ESTIMATES OF GROUND-WATER FLOW COMPONENTS FOR LYMAN LAKE, APACHE COUNTY, ARIZONA

By Donald J. Bills and H.W. Hjalmarson

With a section on **Geochemistry of Surface Water and Ground Water in the Lyman Lake Area**

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, the conversion factors for the inch-pound units used in this report are listed below:

Multiply inch-pound unit	*By*	*To obtain metric unit*
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	square hectometer (hm^2)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
degree Fahrenheit (°F)	(temp °F-32)/1.8	degree Celsius (°C)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

Lyman Lake is an irrigation storage reservoir on the Little Colorado River near St. Johns, Arizona. The main sources of water for the lake are streamflow in the Little Colorado River and spring flow from the underlying Coconino aquifer. The use of ground water at two electric-power generating stations in the Lyman Lake area may affect the quantity of spring flow to Lyman Lake.

The water-budget method and the water-chemistry and isotope data were used to compute the quantity of ground-water flow to and from Lyman Lake. Components of flow used in the water-budget analysis included evaporation from the lake, transpiration from dense vegetation, seepage through the dam, streamflow in and out of the lake, precipitation on the lake, and changes in lake storage that were measured or estimated for 7-day periods during 1985 and 1986. Geochemical data included major ions, trace elements, and the stable isotopes of hydrogen and oxygen.

During the study, the potentiometric level in the Coconino aquifer was above the lake level at the upstream end of the lake and below the lake level at the downstream end. Ground-water flow from the lake is related to the head difference at the downstream end of the lake. Discharge from the aquifer was an average of 5.7 cubic feet per second at Salado Springs downstream from Lyman Lake and an estimated 6.0 cubic feet per second in Lyman Lake. The relation between computed ground-water inflow and the difference in head between the aquifer and the lake at the upstream end was not statistically significant. The interpretation of the geochemical data supports the conceptual model of the water budget, and the calculated percentages are within the range of the results of the water-budget comparison.

INTRODUCTION

Lyman Lake is an irrigation storage reservoir with a capacity of about 30,300 acre-ft on the Little Colorado River in east-central Arizona (fig. 1). Releases from Lyman Lake are allocated to downstream users by court decree (Arizona State Superior Court, 1918). During the winter, controlled releases generally are not made and the lake fills. During the

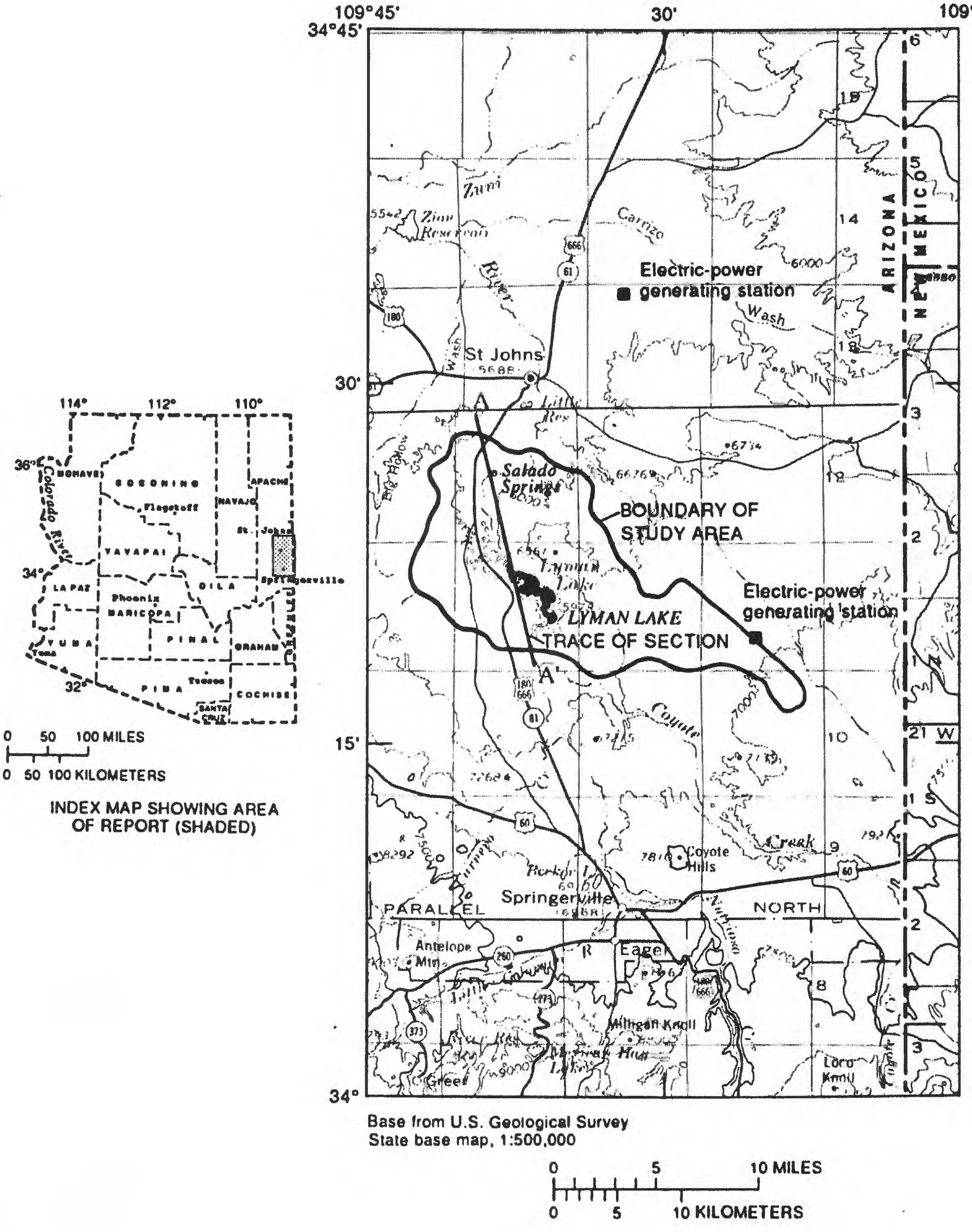


Figure 1.--Location of study area.

