7.3	-16.6	-12.7	20.3	112.2
9,869.8	19.9	112.7	21.4	129.1	-1.5	-7.1	-16.5	-12.7	20.0	110.2
9,869.7	19.7	110.7	21.2	127.0	-1.5	-6.9	-16.3	-12.8	19.8	108.2
9,869.6	19.6	108.7	21.0	124.9	-1.4	-6.7	-16.2	-12.9	19.6	106.2
9,869.5	19.4	106.8	20.8	122.8	-1.4	-6.7	-16.0	-13.0	19.5	104.2
9,869.4	19.2	104.8	20.6	120.7	-1.4	-6.7	-15.9	-13.2	19.3	102.3
9,869.3	19.1	102.9	20.5	118.7	-1.4	-6.8	-15.7	-13.3	19.1	100.5
9,869.2	18.9	101.0	20.3	116.6	-1.4	-6.9	-15.6	-13.4	18.9	98.6
9,869.1	18.7	99.13	20.1	114.6	-1.4	-7.0	-15.46	-13.5	18.7	96.8
9,869.0	18.6	97.27	20.0	112.6	-1.4	-7.0	-15.32	-13.6	18.6	94.9
9,868.9	18.4	95.42	19.8	110.6	-1.4	-7.0	-15.18	-13.7	18.4	93.1
9,868.8	18.3	93.59	19.6	108.6	-1.4	-7.1	-15.04	-13.8	18.2	91.4
9,868.7	18.1	91.77	19.5	106.7	-1.4	-7.1	-14.91	-14.0	18.0	89.6
9,868.6	17.9	89.97	19.3	104.7	-1.4	-7.1	-14.77	-14.1	17.8	87.9
9,868.5	17.8	88.18	19.1	102.8	-1.4	-7.2	-14.63	-14.2	17.6	86.2

24 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach’s 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,868.4	17.6	86.41	19.0	100.9	-1.4	-7.1	-14.49	-14.4	17.4	84.5
9,868.3	17.4	84.66	18.8	99.02	-1.4	-7.2	-14.36	-14.5	17.2	82.8
9,868.2	17.2	82.93	18.6	97.15	-1.4	-7.4	-14.22	-14.6	17.0	81.1
9,868.1	17.0	81.21	18.5	95.30	-1.4	-7.6	-14.08	-14.8	16.8	79.5
9,868.0	16.8	79.52	18.3	93.46	-1.5	-8.0	-13.94	-14.9	16.6	77.8
9,867.9	16.5	77.85	18.1	91.64	-1.6	-8.8	-13.79	-15.0	16.3	76.2
9,867.8	16.3	76.21	18.0	89.83	-1.7	-9.5	-13.62	-15.2	16.1	74.6
9,867.7	16.0	74.60	17.8	88.05	-1.8	-10.1	-13.45	-15.3	15.9	73.0
9,867.6	15.8	73.01	17.6	86.27	-1.9	-10.5	-13.26	-15.4	15.7	71.5
9,867.5	15.6	71.44	17.5	84.52	-1.9	-10.8	-13.08	-15.5	15.5	69.9
9,867.4	15.4	69.89	17.3	82.78	-1.9	-11.1	-12.89	-15.6	15.3	68.4
9,867.3	15.2	68.37	17.1	81.06	-1.9	-11.3	-12.69	-15.7	15.1	67.0
9,867.2	15.0	66.86	16.9	79.36	-2.0	-11.6	-12.50	-15.7	14.9	65.5
9,867.1	14.7	65.38	16.7	77.68	-1.9	-11.7	-12.30	-15.8	14.7	64.0
9,867.0	14.5	63.91	16.4	76.02	-1.9	-11.7	-12.11	-15.9	14.5	62.6
9,866.9	14.3	62.47	16.2	74.39	-1.9	-11.5	-11.92	-16.0	14.3	61.2
9,866.8	14.1	61.05	15.9	72.79	-1.8	-11.3	-11.74	-16.1	14.2	59.8
9,866.7	13.9	59.65	15.7	71.21	-1.7	-11.1	-11.56	-16.2	14.0	58.4
9,866.6	13.8	58.26	15.5	69.65	-1.7	-10.9	-11.39	-16.4	13.8	57.1
9,866.5	13.6	56.89	15.2	68.12	-1.6	-10.7	-11.22	-16.5	13.7	55.7
9,866.4	13.4	55.54	15.0	66.60	-1.6	-10.6	-11.06	-16.6	13.5	54.4
9,866.3	13.2	54.21	14.8	65.11	-1.6	-10.6	-10.90	-16.7	13.3	53.1
9,866.2	13.0	52.90	14.6	63.65	-1.6	-10.8	-10.75	-16.9	13.2	51.8
9,866.1	12.8	51.61	14.4	62.20	-1.6	-11.1	-10.59	-17.0	13.0	50.6
9,866.0	12.6	50.34	14.2	60.77	-1.6	-11.3	-10.43	-17.2	12.8	49.3
9,865.9	12.4	49.10	14.0	59.36	-1.6	-11.4	-10.27	-17.3	12.7	48.0
9,865.8	12.2	47.87	13.8	57.97	-1.6	-11.6	-10.11	-17.4	12.5	46.8
9,865.7	12.1	46.65	13.7	56.60	-1.6	-11.7	-9.95	-17.6	12.3	45.6
9,865.6	11.9	45.46	13.5	55.24	-1.6	-11.9	-9.79	-17.7	12.1	44.4
9,865.5	11.7	44.28	13.3	53.90	-1.6	-12.2	-9.63	-17.9	12.0	43.2
9,865.4	11.5	43.12	13.1	52.58	-1.7	-12.7	-9.46	-18.0	11.8	42.0
9,865.3	11.3	41.99	12.9	51.28	-1.7	-13.0	-9.29	-18.1	11.6	40.9

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,865.2	11.1	40.87	12.7	49.99	-1.7	-13.1	-9.12	-18.3	11.4	39.7
9,865.1	10.9	39.77	12.5	48.73	-1.6	-13.0	-8.96	-18.4	11.3	38.6
9,865.0	10.7	38.69	12.3	47.49	-1.6	-13.1	-8.80	-18.5	11.1	37.5
9,864.9	10.5	37.63	12.1	46.27	-1.6	-13.2	-8.64	-18.7	10.9	36.5
9,864.8	10.3	36.60	11.9	45.07	-1.6	-13.4	-8.48	-18.8	10.7	35.4
9,864.7	10.1	35.57	11.7	43.89	-1.6	-13.5	-8.32	-19.0	10.6	34.3
9,864.6	9.93	34.57	11.5	42.74	-1.55	-13.5	-8.16	-19.1	10.4	33.3
9,864.5	9.74	33.59	11.3	41.60	-1.52	-13.5	-8.01	-19.3	10.2	32.3
9,864.4	9.56	32.62	11.0	40.48	-1.49	-13.5	-7.86	-19.4	10.0	31.3
9,864.3	9.38	31.68	10.9	39.39	-1.47	-13.6	-7.71	-19.6	9.9	30.3
9,864.2	9.20	30.75	10.7	38.31	-1.47	-13.8	-7.56	-19.7	9.7	29.3
9,864.1	9.01	29.84	10.5	37.26	-1.48	-14.1	-7.42	-19.9	9.5	28.3
9,864.0	8.83	28.95	10.3	36.22	-1.48	-14.4	-7.27	-20.1	9.3	27.3
9,863.9	8.65	28.07	10.1	35.19	-1.46	-14.5	-7.12	-20.2	9.2	26.4
9,863.8	8.47	27.22	9.91	34.19	-1.44	-14.5	-6.98	-20.4	9.0	25.5
9,863.7	8.31	26.38	9.73	33.21	-1.41	-14.5	-6.83	-20.6	8.8	24.6
9,863.6	8.16	25.55	9.54	32.25	-1.38	-14.5	-6.69	-20.8	8.6	23.7
9,863.5	8.01	24.75	9.35	31.30	-1.33	-14.3	-6.56	-21.0	8.4	22.9
9,863.4	7.86	23.95	9.16	30.38	-1.29	-14.1	-6.43	-21.2	8.3	22.0
9,863.3	7.72	23.17	8.96	29.47	-1.24	-13.8	-6.30	-21.4	8.1	21.2
9,863.2	7.59	22.41	8.76	28.59	-1.17	-13.4	-6.18	-21.6	7.9	20.4
9,863.1	7.45	21.65	8.58	27.72	-1.12	-13.1	-6.07	-21.9	7.7	19.7
9,863.0	7.32	20.92	8.41	26.87	-1.09	-13.0	-5.96	-22.2	7.5	18.9
9,862.9	7.18	20.19	8.25	26.04	-1.07	-13.0	-5.85	-22.5	7.4	18.2
9,862.8	7.05	19.48	8.11	25.22	-1.05	-13.0	-5.74	-22.8	7.2	17.5
9,862.7	6.93	18.78	7.97	24.42	-1.03	-13.0	-5.64	-23.1	7.0	16.8
9,862.6	6.80	18.09	7.82	23.63	-1.02	-13.0	-5.53	-23.4	6.8	16.2
9,862.5	6.68	17.42	7.68	22.85	-1.00	-13.1	-5.43	-23.8	6.6	15.5
9,862.4	6.55	16.76	7.55	22.09	-1.00	-13.2	-5.33	-24.1	6.5	14.9
9,862.3	6.42	16.11	7.40	21.34	-.98	-13.3	-5.23	-24.5	6.3	14.3

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,862.2	6.28	15.47	7.26	20.61	-0.99	-13.6	-5.14	-24.9	6.2	13.6
9,862.1	6.13	14.85	7.14	19.89	-1.01	-14.1	-5.04	-25.3	6.0	13.0
9,862.0	5.98	14.25	7.02	19.18	-1.04	-14.8	-4.93	-25.7	5.8	12.4
9,861.9	5.83	13.66	6.90	18.49	-1.07	-15.5	-4.83	-26.1	5.7	11.9
9,861.8	5.67	13.08	6.77	17.80	-1.10	-16.2	-4.72	-26.5	5.5	11.3
9,861.7	5.51	12.52	6.65	17.13	-1.14	-17.2	-4.61	-26.9	5.4	10.8
9,861.6	5.35	11.98	6.53	16.47	-1.18	-18.0	-4.49	-27.3	5.2	10.3
9,861.5	5.19	11.45	6.40	15.83	-1.21	-18.9	-4.37	-27.6	5.0	9.8
9,861.4	5.03	10.94	6.26	15.19	-1.23	-19.7	-4.25	-28.0	4.9	9.3
9,861.3	4.87	10.45	6.12	14.57	-1.25	-20.4	-4.13	-28.3	4.7	8.9
9,861.2	4.70	9.969	5.97	13.97	-1.26	-21.2	-4.000	-28.6	4.5	8.5
9,861.1	4.52	9.508	5.81	13.38	-1.29	-22.2	-3.873	-28.9	4.3	8.1
9,861.0	4.32	9.066	5.64	12.81	-1.33	-23.5	-3.742	-29.2	4.1	7.7
9,860.9	4.11	8.644	5.48	12.25	-1.37	-25.0	-3.607	-29.4	4.0	7.3
9,860.8	3.91	8.243	5.33	11.71	-1.41	-26.5	-3.468	-29.6	3.8	7.0
9,860.7	3.72	7.861	5.17	11.19	-1.45	-28.1	-3.325	-29.7	3.6	6.6
9,860.6	3.51	7.500	5.01	10.68	-1.50	-29.9	-3.177	-29.8	3.4	6.3
9,860.5	3.33	7.158	4.85	10.18	-1.52	-31.4	-3.026	-29.7	3.3	6.0
9,860.4	3.16	6.834	4.67	9.708	-1.51	-32.3	-2.874	-29.6	3.1	5.7
9,860.3	2.99	6.526	4.48	9.250	-1.49	-33.2	-2.724	-29.4	3.0	5.4
9,860.2	2.84	6.235	4.26	8.813	-1.42	-33.3	-2.579	-29.3	2.9	5.2
9,860.1	2.71	5.957	4.05	8.398	-1.34	-33.1	-2.441	-29.1	2.7	4.9
9,860.0	2.58	5.693	3.82	8.004	-1.24	-32.4	-2.311	-28.9	2.6	4.6
9,859.9	2.47	5.440	3.62	7.633	-1.14	-31.6	-2.192	-28.7	2.5	4.4
9,859.8	2.39	5.197	3.43	7.280	-1.04	-30.4	-2.083	-28.6	2.4	4.2
9,859.7	2.30	4.963	3.27	6.946	-.97	-29.7	-1.983	-28.5	2.3	3.9
9,859.6	2.21	4.738	3.12	6.626	-.91	-29.2	-1.889	-28.5	2.2	3.7
9,859.5	2.13	4.521	2.99	6.321	-.87	-29.0	-1.800	-28.5	2.1	3.5
9,859.4	2.04	4.312	2.85	6.028	-.80	-28.2	-1.716	-28.5	2.1	3.3
9,859.3	1.97	4.112	2.71	5.751	-.74	-27.2	-1.639	-28.5	2.0	3.1

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,859.2	1.90	3.918	2.58	5.486	-0.68	-26.2	-1.569	-28.6	1.9	2.9
9,859.1	1.84	3.731	2.47	5.234	-.63	-25.6	-1.503	-28.7	1.8	2.7
9,859.0	1.78	3.549	2.38	4.991	-.59	-25.0	-1.442	-28.9	1.8	2.5
9,858.9	1.72	3.374	2.28	4.759	-.56	-24.4	-1.384	-29.1	1.7	2.3
9,858.8	1.66	3.205	2.19	4.535	-.53	-24.2	-1.330	-29.3	1.6	2.2
9,858.7	1.59	3.043	2.11	4.320	-.52	-24.5	-1.278	-29.6	1.5	2.0
9,858.6	1.53	2.887	2.03	4.113	-.50	-24.7	-1.227	-29.8	1.5	1.9
9,858.5	1.47	2.737	1.95	3.914	-.49	-24.8	-1.177	-30.1	1.4	1.7
9,858.4	1.41	2.593	1.88	3.723	-.47	-24.9	-1.130	-30.3	1.3	1.6
9,858.3	1.35	2.455	1.81	3.538	-.46	-25.5	-1.083	-30.6	1.3	1.5
9,858.2	1.29	2.323	1.75	3.360	-.46	-26.0	-1.037	-30.9	1.2	1.3
9,858.1	1.24	2.196	1.69	3.188	-.45	-26.4	-.992	-31.1	1.2	1.2
9,858.0	1.19	2.074	1.62	3.022	-.43	-26.6	-.948	-31.4	1.1	1.1
9,857.9	1.15	1.957	1.56	2.864	-.41	-26.3	-.906	-31.6	1.1	1.0
9,857.8	1.10	1.845	1.49	2.711	-.39	-26.2	-.866	-32.0	1.0	.9
9,857.7	1.05	1.737	1.43	2.565	-.37	-26.2	-.828	-32.3	1.0	.8
9,857.6	1.01	1.634	1.37	2.425	-.362	-26.4	-.791	-32.6	.9	.7
9,857.5	.964	1.536	1.31	2.291	-.343	-26.2	-.756	-33.0	.9	.6
9,857.4	.919	1.441	1.25	2.164	-.333	-26.6	-.722	-33.4	.8	.6
9,857.3	.870	1.352	1.20	2.041	-.332	-27.6	-.689	-33.8	.8	.5
9,857.2	.821	1.267	1.15	1.923	-.333	-28.9	-.656	-34.1	.7	.4
9,857.1	.776	1.187	1.11	1.810	-.332	-29.9	-.622	-34.4	.7	.4
9,857.0	.732	1.112	1.06	1.702	-.327	-30.9	-.590	-34.6	.7	.3
9,856.9	.689	1.041	1.01	1.598	-.322	-31.8	-.557	-34.9	.6	.2
9,856.8	.653	.974	.966	1.499	-.313	-32.4	-.525	-35.0	.6	.2
9,856.7	.619	.911	.921	1.405	-.302	-32.8	-.495	-35.2	.5	.1
9,856.6	.588	.850	.872	1.315	-.284	-32.6	-.465	-35.4	.5	.1
9,856.5	.557	.793	.825	1.231	-.268	-32.5	-.438	-35.6	.5	.1
9,856.4	.525	.739	.782	1.150	-.256	-32.8	-.411	-35.8	.4	0
9,856.3	.498	.688	.738	1.074	-.240	-32.6	-.387	-36.0	.4	0

28 Sedimentation in Goose Pasture Tarn, 1965–2005, Breckenridge, Colorado

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

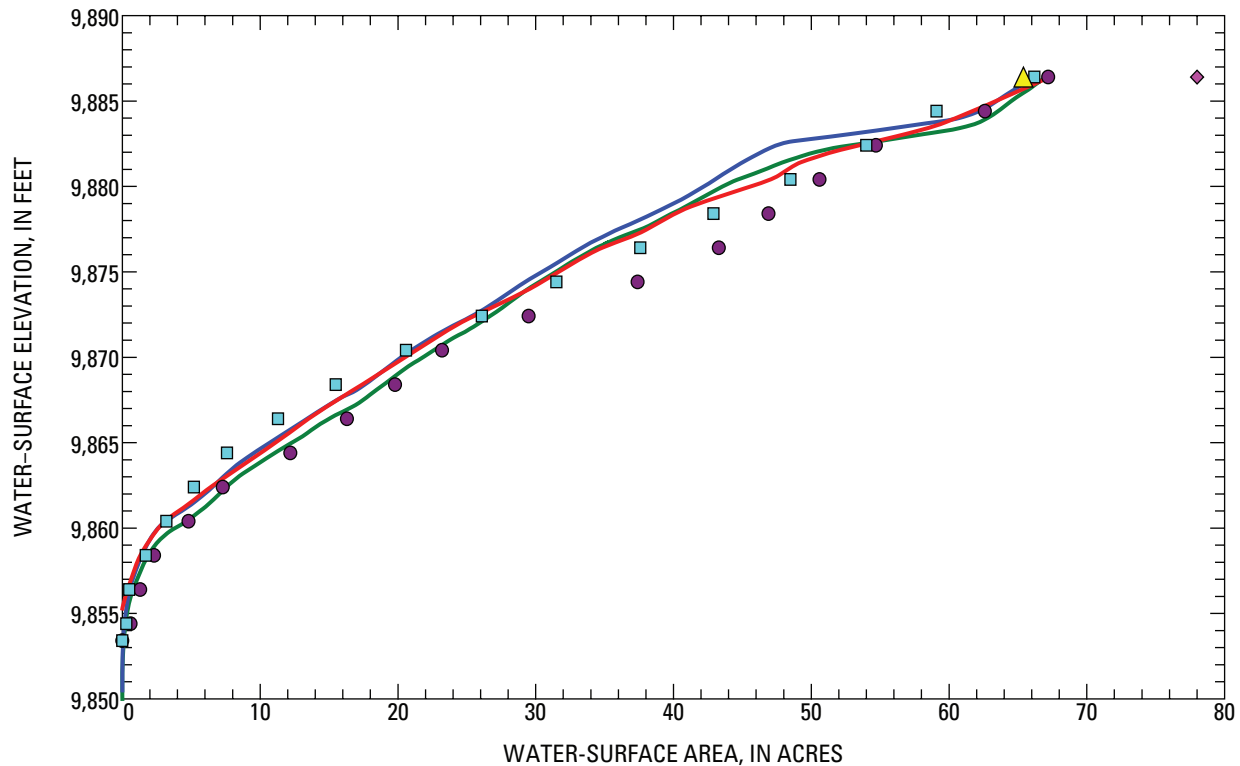
[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach’s 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,856.2	0.470	0.639	0.693	1.003	-0.222	-32.1	-0.363	-36.2	0.3	0
9,856.1	.443	.594	.655	.935	-.211	-32.3	-.342	-36.5	.3	0
9,856.0	.419	.550	.620	.872	-.200	-32.3	-.321	-36.9	.3	0
9,855.9	.399	.510	.585	.812	-.187	-31.9	-.302	-37.2	.2	0
9,855.8	.379	.471	.551	.755	-.172	-31.2	-.284	-37.6	.2	0
9,855.7	.361	.434	.517	.701	-.157	-30.3	-.268	-38.2	.1	0
9,855.6	.343	.399	.487	.651	-.145	-29.7	-.253	-38.8	.1	0
9,855.5	.326	.365	.461	.604	-.135	-29.3	-.230	-39.5	.1	0
9,855.4	.308	.334	.433	.559	-.125	-28.9	-.226	-40.3	.1	0
9,855.3	.290	.304	.409	.517	-.120	-29.2	-.213	-41.3	0	0
9,855.2	.270	.276	.388	.477	-.118	-30.4	-.202	-42.2		
9,855.1	.251	.250	.368	.439	-.117	-31.8	-.190	-43.2		
9,855.0	.231	.226	.349	.404	-.118	-33.8	-.178	-44.1		
9,854.9	.209	.203	.331	.370	-.122	-36.8	-.166	-44.9		
9,854.8	.185	.184	.312	.337	-.127	-40.8	-.154	-45.5		
9,854.7	.163	.166	.292	.307	-.129	-44.1	-.141	-45.8		
9,854.6	.148	.151	.271	.279	-.123	-45.5	-.128	-45.9		
9,854.5	.135	.137	.251	.253	-.116	-46.3	-.116	-45.9		
9,854.4	.125	.124	.230	.229	-.105	-45.8	-.105	-45.9		
9,854.3	.116	.112	.207	.207	-.091	-43.9	-.095	-46.0		
9,854.2	.108	.101	.183	.187	-.075	-41.2	-.087	-46.3		
9,854.1	.099	.090	.166	.170	-.067	-40.1	-.080	-46.9		
9,854.0	.091	.081	.153	.154	-.062	-40.4	-.073	-47.6		
9,853.9	.083	.072	.140	.140	-.057	-40.7	-.068	-48.4		
9,853.8	.076	.064	.128	.126	-.053	-41.0	-.062	-49.2		
9,853.7	.069	.057	.119	.114	-.050	-41.9	-.057	-50.0		
9,853.6	.063	.050	.110	.102	-.047	-43.0	-.052	-50.9		
9,853.5	.056	.044	.102	.092	-.045	-44.6	-.048	-51.7		
9,853.4	.050	.039	.093	.082	-.043	-46.1	-.043	-52.4		
9,853.3	.044	.034	.084	.073	-.041	-48.2	-.039	-53.1		