summer, water is released to Lyman Canal and the river through an outlet works at the base of Lyman Dam. Lyman Canal is concrete lined and parallels the course of the Little Colorado River downstream to the Salado Springs area where it leaves the study area to the north. The canal conveys water from Lyman Lake to a system of turnouts and ditches along the canal downstream in the St. Johns agricultural area.

The Lyman Lake area is underlain by the regionally extensive Coconino aquifer. The Coconino aquifer is confined in the study area, and water leaves the aquifer through an extensive spring system between Lyman Dam and Salado Springs. Historically, surface-water resources of the study area, which include Lyman Lake, Salado Springs, and the base flow of the Little Colorado River, have been completely allocated to downstream users, primarily for agriculture. Since 1980, ground-water resources near Lyman Lake have been developed to support increasing industrial activity, particularly at two coal-fired electric-power generating stations (fig. 1). This additional use of ground water may cause a decline in the potentiometric surface of the Coconino aquifer in the Lyman Lake area and result in a decrease of discharge from the aquifer to the lake.

Ground water from the Coconino aquifer emerges as springs in the Salado Springs area, supplies base flow to the Little Colorado River directly, and flows into Lyman Lake below the lake surface. When lake levels are high, lake water infiltrates the alluvium and travertine deposits at the downstream end of Lyman Lake. Thus, the surface water and ground water in the area are interconnected. The head difference between the lake surface and the potentiometric head of the Coconino aquifer is the driving force for flow of water between the lake and the ground. A change of lake level or potentiometric head therefore will change the quantity of ground water entering or leaving the lake.

The investigation included calculations of ground-water flow to and from Lyman Lake using a water budget and water-chemistry and isotope data. The investigation was begun in 1985 by the U.S. Geological Survey in cooperation with the Salt River Project.

Purpose and Scope

The purpose of the investigation was to define quantitatively the interaction between surface water and ground water in a short reach of the Little Colorado River that includes Lyman Lake and Salado Springs. This report describes the hydrology of the study area and presents a conceptual model of the flow system that was used for the water budgets. The water-budget data and associated errors are presented and evaluated relative to the estimated quantity of ground-water flow to and from Lyman Lake. Chemical and isotope data were collected and an independent calculation of the water budget is presented for the Lyman Lake and Salado Springs area.

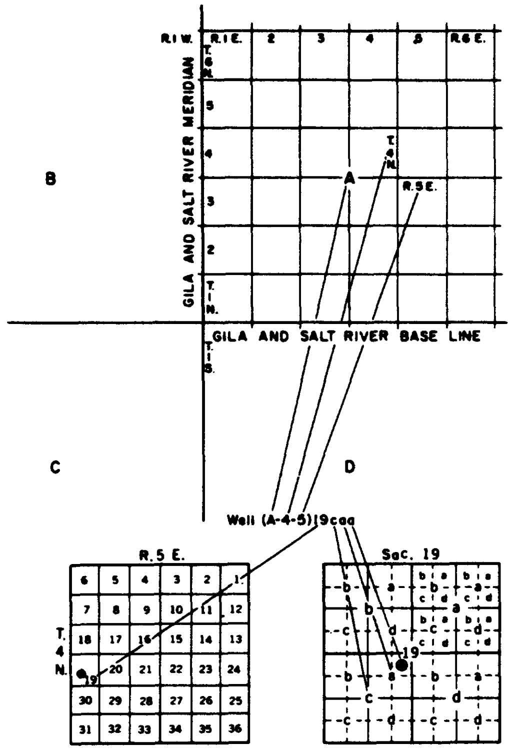
The quantity of ground-water flow to and from Lyman Lake was computed from measured or estimated flow components of 7-day water budgets for the area during the nearly 2 years of the study. Because the ground-water flow components were computed as the difference (residual) of all measured and estimated components of flow and an estimate of storage change in the lake, the computed values contain the sum of errors of all the components. Large errors may mask the computed component of ground-water flow, and the computation may be unreliable. Thus, errors for individual budget components were carefully computed or estimated and used in an analysis of error for the computed quantity of ground-water inflow and outflow. Geochemical data, which include dissolved-chemical constituents of major ions and trace elements and the stable isotopes of hydrogen and oxygen, were used as an independent means to calculate ground-water components of the water budget. Analysis of these data qualitatively and, for the most part, quantitatively supported the water budget.

Previous Investigations and Available Data

The regional geology and hydrology of Apache County, in which the Lyman Lake area is located, have been described by several investigators, most of whom are cited in a report on geology and ground water in central Apache County by Akers (1964). Sirrine (1958) discussed in detail the geology of the Springerville area with an emphasis on the travertine deposits that surround Lyman Lake. Wilson and others (1960) mapped the geology of Navajo and Apache Counties. The regional assessment of ground-water resources by Akers (1964) was updated by Harper and Anderson (1976) and by Mann and Nemecek (1983) to include surface water and water use. These reports as well as the report by Akers show surface geology, structure, geohydrology, and water-quality information on a regional scale. Surface-water data for the Little Colorado River above and below Lyman Lake and lake contents are published in Water Resources Data for Arizona (U.S. Geological Survey, 1975-86). Water-level and ground-water-quality data from observation wells and monitoring networks near the Lyman Lake area are available as unpublished data on file with the U.S. Geological Survey. Well locations are described in accordance with the well-numbering system used in Arizona, which is explained and illustrated in figure 2.