Table 2. Reservoir surface area and capacity of Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; acre-ft, acre-feet; %, percent; full-pool water-surface elevation 9,886.4 ft; Res Engr, Resource Engineering estimates; Resource Engineering, Inc. (2002) study converted Tipton and Kalmbach's 1987 spillway elevation from 9,882 ft to 9,886.4 ft to coincide with NAVD 88 datum]

Water-surface elevation (ft)	2005		1965		1965–2005				2002	
	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Reservoir surface area (acres)	Reservoir capacity (acre-ft)	Change in surface area (acres)	Change in surface area (%)	Change in reservoir capacity (acre-ft)	Change in reservoir capacity (%)	Surface area Res Engr (acres)	Reservoir capacity Res Engr (acre-ft)
9,853.2	0.037	0.030	0.077	0.065	-0.039	-51.3	-0.035	-53.5		
9,853.1	.032	.027	.070	.058	-.038	-53.8	-.031	-53.6		
9,853.0	.028	.024	.063	.051	-.035	-55.1	-.027	-53.5		
9,852.9	.025	.021	.057	.045	-.032	-55.8	-.024	-53.2		
9,852.8	.023	.019	.051	.040	-.029	-55.9	-.021	-52.8		
9,852.7	.021	.017	.045	.035	-.024	-54.3	-.018	-52.5		
9,852.6	.019	.015	.039	.031	-.020	-51.8	-.016	-52.4		
9,852.5	.017	.013	.034	.027	-.016	-48.7	-.014	-52.7		
9,852.4	.016	.011	.029	.024	-.013	-45.7	-.013	-53.4		
9,852.3	.015	.010	.025	.021	-.011	-42.4	-.012	-54.6		
9,852.2	.013	.008	.022	.019	-.009	-39.4	-.011	-56.3		
9,852.1	.012	.007	.020	.017	-.008	-39.6	-.010	-58.4		
9,852.0	.011	.006	.019	.015	-.007	-40.7	-.009	-60.7		
9,851.9	.010	.005	.017	.013	-.007	-42.2	-.008	-63.4		
9,851.8	.009	.004	.016	.012	-.007	-44.0	-.008	-66.3		
9,851.7	.008	.003	.015	.010	-.007	-46.3	-.007	-69.6		
9,851.6	.007	.002	.014	.009	-.007	-49.1	-.006	-73.1		
9,851.5	.006	.002	.012	.007	-.007	-52.8	-.006	-77.1		
9,851.4	.005	.001	.011	.006	-.007	-57.5	-.005	-81.4		
9,851.3	.004	.001	.010	.005	-.007	-64.2	-.004	-85.7		
9,851.2	.002	0	.009	.004	-.007	-73.3	-.004	-89.7		
9,851.1	.002	0	.008	.003	-.007	-80.6	-.003	-93.0		
9,851.0	.001	0	.007	.002	-.006	-87.2	-.002	-95.6		
9,850.9	0	0	.006	.002	-.006	-91.9	-.002	-97.7		
9,850.8	0	0	.005	.001	-.005	-95.9	-.001	-99.2		
9,850.7	0	0	.004	0	-.004	-99.0	-.001	-99.9		
9,850.6	0	0	.003	0	-.003	-100.0	-0	-100.0		
9,850.5	0	0	.002	0	-.002	-100.0	-0	-100.0		
9,850.4			.001	0						



EXPLANATION

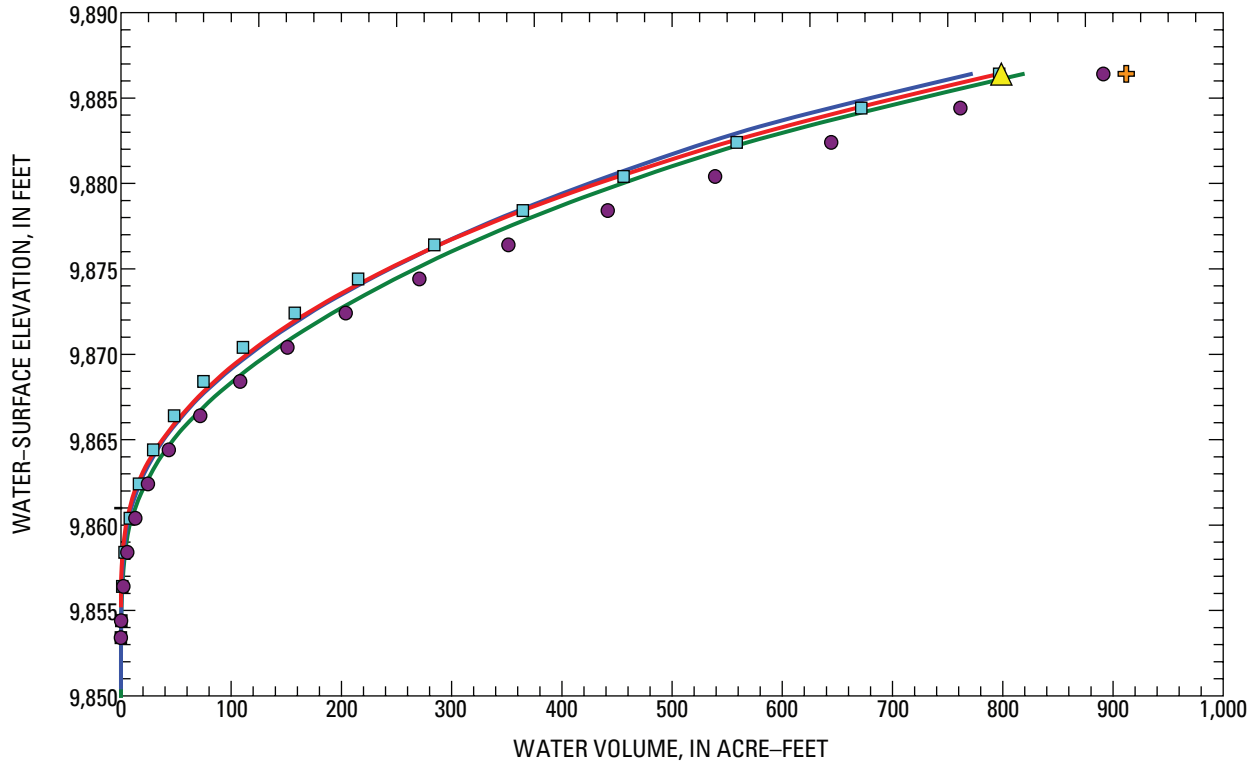
- 1965 (U.S. Geological Survey, this report)
- 2002 (Resource Engineering, Inc., 2002)
- 2005 (U.S. Geological Survey, this report)
- ◆ 1965 (Tipton and Kalmbach, 1987)
- ▲ 1982 (Lewis and others, 1982)
- 1983 (Tipton and Kalmbach, 1987)
- 1991 (WRC Engineering, 1991, *in* Resource Engineering, Inc., 2002)

Figure 9. Reservoir stage and water-surface area.

Engineering study are in close agreement at most elevations except from about 9,881.8 to about 9,882.8 ft. This elevation range corresponds to a water depth of about 3.6 to 4.6 ft when the reservoir is filled to capacity at full pool. *Elodea sp.* growth in shallow-water areas was noted as a problem in the Resource Engineering study and was a problem with this study when bathymetric measurements were first attempted in August 2004. The differences between the two studies could be attributed largely to poor bathymetric definition in this narrow zone because, with the low streamflow levels occurring in the intervening years, sediment deposition was unlikely on the scale needed to explain the differences between the two studies. Elevation-capacity values from this study and the Resource Engineering study are in very close agreement below approximately 9,880 ft.

Several previous studies made estimates of original and subsequent reservoir surface area and capacities and were

discussed in the “Previous Investigations” section of this report. The 1964 map of the proposed dam and impoundment area indicated that the reservoir’s projected capacity would be 912 acre-ft at the spillway elevation (Ketchum, Konkel, Ryan, and Fleming Consulting Engineers, Inc., 1964, *in* Resource Engineering, Inc., 2002), and a subsequent study estimated the 1965 surface area to be 78 acres (Tipton and Kalmbach Consulting Engineers, Inc., 1987, *in* Resource Engineering, Inc., 2002). The original surface-area estimate appears to be overstated compared to more recent estimates of the reservoir area (fig. 9). Tipton and Kalmbach’s (1987) estimated 1965 area is 10.9 acres (16 percent) greater than the reconstructed 1965 surface area from this report (67.1 acres), a discrepancy possibly caused by the earlier reliance on a map drawn with 10-ft contour lines. The preconstruction estimate of the original reservoir capacity, 912 acre-ft (Ketchum, Konkel, Ryan, and Fleming Consulting Engineers, Inc., 1964), also appears



EXPLANATION

- 1965 (U.S. Geological Survey, this report)
- 2002 (Resource Engineering, Inc., 2002)
- 2005 (U.S. Geological Survey, this report)
- + 1964 (Ketchum, Konkell, Ryan, and Fleming, 1964, *in* Resource Engineering, Inc., 2002)
- ▲ 1982 (Lewis and others, 1982)
- 1983 (Tipton and Kalmbach, 1987)
- 1991 (WRC Engineering, 1991, *in* Resource Engineering, Inc., 2002)

Figure 10. Reservoir stage and capacity.

to be overstated (fig. 10). The 1964 estimate of original reservoir capacity is 94 acre-ft (11 percent) greater than the reconstructed 1965 capacity from this report, a discrepancy that, again, could be caused by reliance on the early map with 10-ft contour lines.

The 1991 study of reservoir depth done by WRC Engineers (Resource Engineering, Inc., 2002, *in* Resource Engineering, Inc., 2002) was based on 159 survey points. The 1991 study determined the reservoir surface area to be 67.2 acres, similar to all other surface-area estimates except that of the 1965 estimate (fig. 9); however, the 1991 study estimated the reservoir capacity to be 891.4 acre-ft, noticeably different than most other capacity calculations (fig. 10). The discrepancy between the 1991 capacity estimate and other estimates could be due to the relatively small number of bathymetric points used to map the reservoir-bed topography.

Sediment Volume in Goose Pasture Tarn

The volume of sediment that has accumulated in Goose Pasture Tarn since the reservoir was completed in 1965 was estimated from seismic profiling and manual probing with a graduated rod. Data from the seismically profiled, postreservoir sediment thickness in Goose Pasture Tarn and data from the probed, postreservoir sediment thickness in the deltas were merged in GIS to create combined point data of reservoir-sediment thickness. Seismically profiled data that overlapped probed delta data were removed in this process. The merged point data were used in a Natural Neighbors interpolation to generate a sediment-thickness surface (Environmental Systems Research Institute, Inc., 2004b). The resultant surface then was used in a cut/fill analysis (Environmental Systems Research Institute, Inc., 2004c) to calculate total sediment volume in the

reservoir. No attempt was made to determine the accumulated sediment mass because density measurements were not made (Lara and Pemberton, 1965), and density appeared to vary greatly from the cored reservoir sediment to the excavated deltaic material.

The sediment volume determined from seismic profiling and delta probing included sediment that had accumulated in the reservoir as well as material that had accumulated on the exposed parts of the deltas, above the 9,866.4-ft water-surface elevation of the full reservoir. The total sediment volume accumulated since 1965 in Goose Pasture Tarn and in the Blue River and Indiana Creek deltas is approximately 47.5 acre-ft.

The difference between the area-capacity curves estimated for 1965 and measured in 2005, described in the previous “Reservoir Area and Capacity” section, was 46.9 acre-ft (table 2). This difference is another estimate of the accumulated sediment volume but accounts only for sediment below the full-pool water surface. The 0.6-acre-ft difference between 46.9 and 47.5 acre-ft is the approximate volume of sediment in the two deltas that is visible above the full-pool water surface and accounts for 1.3 percent of all deposited sediment. Aerial photographic analysis of the accumulated exposed delta areas, discussed in the “Aerial Photography Interpretation, 1968 to 2005” section, indicated a total delta area of 0.9 acre (fig. 7), and a simple calculation gives a mean delta thickness of about 0.6 to 0.7 ft. Greater sediment thicknesses were found by probing, but probing attempts were intentionally concentrated in thicker delta areas to determine the maximum sediment thickness.

The sediment in Goose Pasture Tarn has accumulated by two fluvial mechanisms. Low streamflow and nonflood discharges occur frequently (fig. 4) but transport a small volume of finer sediment, as indicated by the suspended-load and bedload data collected in 2004 and 2005 (table 1). Intermittent flood discharges, like the flood on June 18, 1995, are short lived but deliver larger amounts of fine and coarse sediment and may be responsible for noticeable and abrupt increases in delta areas (figs. 3 and 6). Over the past 40 years, an average of 1.19 acre-ft/yr of sediment, mostly in the silt- and sand-size range, has accumulated in Goose Pasture Tarn. The 2005 reservoir capacity is 771.1 acre-ft (table 2). If the future average sediment delivery rate to Goose Pasture Tarn is comparable to the past 40 years, the reservoir has many years of useful life remaining. However, changes in the watershed related to climate, land use, and especially large-scale, severe forest fires can increase sediment loads by orders of magnitude and greatly shorten the useful life of reservoirs (Elliott and Parker, 2001; Moody and Martin, 2001; Elliott and others, 2005).

Lacustrine Sediment Particle Size

Twenty sediment cores collected in Goose Pasture Tarn were used to determine postreservoir sediment accumulation and to calibrate the seismic profile thicknesses, as described

in the “Lacustrine Sediment Coring and Analysis” section of this report (fig. 5). Material from some of these sediment cores also was analyzed for particle-size distribution and for a sediment-chemistry inventory. Sediment chemistry is discussed in the following section of the report. Particle-size analyses were performed on sediment from five cores extracted from the reservoir bed in deepwater areas and from shallow areas near the deltas. Particle-size analyses also were performed on surficial sediment sampled on the Blue River and Indiana Creek deltas when the water surface was temporarily drawn down. The stratigraphy of the delta deposits also was examined in pits excavated when the water surface was drawn down.

Sediment core 6 (fig. 11C) was extracted from a deep-water area near the north shore of Goose Pasture Tarn and may be typical of postreservoir sediment deposited in other deep-water areas of the reservoir. The sediment thickness of core 6 was 0.55 ft. Black medium silt (median grain size 0.013 mm) was found 0.10 to 0.55 ft below the bed of the reservoir, and a brown, low-density, very-fine silt (median grain size 0.005 mm) was resting on top of the black medium silt (fig. 11C). Both strata were composed of at least 35 percent clay-size material.

Sediment core 1 (fig. 11A) was located approximately 130 ft northeast of the south reservoir shoreline and approximately 200 ft northwest of the exposed part of the Blue River delta (fig. 5) and showed distinct stratigraphic layers that were analyzed separately. The sediment thickness in core 1 was 1.68 ft. Sediment from the bottom of core 1 (1.4 to 1.6 ft beneath the contemporary reservoir bed) was a grey-black, mottled, medium silt (median grain size 0.014 mm) resting on the former, preinundation land surface (fig. 11A). Immediately on top of the mottled silt and 0.9 to 1.4 ft beneath the reservoir bed was a black, organic-rich, medium silt (median grain size 0.012 mm). Above the silt layers was a brown, very coarse sand deposit (median grain size 1.35 mm) 0.3 to 0.9 ft below the current reservoir bed. Both silt layers are interpreted to be sediments deposited in relatively calm water and were similar in size to deepwater sediments like core 6. Deposition of the very coarse sand on top of the silt layers could represent a storm deposit or the redirection of one of the Blue River inflow channels transporting sandy bedload.

Sediment of the Blue River delta was excavated by hand on May 21, 2004, when the reservoir was drawn down for dam maintenance. Excavation revealed 1.6 ft of deltaic sediment deposited on top of a blue-gray, sandy gravel believed to be a buried stream-channel deposit. This delta sediment was composed of alternating layers of black and grey silt, organic material, and a medium yellow sand. Material on top of the delta at this location was a brown, very fine sand (median grain size 0.080 mm) (fig. 12A).

Sediment core 9 (fig. 11D) was located at the north distal margin of the Indiana Creek delta in approximately 4.5 ft of water at full pool (fig. 5). The thickness of core 9 was 1.6 ft, and sediment from the core showed distinct stratification by particle size and color. Sediment from the bottom of the core, 1.6 to 1.3 ft below the reservoir bed, was a brown,