Acknowledgments

Ross Carpenter and John Petrosky, State Park Rangers for the Lyman Lake State Park, assisted with the collection of meteorologic data for the project. Salt River Project personnel provided ground-water, well, and surface-water data. Tucson Electric Power Company personnel provided ground-water data and access to several of their wells for sampling and water-level measurements. The Lyman Irrigation District and several land owners allowed access to their wells for water-level measurements. The assistance of these people and access to these data provided support needed to complete this study. Ivan Barnes of the U.S. Geological Survey isotope laboratory in Menlo Park contributed his time and laboratory to analyze the stable-isotope samples.



The well numbers used by the Geological Survey in Arizona are in accordance with the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants. These quadrants are designated counterclockwise by the capital letters A, B, C, and D. All land north and east of the point of origin is in A quadrant, that north and west in B quadrant, that south and west in C quadrant, and that south and east in D quadrant. The first digit of a well number indicates the township, the second the range, and the third the section in which the well is situated. The lowercase letters a, b, c, and d after the section number indicate the well location within the section. The first letter denotes a particular 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. These letters also are assigned in a counterclockwise direction, beginning in the northeast quarter. If the location is known within the 10-acre tract, three lowercase letters are shown in the well number. In the example shown, well number (D-4-5)19caa designates the well as being in the $NE\frac{1}{4}NE\frac{1}{4}SW\frac{1}{4}$ sec. 19, T. 4 S., R. 5 E. Where more than one well is within a 10-acre tract, consecutive numbers beginning with 1 are added as suffixes.

Figure 2.--Well-numbering system in Arizona.

PHYSIOGRAPHIC SETTING

The study area is along the Little Colorado River and includes about 100 mi^2 of the Little Colorado River drainage basin from about 3 mi upstream from Lyman Lake to about 10 mi downstream (fig. 1). The Lyman Lake area is north of the White Mountains along the south edge of the Colorado Plateau near the Arizona-New Mexico border. The Little Colorado River and small tributary streams generally flow south to north through terrain that consists of moderately to sparsely vegetated valleys, hills, and mesas. The valleys range in altitude from 5,790 to 6,000 ft above sea level. The hills and mesas rise to several hundred feet above the valley floors and those in the south end of the study area reach altitudes of about 7,200 ft. The climate is arid (Sellers and Hill, 1974). Precipitation from winter storms that generally move into the area from the south or northwest occurs as snow along the White Mountains. Snowmelt in the White Mountains produces most of the streamflow in the area and is also a major source of recharge to ground-water resources that underlie the area. In the summer months, most of the rainfall is from sporadic and intense local thunderstorms. Normally, only a small amount of precipitation occurs during the spring and fall.

Geology

Lyman Lake is in an erosional valley carved out by the Little Colorado River between two mesas composed of basalt. The basalts overlie a sequence of bedded sedimentary rocks that are typical of those exposed on the Colorado Plateau. Lyman Lake is situated on an eroded surface of bedded sedimentary rocks that consist of the Moenkopi and overlying Chinle Formations, both of Triassic age. These formations do not readily transmit water except at joints and fractures. In places, these formations have been overlain by deposits of travertine and alluvium (fig. 3). Travertine deposits result from mineralized ground water being discharged from the Coconino aquifer in the Permian Coconino Sandstone and adjacent formations through fractures in the confining Moenkopi and Chinle Formations to the land surface. These deposits trend northwestward to northward, mainly parallel to the structural trends of the area (Akers, 1964). The travertine deposits are more extensive downstream from Lyman Lake where they overlap into massive deposits. Most of the deposits are dome shaped and surround current or historical spring outlets. Alluvium occurs as thin deposits along the main stem of the Little Colorado River and small tributary streams throughout the study area. Lyman Lake has accumulated a relatively thick deposit of silt primarily along the old main course of the river and at the upstream end of the reservoir (Sanders, 1984).

A few geologic structural features in the Lyman Lake and Salado Springs area exert some control on the occurrence and movement of water. The study area is characterized by a broad gentle dip of rock units to the northeast modified in a few places by northwestward-trending folds. One fault north of Salado Springs is described by Akers (1964) as a high-angle normal fault with about 75 ft of displacement on the downthrown side. This fault has diverted the flow of the Little Colorado River for about a mile and probably is also partly responsible for the rise of Salado

Springs. This fault and other structures in the area probably are continuous in the subsurface but are obscured by overlying material. Most outcrops of the sedimentary rocks also exhibit a high degree of joint fractures as well as conjugate fractures coincident with the structure. Fractures in the Moenkopi and Chinle Formations serve as conduits of flow for water in the Coconino aquifer as evidenced by numerous travertine deposits and springs in the Lyman Lake area. The hydraulic character of the Coconino aquifer varies widely from place to place. The variation is due to the areal distribution of joint fractures, solution cavities, and folding and faults as well as areal differences in lithology (Akers, 1964; Mann and Nemecek, 1983). For more detailed geology of the study area, the reader is referred to the reports by Sirrine (1958), Wilson and others, (1960), and Akers (1964).

Hydrology

The Little Colorado River is the only perennial stream in the study area. The sources of the perennial flow are snowmelt, spring discharge from volcanic rocks near its headwaters in the White Mountains to the south, and ground-water discharge from the Coconino aquifer. Base flow of the Little Colorado River is about 1 to 2 ft^3/s upstream from Lyman Lake and about 7 to 12 ft^3/s downstream from Salado Springs (U.S. Geological Survey, 1975-86). Tributary streams to the study area are dry most of the time. Flow in these tributary streams generally is related to intense local summer thunderstorms.

The water level in Lyman Lake fluctuates in response to inflows of seasonal runoff and releases to meet the demands of water users downstream. Runoff of the Little Colorado River is stored in Lyman Lake throughout the fall and winter and released in the spring and summer to the Little Colorado River and Lyman Canal. Occasionally, runoff is great enough in the early spring to fill the lake to capacity. In such cases, the excess runoff flows uncontrolled over Lyman Lake spillway.

Flow in Lyman Canal is about 30 to 35 ft^3/s throughout the spring and summer months. The canal leaks significantly at discharges greater than about 30 ft^3/s and overflows in places at discharges greater than about 40 ft^3/s. Field observations also indicate that leakage from the canal is insignificant at discharges less than 30 ft^3/s. Observations of flow and estimates of discharge made during the study indicate that most of the leakage and overflow is lost to evaporation and transpiration and only small quantities of flow return to the Little Colorado River within the study area.

Ground water in unconsolidated and consolidated sediments throughout the study area occurs under both confined and water-table conditions. The most productive water-bearing zone is the Coconino aquifer. Ground water in the Coconino aquifer is highly mineralized compared with surface waters and other local water-bearing zones. The Coconino aquifer is formed, in ascending order, by Permian sedimentary rocks of the upper Supai Formation, Coconino Sandstone, and Kaibab Formation (fig. 3). Ground water in the Coconino aquifer is confined throughout most of the study area by the very fine grained sedimentary rocks of the Moenkopi Formation and Chinle Formation (Mann and Nemecek,

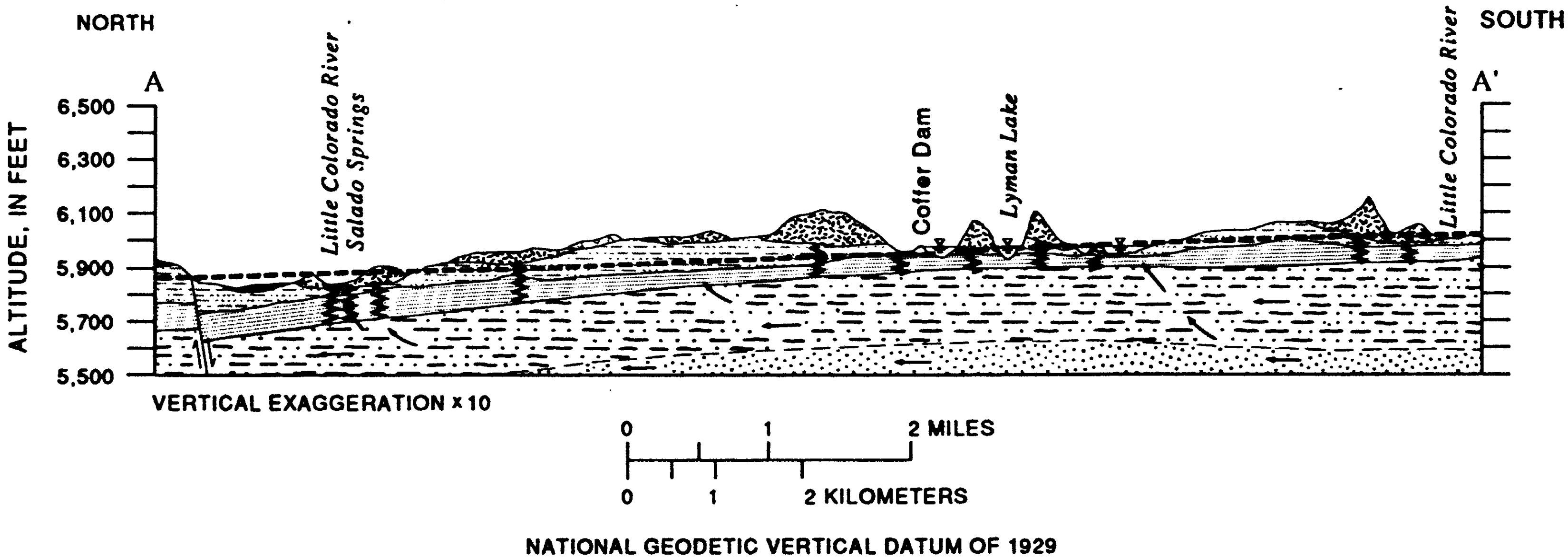


Figure 3.--Generalized geohydrologic north-south section through the study area.

EXPLANATION

QUATERNARY AND TERTIARY

ALLUVIUM—Sand and silt; water bearing

TRAVERTINE DEPOSITS—Calcite and aragonite; does not yield water to wells

VOLCANIC ROCKS—Basalt; locally water-bearing

UNCONSOLIDATED SEDIMENTS—Gravel, poorly cemented; locally water bearing

TRIASSIC

CHINLE FORMATION—Claystone, sandstone, siltstone, and conglomerate; in places, yields water to wells

MOENKOPI FORMATION—Siltstone, mudstone, and claystone; does not yield water to wells

PERMIAN

KAIBAB FORMATION—Bedded limestone and sandstone lenses; water bearing, confined conditions

COCONINO SANDSTONE—Fine- to medium-grained sandstone; water bearing, confined conditions

CONTACT—Dashed where approximately located

FAULT—Arrows show direction of probable relative movement

FRACTURE ZONES—Location inferred by presence of springs and travertine

GENERALIZED DIRECTION OF GROUND-WATER FLOW

APPROXIMATE POSITION OF POTENTIOMETRIC SURFACE OF COCONINO AQUIFER [KAIBAB FORMATION, COCONINO SANDSTONE, AND SUPAI FORMATION (NOT SHOWN)]

SURFACE OF LYMAN LAKE

Figure 3.