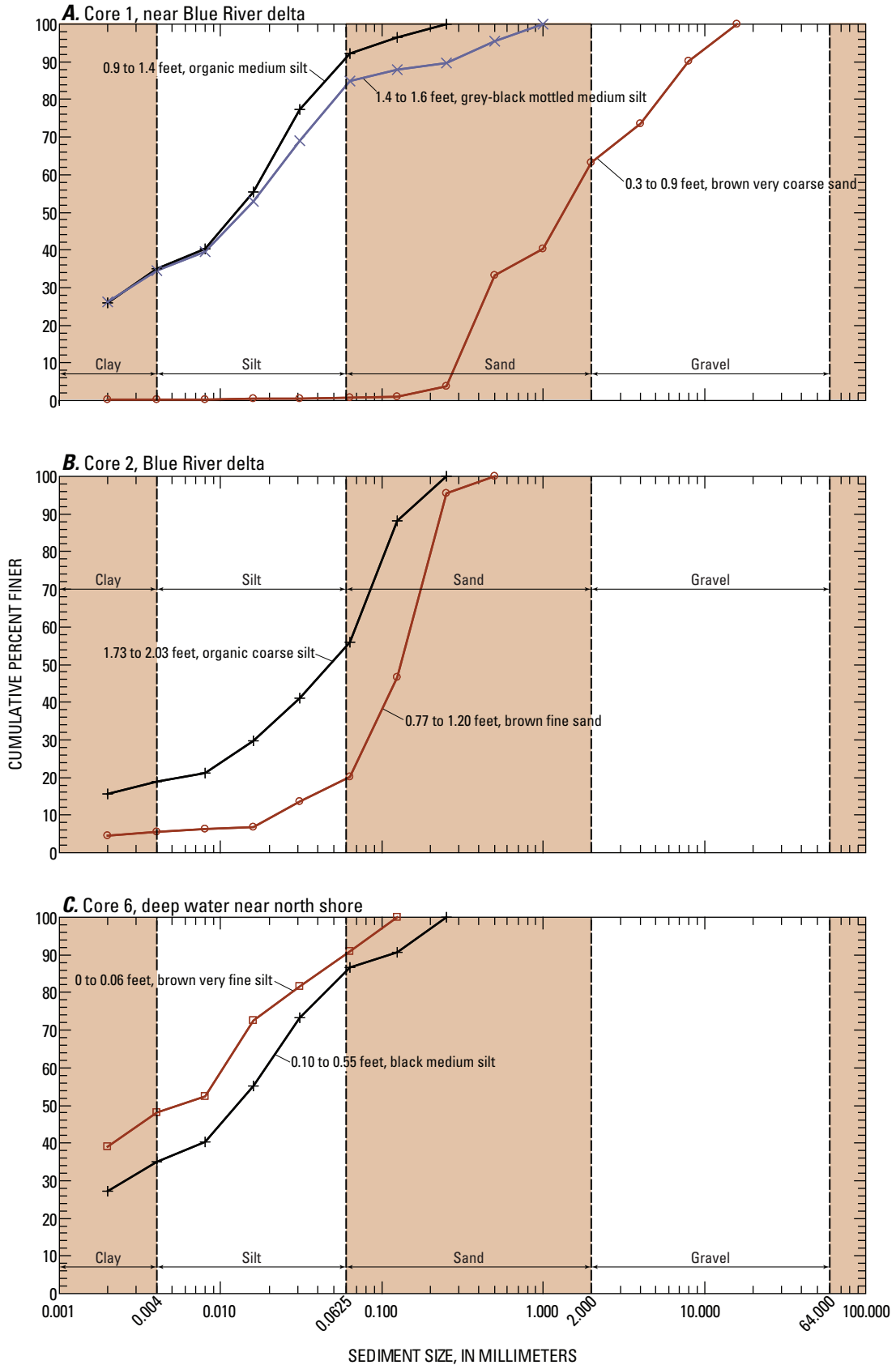


Figure 11. Cumulative sediment-size distribution of cores extracted from Goose Pasture Tarn.

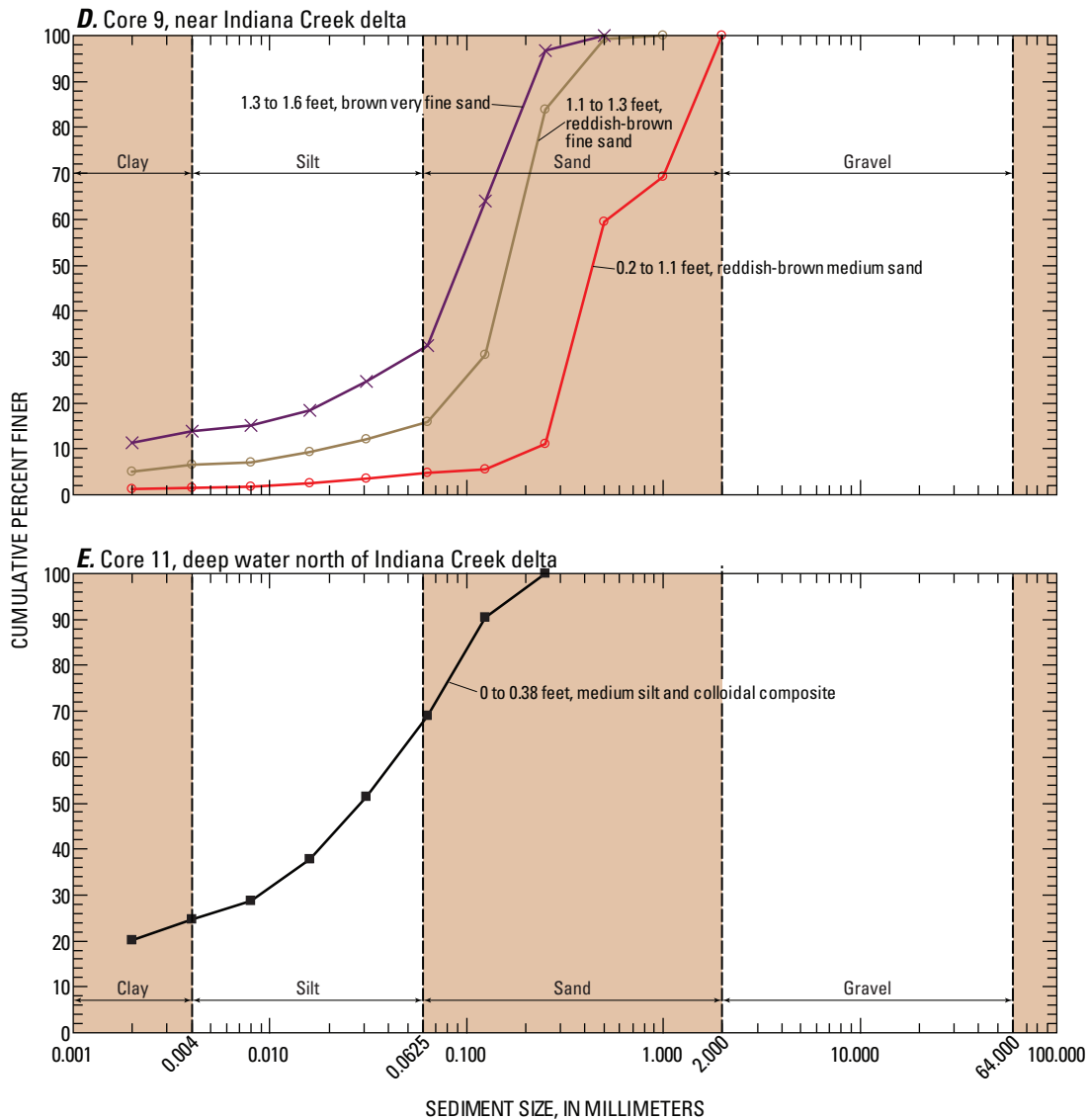


Figure 11. Cumulative sediment-size distribution of cores extracted from Goose Pasture Tarn.—Continued

very fine sand (median grain size 0.09 mm) including about 33 percent silt- and clay-size material (particle sizes less than 0.0625 mm) (fig. 11D). Two more layers of sand with decreasing amounts of silt- and clay-size material rested on top of the lowest layer—a reddish-brown, fine sand (median grain size 0.16 mm) from 1.1 to 1.3 ft beneath the bed surface, and a reddish-brown, medium sand (median grain size 0.44 mm) from 0.2 to 1.1 ft beneath the bed surface. The lowest layer is interpreted to be sediment deposited in relatively calm water, whereas the two superimposed sand layers are probably stream deposits.

The Indiana Creek delta was excavated by hand on May 21, 2004, when the reservoir was drawn down for dam maintenance. Excavation revealed 1.6 ft of deltaic sediment deposited on top of a brown sandy gravel with large cobbles, interpreted to be a buried stream-channel deposit. The Indiana Creek deltaic sediment had a distinct pattern of alternating black,

sandy silt and dark-brown or reddish-brown sand. Material on the exposed surface of the delta at this location was medium sand (median grain size 0.35 mm) (fig. 12C). This sequence is interpreted to represent alternating cycles of suspended-sediment deposition in calm water and bedload deposition of sand from Indiana Creek.

Lacustrine Sediment Chemistry

Reservoir sediment from four cores was analyzed for inorganic chemical constituents to better understand and assess the distribution and concentration of trace elements in the sediment. Most of the cores showed stratification by sediment-particle size, indicative of different depositional dates or mechanisms. Therefore, three of the four cores selected for chemical analysis were subsampled according to stratigraphy.

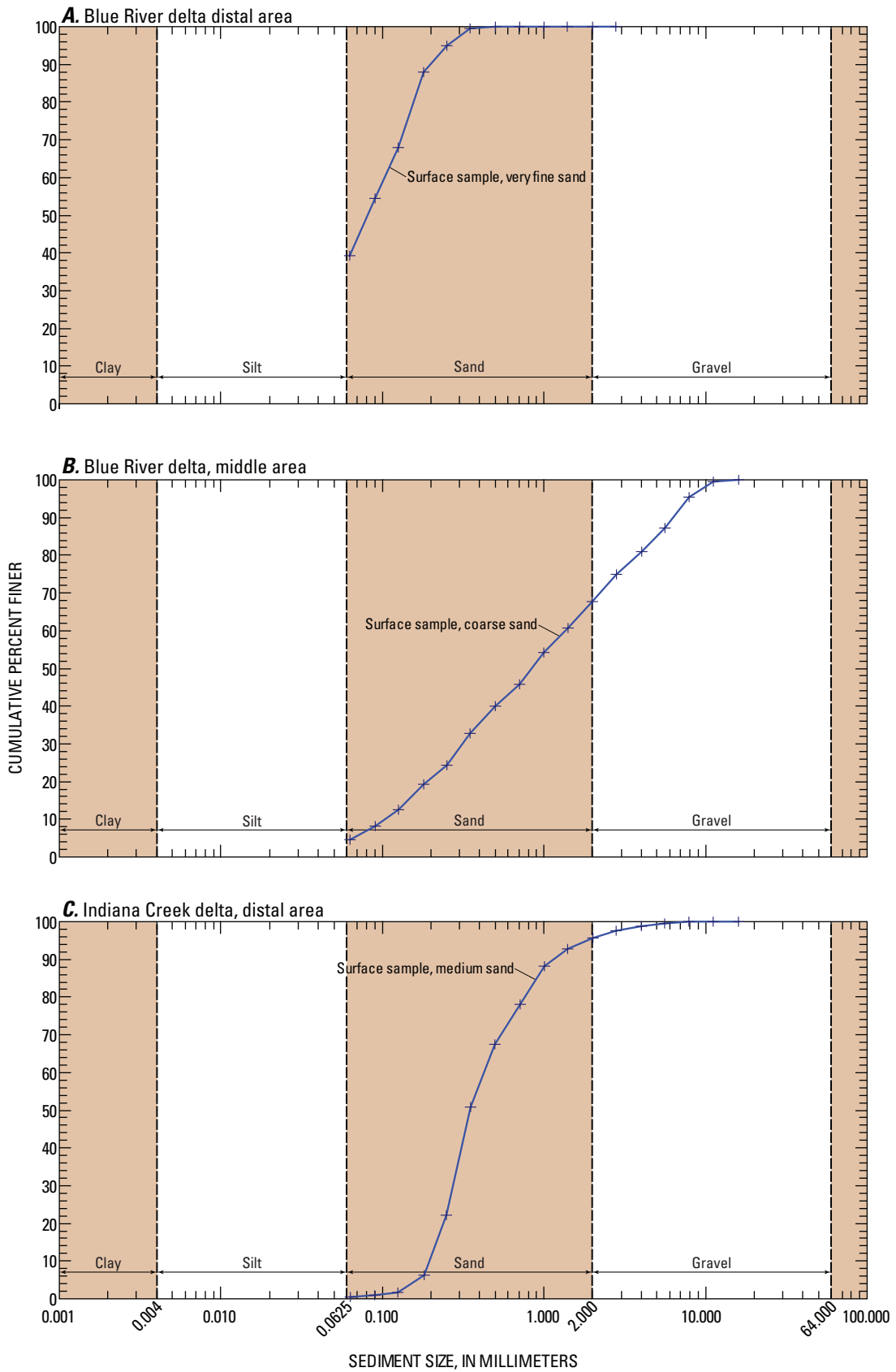


Figure 12. Cumulative sediment-size distribution of surficial sediment excavated from delta areas.

The fourth core (core 11) was 0.38 ft long, did not show stratification, and was analyzed as a single sample.

The four cores represented different depositional environments in Goose Pasture Tarn (fig. 5). Core 6 was collected from deep water (greater than about 20 ft) near the north shore of the tarn. The stratified silt and clay from core 6 (fig. 11C) is representative of fine sediments deposited in relatively calm water. Core 11 was collected from deep water (greater than about 23 ft) north of the Indiana Creek delta and near the east shore of the reservoir. The silt and clay in core 11 were unstratified but representative of fine sediments deposited in relatively calm water. Core 1 was collected in shallow water approximately 200 ft from the Blue River inflow and contained both silt and sand layers. The sand and possibly the silt were delivered to the reservoir by one of the numerous inflow channels of the Blue River (fig. 6). Core 9 was collected in shallow water from submerged delta deposits near the mouth of Indiana Creek. The stratified sand in core 9 originated from Indiana Creek.

Core sediment samples were sieved, and the fraction finer than 2.0 mm was analyzed for metals and trace constituents. The USGS Geologic Discipline Geochemistry Analytical Laboratory in Denver, Colorado, analyzed the sediment samples for 47 trace elements, including major, minor, and rare earth elements. The vast majority of elements were determined by inductively coupled plasma-atomic emission spectroscopy (ICP–AES). Digestion methods used for both ICP–AES and for the few elements measured using atomic-absorption spectroscopy (AAS) were by total acid digestion, which provides the highest recovery of elemental concentrations during analyses and includes the crystal mineral fraction, which may not represent the bioavailable fraction (Abrogast, 1990). Metal and constituent levels from the cores were compared with three standards: (1) the maximum background level of sediments in the Southern Rocky Mountains (V.C. Stephens, USGS, written commun., 2005), (2) the Threshold Effect Concentration (MacDonald and others, 2000), and (3) the Probable Effect Concentration (MacDonald and others, 2000) (table 3).

Background levels of metals and trace constituents for Southern Rocky Mountain region stream sediments were determined as part of the Colorado River National Water-Quality Assessment (NAWQA) Program. These levels were derived from bed-sediment samples collected from 14 streams in the Southern Rocky Mountain physiographic province that had no substantial effects from mining, urban development, silviculture, or agriculture and, therefore, were considered to be representative of the highest natural background conditions in the region. For the purposes of this report, maximum background concentration is defined as a concentration representing low-level effects from anthropogenic sources. Because many of the trace elements of environmental concern are distributed by atmospheric deposition and historical mining activities, it is difficult to establish true background (prior to anthropogenic effects) levels; therefore, the term “background” is defined as a concentration with minimal anthropogenic enrichment.

Knowledge of a range of natural trace element background levels within a regional setting provides a frame of reference for assessing changes that might be related to enrichment. For comparative purposes in this report, background levels of metals and trace constituents were derived by selecting 16 streambed samples collected as a part of the USGS National Water-Quality Assessment (NAWQA), with watersheds located in the Southern Rocky Mountain physiographic province that represent no substantial effects from mining or urban development. These samples were considered to be representative of the highest natural background conditions within the same physiographic region and were analyzed using identical methods. If multiple samples were collected from a site, the sample collected first in time was retained for the highest background determination. These data are available in the USGS NAWQA Data Warehouse (<http://infotrek.er.usgs.gov/>; search by “Southern Rocky Mountain physiographic province” and “land use”).

The Threshold Effect Concentration (TEC) is a freshwater sediment guideline for which lesser concentrations are not expected to show harmful effects, whereas the Probable Effect Concentration (PEC) is a guideline above which harmful effects to benthic invertebrate communities are likely to be observed (MacDonald and others, 2000). These guidelines are threshold values that have no regulatory status but are issued in an advisory capacity to protect aquatic-life resources. The consensus-based guidelines were developed by calculating the geometric means of three or more other guideline values developed by different entities using various approaches for a particular contaminant (Ingersoll and others, 2000). The development of TEC and PEC guidelines by combining other theoretical and empirically derived guidelines into one value creates a simple index of potential biological effects. Ingersoll and others (2000) found that the predictive ability of the consensus-based TECs and PECs was accurate greater than or equal to 75 percent of the time for all metals for which a TEC or PEC had been calculated, with the exception of mercury.

Metals and trace constituents equal to or exceeding the three reference benchmarks are highlighted for emphasis in table 3. Silver, cadmium, europium, lead, and zinc were detected in concentrations greater than Southern Rocky Mountain background levels in all four sediment cores, and cadmium, lead, and zinc levels also were equal to or exceeded the TEC standards in these cores. The only metal exceeding the PEC standard was lead detected in silt from cores 1 (Blue River delta) and 6 (deepwater near north shore) (fig. 5). Tin was detected at concentrations greater than Southern Rocky Mountain background levels in three cores 1, 6, and 11 (deepwater near east shore), and chromium and copper levels also were equal to or exceeded the TEC standards in these cores. Other constituents exceeding background level and TEC standards were detected in the cores. The elevated values were detected more often, but not exclusively, in the silt layers than in the sand layers.

Table 3. Results of sediment-core particle-size and trace-constituent analysis of sample cores from Goose Pasture Tarn near Breckenridge, Colorado.

[ft, feet; mm, millimeters; ppm, parts per million; na, data or standard not available or not presented. <, less than; green highlight, values greater than maximum background levels for stream sediment in the Southern Rocky Mountains (V.C. Stephens, U.S. Geological Survey, oral commun., 2005); orange highlight, values at or above TEC, Threshold Effect Concentration, lesser values not expected to be toxic (MacDonald and others, 2000); pink highlight, values at or above PEC, Probable Effect Concentration, greater values likely to be toxic (MacDonald and others, 2000)]

Sedi-ment core number (fig. 5)	Strata sampled below bed (ft)	Sediment finer than 0.063 mm (percent)	Median sediment particle size (mm)	Sediment wet color	Sediment description	Alumi-num (Al) (per-cent)	Antimo-ny (Sb) (ppm)	Arsenic (As) (ppm)	Bar-ium (Ba) (ppm)	Berylli-um (Be) (ppm)	Bismuth (Bi) (ppm)	Cad-mium (Cd) (ppm)	Calcium (Ca) (percent)
Site number 392658106020501, Blue River deltaic deposit (west of Blue River delta, near south shore)													
1	0 to 0.1	na	na	Dark	Silt	6.9	0.33	6.4	760	4.4	<1	1.6	0.80
	0.3 to 0.9	0.75	1.350	Brown	Very coarse sand	5.3	.16	2.4	750	2.0	<1	.14	.35
	0.9 to 1.4	92.3	.012	Dark organic	Medium silt	7.5	.46	6.3	740	4.2	1	2.3	.86
	1.4 to 1.6	85.0	.014	Grey-black mottled	Medium silt	8.1	.36	5.3	840	4.7	<1	1.2	.65
	1.60 to 1.68	na	na	Blue-grey	Sand and gravel	5.0	1.6	2.9	690	1.8	<1	.16	.42
Site number 392658106020201, Blue River deltaic deposit (north distal margin of Blue River delta)													
2	0.77 to 1.20	20.2	.131	Brown with organics	Fine sand	na	na	na	na	na	na	na	na
	1.73 to 2.03	55.9	.048	Dark organic	Coarse silt	na	na	na	na	na	na	na	na
Site number 392712106020201, deep water deposit (near north shore between dam and highway)													
6	0 to 0.06	91.0	.005	Brown	Very fine silt, colloidal	7.5	.85	14	890	4.0	<1	2.4	.92
	0.10 to 0.55	86.7	.013	Black	Medium silt	4.7	.42	11	620	2.0	<1	2.5	1.2
Site number 392713106014601, Indiana Creek deltaic deposit (north distal margin of Indiana Creek delta)													
9	0.2 to 1.1	4.76	.440	Reddish brown	Medium sand	5.3	.75	12	720	1.9	<1	.71	.38
	1.1 to 1.3	15.9	.160	Reddish brown	Fine sand	5.4	.75	9.9	620	2.2	<1	.60	.42
	1.3 to 1.6	32.6	.090	Dark brown organic	Very fine sand	5.8	.96	10	680	2.4	<1	1.2	.57
Site number 392714106014601, deep water deposit (north of Indiana Creek delta, near east shore)													
11	0 to 0.38	69.1	.029	Black mottled	Medium silt, colloidal	6.7	1.2	12	760	3.2	<1	1.8	.78
Reference standards:													
Maximum background, Southern Rocky Mountains sites, (V.C. Stephens, USGS, 2005)													
TEC, Threshold Effect Concentration (MacDonald and others, 2000)													
PEC, Probable Effect Concentration (MacDonald and others, 2000)													