1983). Where encountered in drilling in the study area, the Moenkopi and Chinle Formations contain water but generally are not considered aquifers. Although these formations act as confining layers, the joints and fractures that occur in the study area provide paths for water to move vertically. This flow of water is evident by the occurrence of massive deposits of travertine coincident with a small anticlinal structure at Lyman Dam (Sirrine, 1958), by the lineation of travertine deposits along the southwest flank of the Cedar Mesa anticline (Akers, 1964), and by the change in chemical constituents in the Little Colorado River as it flows through the area. The unconsolidated alluvial material along the main stem of the Little Colorado River is also water bearing and, in many places, is hydraulically connected to the river. The limited size and extent of these deposits and the location of the deposits relative to the underlying and shoreward bedrock result in a small amount of bank storage during low flows. During high flows, especially when the river overflows its banks, large quantities of water are stored in the alluvial material. As the high flows recede, the stored water is released back to the river.

Contours of potentiometric head of ground water in the Coconino aquifer indicate that the potentiometric surface is above the elevation of the lake at full pool at the upstream end of Lyman Lake and just above the land surface near Lyman Dam and at Salado Springs (fig. 4). Several areas of travertine deposits surround the lake and are known to be present on the bottom of the lake. Many of these deposits are still connected to the Coconino aquifer as evidenced by the mineral content of the water in spring outlets at the potentiometric surface (John Petrosky, State Park Ranger, Arizona State Parks, oral commun., 1986).

Salado Springs, downstream from Lyman Lake, is a major discharge point for water from the Coconino aquifer. The main outlet of the springs is at the base of a massive travertine mound near the river about 6 mi downstream from the lake. Several other springs are downstream from Lyman Lake. Most of the spring discharge actively deposits travertine. The average discharge of the springs downstream from the lake is about 5.7 ft^3/s. On the basis of the age of the travertine deposits, spring flow from the Coconino aquifer has occurred in the area for about the past 1.5 million years (Sirrine, 1958).

Water-level data from wells (A-12-28)7cdb and (A-11-28)21aba were used to determine the hydraulic gradient of the Coconino aquifer underlying the Lyman Lake area. The hydraulic gradient of the aquifer has been relatively stable since 1975 except for small changes of gradient in the late 1970's and again in 1985-86 (fig. 5). Hydrographs of the lake elevation and the water levels in observation wells around Lyman Lake are shown in figure 6. The lake hydrograph shows a pronounced seasonality that is not reflected by most of the observation-well hydrographs. The water level of observation well (A-11-28)9dad was affected by local pumping in April and May 1986. Water levels in wells (A-11-28)22bda2 and (A-11-28)9acc1 where continuous records are obtained were affected by earthquake activity in Mexico in September 1985. The effect, if any, of the earthquake on water levels of other wells is unknown because only periodic measurements of depth to water were obtained. All other water-level changes in the observation wells are likely to be a result of seasonal recharge, local ground-water pumping, and seasonal water-level fluctuations in Lyman Lake. With the exception of well (A-11-28)9dad, the water level in three of the wells had a small net rise and the water level in the other three wells had a small net decline during the study period. The average net change in water level for the six wells was less than 0.5 foot.

CONCEPTUAL MODEL

Flow components for a conceptual model of the water budget of the lake and spring areas are shown in figure 7. The water-budget method can be used to determine ground-water flow to and from the lake if all other flow components can be accurately determined. Because both ground-water inflow and outflow for the lake are unknown, the ground-water outflow must first be determined by using a water budget for the spring area.

The water-budget method can be used to determine estimates of the unmeasured variable under certain conditions. The method physically accounts for components of outflow from the system, inflow to the system, and changes of storage within the system. If all but one component can be measured, the unmeasured component can be computed. For unsteady flow conditions, a storage change in the system occurs over a finite interval of time. Thus, the time interval selected for the water budget should allow for the accounting of storage changes in the system. Also, the error of the computed flow component is related to the sum of the errors of the measured components, and therefore the components should be accurately determined for the selected time interval. Finally, the magnitude of the computed component should be large relative to the measured flow components so that the amount of the computed component is not masked by the error of the computation.

Ground-water discharge from the Coconino aquifer has been fairly constant for the past several years on the basis of current-meter measurements of spring flow (U.S. Geological Survey, 1975-86) and measurements of the level of the potentiometric surface of the aquifer (fig. 5). Because the potentiometric surface of the Coconino aquifer is above the river in the spring area, ground-water outflow from Lyman Lake returns to the river a short distance downstream from the dam mixed with spring discharge. The driving force for ground-water outflow from the lake is the head difference between the lake level and the potentiometric surface of the Coconino aquifer. When the lake level and the potentiometric surface coincide, the driving force is not present and ground-water outflow from the lake does not occur. Thus, a relation between the head difference of Lyman Lake and the Coconino aquifer and the total ground-water inflow to the spring area can be used to determine or separate the two "mixed" ground-water components. A preliminary analysis of lake level and total ground-water flow to the river indicated that such a relation exists and therefore all flow components shown in figure 7 potentially could be measured, estimated, or calculated.

For purposes of this study, the study area was divided into two areas—the lake area and the spring area (fig. 7). The lake area includes Lyman Lake from inflow to Lyman Dam, and the spring area includes the area between Lyman Dam and Salado Springs. The total ground-water inflow component for the spring area could be computed using a water budget. The ground-water outflow component for the lake area could be calculated from

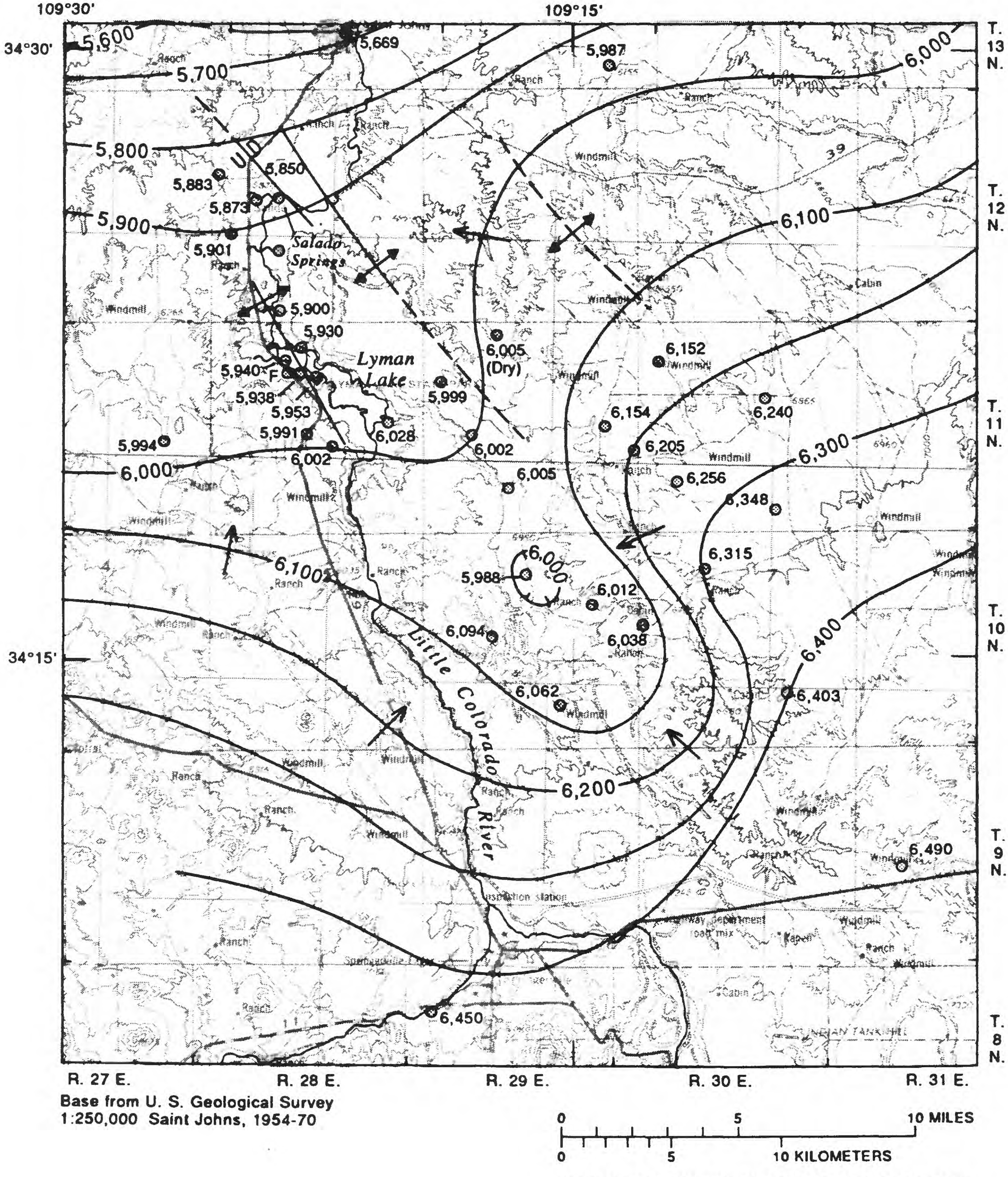


Figure 4.--Ground-water conditions in the Coconino aquifer, 1985-96.

EXPLANATION

6,000	POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in a tightly cased well developed in the Coconino aquifer. Hachures indicate cone of depression associated with electric-power generating station well field. Contour interval 100 feet. Datum is sea level
	ANTICLINE—Shows trace of crestal plane; dashed where approximate
U D	FAULT—U, upthrown side; D, downthrown side. Dashed where approximate
	GENERALIZED DIRECTION OF GROUND-WATER FLOW
5,994	WELL DEVELOPED IN COCONINO AQUIFER—Number, 5,994, is altitude of water level, in feet. F, indicates that well flows at the land surface
5,850	SPRING THAT DISCHARGES FROM THE COCONINO AQUIFER—Number, 5,850, is altitude of the land surface at the spring outlet, in feet

Figure 4.