Table 3. Results of sediment-core particle-size and trace-constituent analysis of sample cores from Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; mm, millimeters; ppm, parts per million; na, data or standard not available or not presented. <, less than; green highlight, values greater than maximum background levels for stream sediment in the Southern Rocky Mountains (V.C. Stephens, U.S. Geological Survey, oral commun., 2005); orange highlight, values at or above TEC, Threshold Effect Concentration, lesser values not expected to be toxic (MacDonald and others, 2000); pink highlight, values at or above PEC, Probable Effect Concentration, greater values likely to be toxic (MacDonald and others, 2000)]

Sedi- ment core number (fig. 5)	Strata sampled below bed (ft)	Carbon, organic (percent)	Carbon, total (percent)	Carbonate (percent)	Cerium (Ce) (ppm)	Chromi- um (Cr) (ppm)	Cobalt (Co) (ppm)	Copper (Cu) (ppm)	Europium (Eu) (ppm)	Gallium (Ga) (ppm)	Gold (Au) (ppm)	Holmium (Ho) (ppm)	Iron (Fe) (percent)	
1	Site number 392658106020501, Blue River deltaic deposit (west of Blue River delta, near south shore)													
	0 to 0.1	6.49	6.57	0.08	91	62	10	29	1.6	18	<1	<1.0	3.8	
	0.3 to 0.9	.15	.15	<.01	55	23	3.3	5.3	<1.0	12	<1	<1.0	1.3	
	0.9 to 1.4	6.86	6.95	.09	83	86	12	38	1.6	20	<1	<1.0	4.0	
	1.4 to 1.6	6.49	6.52	.03	98	87	13	32	2.0	22	<1	<1.0	3.2	
	1.60 to 1.68	.45	.45	<.01	66	24	3.4	5	1.0	11	<1	<1.0	.92	
2	Site number 392658106020201, Blue River deltaic deposit (north distal margin of Blue River delta)													
	0.77 to 1.20	na	na	na	na	na	na	na	na	na	na	na	na	
	1.73 to 2.03	na	na	na	na	na	na	na	na	na	na	na	na	
6	Site number 392712106020201, deep water deposit (near north shore between dam and highway)													
	0 to 0.06	7.19	7.27	.08	70	69	14	43	1.6	20	<1	<1.0	5.3	
	0.10 to 0.55	17.6	17.7	.12	42	62	10	26	<1.0	12	<1	<1.0	2.5	
9	Site number 392713106014601, Indiana Creek deltaic deposit (north distal margin of Indiana Creek delta)													
	0.2 to 1.1	.84	.85	.01	61	23	6.2	12	1.0	12	<1	<1.0	1.9	
	1.1 to 1.3	1.42	1.43	<.01	69	30	5.7	16	1.2	12	<1	<1.0	2.0	
	1.3 to 1.6	3.29	3.35	.06	65	39	7.2	28	1.4	14	<1	<1.0	2.2	
11	Site number 392714106014601, deep water deposit (north of Indiana Creek delta, near east shore)													
	0 to 0.38	4.95	5	.05	81	52	10	39	1.7	17	<1	<1.0	3.0	
Maximum background		9.20	na	na	240	76	19.0	75	1.00	22	na	na	6.80	
TEC		na	na	na	na	43	na	32	na	na	na	na	na	
PEC		na	na	na	na	111	na	149	na	na	na	na	na	

Table 3. Results of sediment-core particle-size and trace-constituent analysis of sample cores from Goose Pasture Tarn near Breckenridge, Colorado.—Continued

[ft, feet; mm, millimeters; ppm, parts per million; na, data or standard not available or not presented. <, less than; green highlight, values greater than maximum background levels for stream sediment in the Southern Rocky Mountains (V.C. Stephens, U.S. Geological Survey, oral commun., 2005); orange highlight, values at or above TEC, Threshold Effect Concentration, lesser values not expected to be toxic (MacDonald and others, 2000); pink highlight, values at or above PEC, Probable Effect Concentration, greater values likely to be toxic (MacDonald and others, 2000)]

Sedi-ment core number (fig. 5)	Strata sam-pled below bed (ft)	Lantha-num (La) (ppm)	Lead (Pb) (ppm)	Lithium (Li) (ppm)	Magne-sium (Mg) (percent)	Man-ganese (Mn) (ppm)	Mercury (Hg) (ppm)	Molybde-num (Mo) (ppm)	Neodym-ium (Nd) (ppm)	Nickel (Ni) (ppm)	Nobium (Nb) (ppm)	Phospho-rus (P) (percent)	Potas-sium (K) (percent)
Site number 392658106020501, Blue River deltaic deposit (west of Blue River delta, near south shore)													
1	0 to 0.1	49	91	27	0.91	970	0.15	1.2	45	22	21	0.11	2.7
	0.3 to 0.9	29	38	13	.33	140	.02	<.5	26	7.0	9.3	.05	3.1
	0.9 to 1.4	45	140	31	1.2	470	.22	3.1	42	42	21	.10	2.7
	1.4 to 1.6	54	57	35	1.2	470	.05	4.2	51	29	28	.083	2.8
	1.60 to 1.68	35	24	12	.32	160	<.02	.52	31	7.6	9.4	.048	2.6
Site number 392658106020201, Blue River deltaic deposit (north distal margin of Blue River delta)													
2	0.77 to 1.20	na	na	na	na	na	na	na	na	na	na	na	na
	1.73 to 2.03	na	na	na	na	na	na	na	na	na	na	na	na
Site number 392712106020201, deep water deposit (near north shore between dam and highway)													
6	0 to 0.06	38	140	38	.99	2,500	.21	2.0	36	27	19	.16	2.6
	0.10 to 0.55	22	75	24	.63	780	.18	3.8	21	19	9.6	.086	1.5
Site number 392713106014601, Indiana Creek deltaic deposit (north distal margin of Indiana Creek delta)													
9	0.2 to 1.1	34	65	20	.31	390	<.02	.80	28	8.8	13	.076	2.4
	1.1 to 1.3	38	70	22	.34	270	.02	.75	32	11	15	.09	2.2
	1.3 to 1.6	35	93	26	.43	320	.04	1.0	32	15	16	.11	2.2
Site number 392714106014601, deep water deposit (north of Indiana Creek delta, near east shore)													
11	0 to 0.38	44	120	34	.62	540	.08	1.7	40	22	19	.12	2.4
Maximum background													
		na	61	na	1.70	4,500	.10	12.5	na	30	na	.23	2.50
TEC													
		na	36	na	na	na	.18	na	na	23	na	na	na
PEC													
		na	128	na	na	na	1.06	na	na	49	na	na	na

Table 3. Results of sediment-core particle-size and trace-constituent analysis of sample cores from Goose Pasture Tarn near Breckenridge, Colorado.—Continued

Sediment core number (fig. 5)	Strata sampled below bed (ft)	Vanadium (V) (ppm)	Ytterbium (Yb) (ppm)	Yttrium (Y) (ppm)	Zinc (Zn) (percent)
1	Site number 392658106020501, Blue River deltaic deposit (west of Blue River delta, near south shore)				
	0 to 0.1	57	1.8	20	310
	0.3 to 0.9	24	<1.0	7.3	67
	0.9 to 1.4	66	2.1	21	440
	1.4 to 1.6	78	2.2	23	290
1.60 to 1.68	21	<1.0	8.2	54	
2	Site number 392658106020201, Blue River deltaic deposit (north distal margin of Blue River delta)				
	0.77 to 1.20	na	na	na	na
6	Site number 392712106020201, deep water deposit (near north shore between dam and highway)				
	0 to 0.06	96	2.0	22	400
9	Site number 392713106014601, Indiana Creek deltaic deposit (north distal margin of Indiana Creek delta)				
	0.2 to 1.1	49	1.1	9.9	130
	1.1 to 1.3	58	1.2	12	130
	1.3 to 1.6	74	1.5	16	170
11	Site number 392714106014601, deep water deposit (north of Indiana Creek delta, near east shore)				
	0 to 0.38	97	2.1	22	250
Maximum background		130	na	na	330
TEC		na	na	na	121
PEC		na	na	na	459

[ft, feet; mm, millimeters; ppm, parts per million; na, data or standard not available or not presented. <, less than; green highlight, values greater than maximum background levels for stream sediment in the Southern Rocky Mountains (V.C. Stephens, U.S. Geological Survey, oral commun., 2005); orange highlight, values at or above TEC, Threshold Effect Concentration, lesser values not expected to be toxic (MacDonald and others, 2000); pink highlight, values at or above PEC, Probable Effect Concentration, greater values likely to be toxic (MacDonald and others, 2000)]

Summary and Conclusions

Goose Pasture Tarn, created in 1965 when a dam was constructed on the Blue River, is the principal domestic water-storage facility for the Town of Breckenridge, Colorado, and collects runoff from approximately 42 mi² of the upper Blue River watershed. Concerns have been expressed about possible economic losses and decreased reservoir-storage capacity from sedimentation. A study was undertaken by USGS in 2004 to determine the volume of accumulated sediment in Goose Pasture Tarn, the long-term sedimentation rate for the reservoir, and the particle-size and chemical characteristics of the sediment.

Two perennial streams provide most of the inflow and sediment to Goose Pasture Tarn. The Blue River (drainage area approximately 35 mi²) is a low-gradient, braided channel and transports gravel- to silt-size sediment. Indiana Creek (drainage area approximately 5 mi²) is a steep-gradient channel that transports boulder- to silt-size sediment. Deltaic sedimentary deposits are visible in Goose Pasture Tarn at both inflow areas. Sediment deposited by the Blue River is relatively fine (gravel, sand, and silt), whereas sediment deposited by Indiana Creek is coarser (gravel and cobbles) near the inflow but becomes sand and silt distally into the reservoir in the direction of the dam. The downstream reaches of Indiana Creek are bordered by flood and debris-flow deposits, suggesting some episodic coarse-sediment delivery in addition to the finer sediment transported by perennial streamflow. A flood in June 1995 may have supplied a large amount of sediment to the reservoir from Indiana Creek.