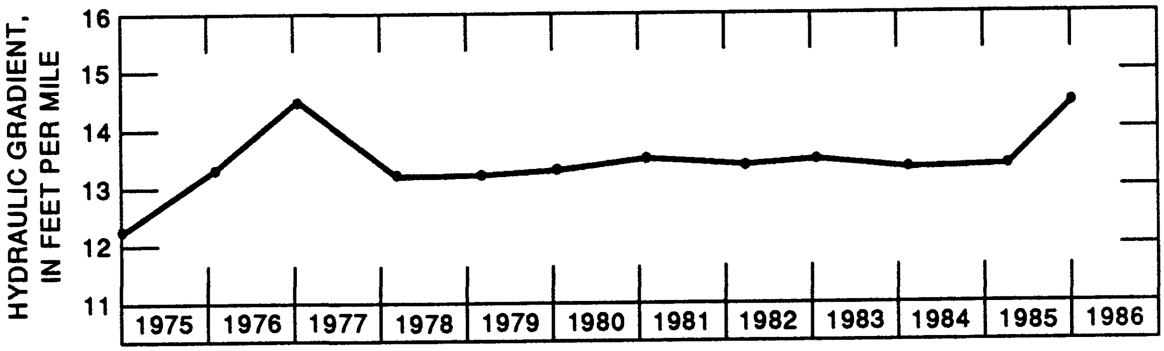


Figure 5.--Estimated hydraulic gradient of the Coconino aquifer underlying the Lyman Lake area, 1975-86.

the relation of the head difference between the lake and underlying aquifer and the total ground-water inflow component for the spring area. With the calculated ground-water outflow for the lake, a water budget for Lyman Lake could be used to calculate the ground-water flow into the lake.

The potentiometric surface of the Coconino aquifer is above the land surface, although below full-pool lake level at the downstream end of Lyman Lake and at or above full-pool lake level from about the middle of the lake to the upstream end of the lake. Thus, ground water could flow into the lake upstream while the lake could lose water to the subsurface downstream near the dam.

The only change in storage accounted for in this analysis is the contents of Lyman Lake (fig. 7). A change of only a few hundredths of a foot of lake level corresponds to a large change of lake storage relative to the magnitude of the other flow components. Water also enters and leaves bank storage along the lake edge, but the potential amount of bank storage is small and for small changes in lake level, this component is considered insignificant. In the spring area, the main channel is narrow and small changes in stream stage produce only small changes in channel storage relative to the amount of flow entering and leaving the river in this area. The alluvial deposits along the river generally are thin and narrow, and, in many places, the ground-water gradient is toward the river with little potential for changes in bank storage for small changes in river stage. For example, a 0.01-foot change of river stage in the spring area may result in an estimated 0.1-acre-foot change of channel and bank storage along the river. For a typical 7-day period of flow, this amount is less than 1 percent of the flow in the river. Thus, the only significant change in storage in the study area corresponding to changes in lake or river level of a few hundredths of a foot is in Lyman Lake. Changes in bank and channel storage are small relative to the amounts of inflow and outflow for the area.

Runoff from thunderstorms or snowmelt can cause relatively large changes of storage in the lake and along the river. The lake surface may be mounded in areas of incoming floodflow and the resulting wedgelike