Intermittent spillway modifications and repairs require lowering the reservoir water surface by approximately 4 ft. Pool lowering could be accompanied by downcutting into, and erosion of, the deltaic deposits that are normally underwater when the reservoir is full. Reservoir dredging to increase storage capacity also could entrain sediment now stored throughout the reservoir. Quantification of long-term sedimentation rates in Goose Pasture Tarn was needed to determine whether dredging is necessary. Chemical analysis of lacustrine sediments was needed to identify the presence of constituents with the potential to degrade the municipal water supply if disturbed.

Aerial photographs from 5 years were used to assess the accumulation of deltaic sediment from the Blue River and Indiana Creek to Goose Pasture Tarn. Photographs from 1968, 1975, and 1983 and a 2001 digital image rectified to known coordinates of ground features visible in the photograph were registered to a 2005 digital orthophoto quadrangle. A reference shoreline was determined from the September 9, 1968, aerial photograph, which was the first taken after the reservoir was filled in 1965. The exposed areas of deltaic deposits in each subsequent photograph were delineated and areas computed in GIS. By 2005, 40 years after construction of Goose Pasture Tarn Dam, the Blue River exposed delta was 0.37 acre, and the Indiana Creek exposed delta was 0.54 acre. Delta accretion

occurred at different rates; the most rapid growth rates appear to be related to periods of larger-than-average floods.

Streamflow in the Blue River and Indiana Creek was low in 2004 and 2005 because of relatively little snowmelt runoff in 2004 and transmountain diversions from the Blue River headwater tributaries both years; consequently, sediment entrainment and transport in the two streams were small, and little sediment was delivered to the reservoir. Streamflow ranged from 3.7 to 49.3 ft³/s in the Blue River and from 2.5 to 32.0 ft³/s in Indiana Creek when sediment measurements were made in 2005. Suspended-sediment concentrations ranged from 1 to 12 mg/L in the Blue River and from 4 to 19 mg/L in Indiana Creek in 2005. Suspended-sediment loads ranged from 0.02 to 1.6 ton/d in the Blue River and from 0.06 to 1.55 ton/d in Indiana Creek in 2005. The composition of the suspended sediment collected in the two streams was mostly in the sand-size range (0.0625 to 2.0 mm diameter). Bedload was 0.26 ton/d in the Blue River on July 25, 2005, and ranged from 0.0041 to 0.071 ton/d in Indiana Creek on the 4 days when it was measured. Bedload was mostly sand-size material, with a few small gravel particles. Bedload as a percentage of total sediment load ranged from 9 to 27 percent during the relatively low streamflows for which measurements were made. Sediment-transport relations and sediment budgets could not be computed for suspended sediment and bedload sediment in the Blue River and Indiana Creek because of the minimal streamflow during the duration of this study and the infrequently observed sediment transport.

Bathymetric and seismic surveys of Goose Pasture Tarn were performed in August 2004 and June 2005. The reservoir-bed surface was mapped from 5,421 bathymetrically derived elevation points and used to define (1) stage-area and stage-capacity relations and (2) the topography of accumulated lacustrine sediment. Bed-elevation data from May 2004 topographic surveys made when the reservoir was drawn down were substituted for bathymetric data in normally shallow areas because the reliability of the bathymetric data can be questionable at water depths of less than about 3.3 ft. The maximum water depth at full-pool conditions was 35.8 ft, and the mean water depth was 13.5 ft.

Seismic data were calibrated with lacustrine sediment cores and were used to estimate (1) the original reservoir-bed surface and (2) the thickness and volume of accumulated postreservoir sediment. The original reservoir-bed surface was used to estimate the original (1965) reservoir stage-area and stage-capacity relations. Probe-determined sediment thicknesses from the low-water topographic survey of the Blue River and Indiana Creek deltas were merged with seismically determined, reservoir-sediment thicknesses. Sediment thickness determined with seismic profiling ranged from 0 to 4.0 ft and averaged 0.7 ft, with lesser thicknesses in the deeper parts of Goose Pasture Tarn and greater thicknesses near the deltas. Probe-determined sediment thickness ranged from 1.0 to 4.4 ft and averaged 2.8 ft near the Blue River delta and from 0.3 to 6.0 ft and averaged 3.6 ft near the Indiana Creek delta.

The surface area of Goose Pasture Tarn in 2005 was 66.4 acres, and the reservoir capacity, or volume, was 771.1 acre-ft at a full-pool elevation of 9,886.4 ft. The original area and capacity of Goose Pasture Tarn in 1965 were estimated from the 2005 seismic profiling and manual probing of delta deposits that, together, identified the prereservoir land surface. At full-pool elevation, the 1965 surface area was 67.1 acres, and the reservoir capacity was 818.0 acre-ft. On the basis of the 2005 survey and the estimate of the original reservoir-bed topography, the full-pool reservoir surface area has decreased by 0.7 acre, or about 1.1 percent since 1965. Reservoir capacity, or volume, has decreased by 46.9 acre-ft, or about 5.7 percent over the same 40-year period.

Reservoir surface area and capacity estimates from a 2002 survey were compared to this study. Water-surface areas from the two studies are in close agreement at most elevations except from about 9,881.8 to about 9,882.8 ft. This elevation range corresponds to a water depth of about 3.6 to 4.6 ft when the reservoir is filled to capacity at full pool. *Elodea sp.* growth in shallow-water areas created problems with bathymetric interpretation in both studies; however, these problems were eliminated by a replicate survey in June 2005 before the seasonal *Elodea sp.* growth occurred. The differences between the 2002 and 2005 studies could be attributed largely to poor bathymetric definition by the 2002 study in this narrow elevation zone. Elevation-capacity values from this study and the 2002 study are in very close agreement below approximately 9,880 ft.

The volume of sediment that has accumulated in Goose Pasture Tarn since the reservoir was completed in 1965 was estimated from seismic profiling and manual probing. Data from the seismically profiled, postreservoir sediment thickness in Goose Pasture Tarn and data from the probe-determined, postreservoir sediment thickness in the deltas were merged in GIS to create combined point data of reservoir-sediment thickness. The total sediment volume that has accumulated since 1965 in the reservoir and material that has accumulated on the Blue River and Indiana Creek deltas, above the 9,866.4-ft water-surface elevation of the full reservoir, is approximately 47.5 acre-ft.

The difference between the area-capacity curves estimated for 1965 and measured in 2005 was 46.9 acre-ft and is another estimate of the accumulated sediment volume but only accounts for sediment below the full-pool water surface. The 0.6 acre-ft difference between 46.9 and 47.5 acre-ft is the approximate volume of sediment in the two deltas visible above the full-pool water surface and accounts for approximately 1.3 percent of all deposited sediment. Aerial photographic analysis of the accumulated exposed delta areas indicated a total delta area of 0.9 acre, giving a mean exposed delta thickness of about 0.6 to 0.7 ft. Greater sediment thicknesses were found by probing, but probing attempts were intentionally concentrated in thicker delta areas to determine the maximum sediment thickness.

An average of 1.19 acre-ft/yr of sediment, mostly in the silt- and sand-size range, has accumulated in Goose Pasture Tarn and the two deltas over four decades. Low-flow and non-flood discharges occur frequently but usually transport only a small volume of finer sediment, as indicated by the suspended-load and bedload data collected in 2004 and 2005. Intermittent flood discharges, like the June 18, 1995, flood, are short lived but deliver larger amounts of fine and coarse sediment and may be responsible for noticeable and abrupt increases in delta areas.

Particle-size analyses were performed on sediment from five cores extracted from the reservoir bed in deepwater areas and from shallow, near-delta areas, and from pits excavated on the deltas when the water was drawn down in 2004. Distribution of sediment in Goose Pasture Tarn is mostly in the deltaic regions where sediment has been transported into the reservoir from the Blue River and Indiana Creek. Sediment in these deltaic regions is mostly sand size, but some sediment cores revealed alternating layers of silt and sand. Sediment also has been deposited in a thinner layer over a wide area of the reservoir. These sediments are predominantly silt and clay size, and some of the clay appears to be colloidal, or held in suspension just above the bed surface.

Reservoir sediment from four cores was analyzed for chemical constituents to determine the presence and levels of potentially hazardous material. Most of the cores showed stratification by sediment-particle size, indicative of different depositional dates or mechanisms. Metal and trace constituent levels from the cores were compared with three standards: (1) the maximum background level of sediments in the Southern Rocky Mountains, (2) the Threshold Effect Concentration, and (3) the Probable Effect Concentration. Silver, cadmium, europium, lead, and zinc were detected in concentrations greater than Southern Rocky Mountain background levels in all four sediment cores, and cadmium, lead, and zinc levels also were equal to or exceeded the TEC standards in these cores. The only metal exceeding the PEC standard was lead detected in silt from cores 1 (Blue River delta) and 6 (deepwater near north shore). Tin was detected in concentrations greater than Southern Rocky Mountain background levels in cores 1, 6, and 11 (deepwater near east shore), and chromium and copper levels also were equal to or exceeded the TEC standards in these cores. Other constituents exceeding background level and TEC standards were detected in the cores. The elevated values were detected more often, but not exclusively, in the silt layers than in the sand layers.

The 2005 reservoir capacity is 771 acre-ft. If the future average sediment delivery rate to Goose Pasture Tarn is comparable to the past 40 years, the reservoir has many years of useful life remaining. However, changes in the watershed related to climate, land use, and especially large-scale, severe forest fires can increase sediment loads by orders of magnitude and greatly shorten the useful life of reservoirs.

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For more information concerning the research described in this report,
contact:

U.S. Geological Survey
Denver Federal Center, MS 415
Bldg. 53, Room E-2313
Lakewood, CO 80225
<http://co.water.usgs.gov>



Index map