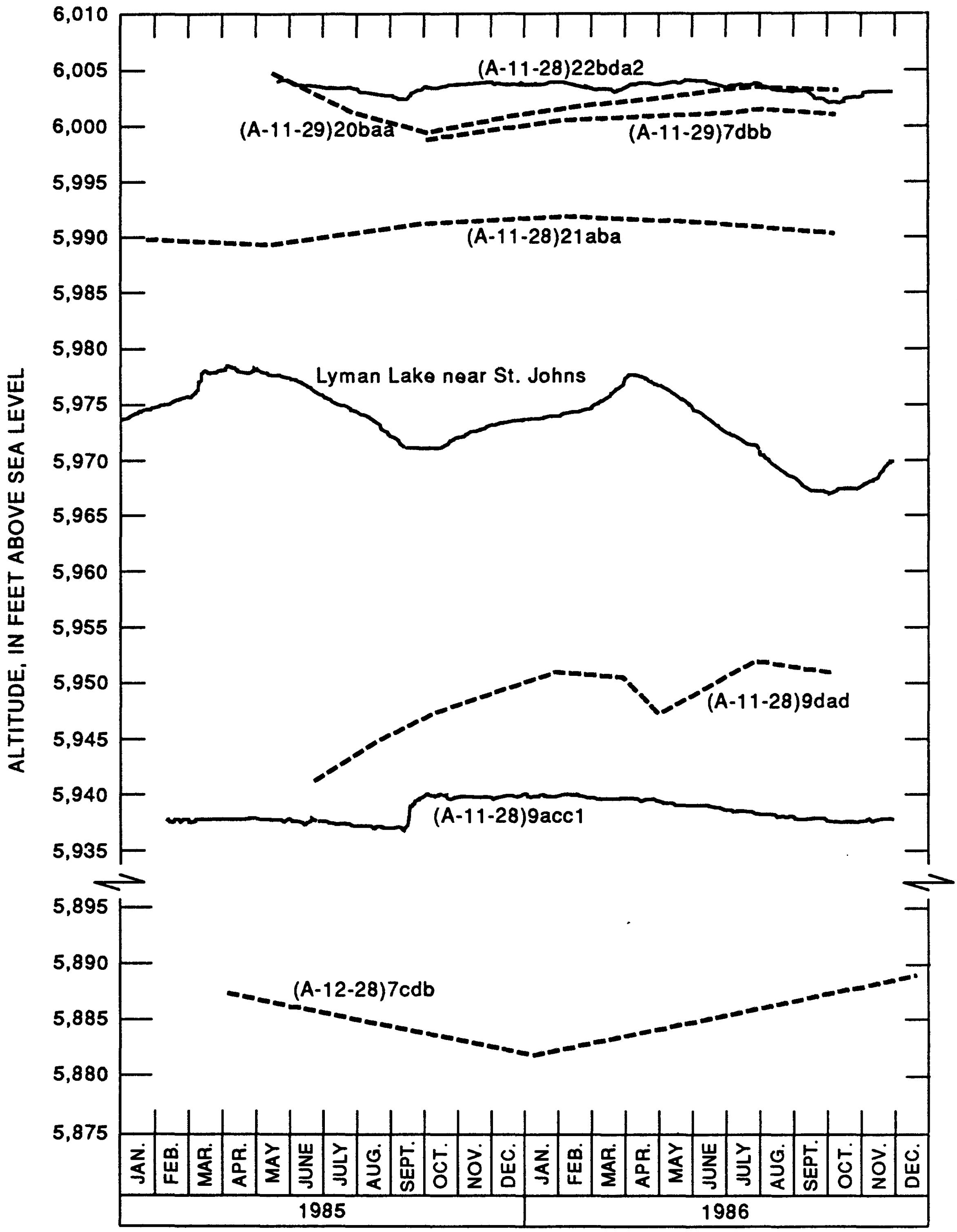


Figure 6.--Lake elevation and altitudes of the water levels in wells.

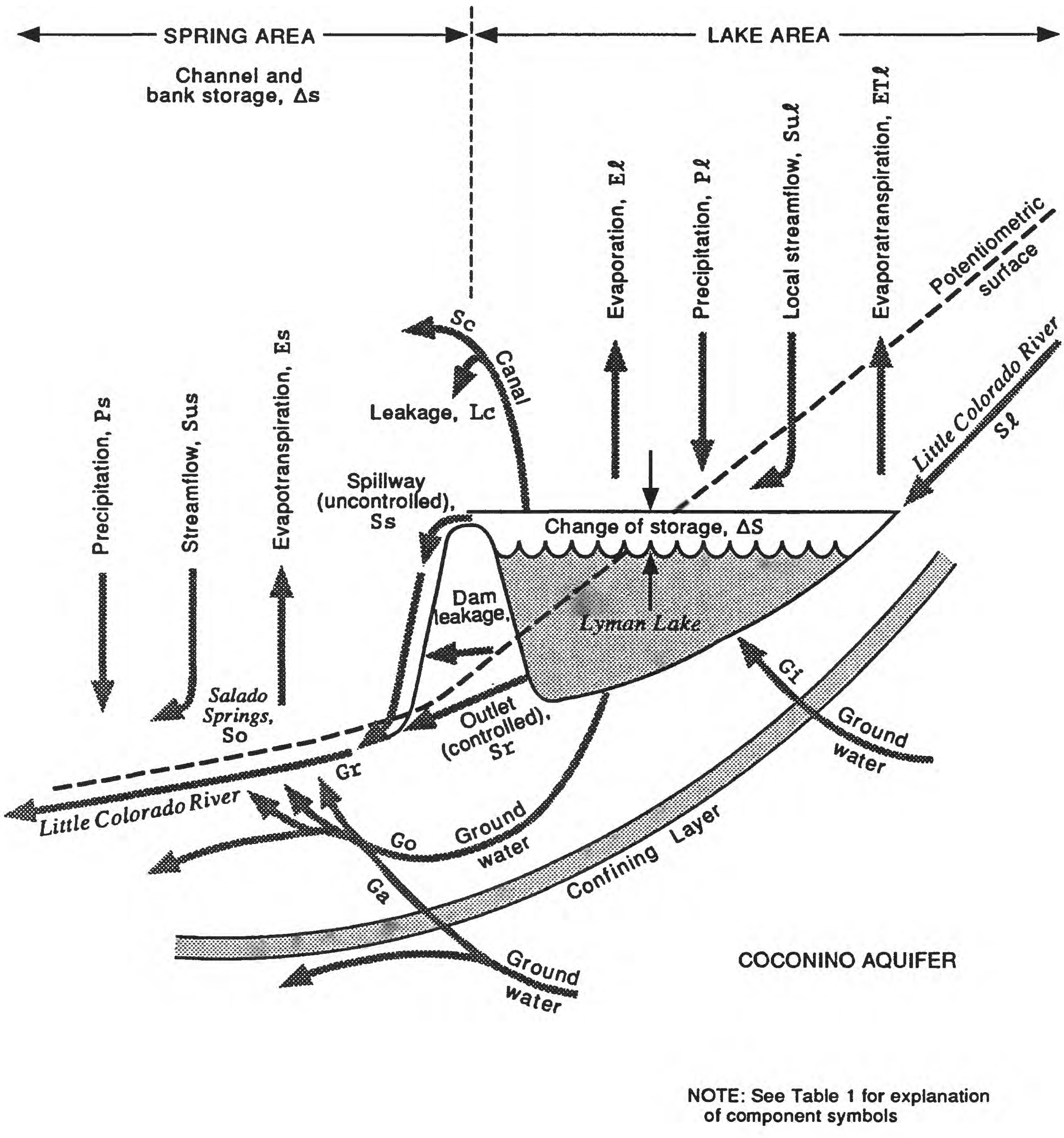


Figure 7.--Flow components for a conceptual model of the water budget of Lyman Lake and the spring area downstream.

change of storage is not defined. Floodwater may spread over the alluvial deposits along the river, and changes in channel and bank storage are large and undefined. Runoff from thunderstorms in tributary basins may be large and unmeasured. Thus, periods of snowmelt and thunderstorm runoff were excluded from the analysis.

The selection of the period for the water budgets is based on the previously described hydrologic conditions and on the estimated time for the flow system to respond to small changes in flow. For example, a small increase of flow in the Little Colorado River upstream from Lyman Lake may take a day or two to pass through the lake and spring areas. If the budget period is less than a day or two, only part of the flow components of the water budget would reflect the increase. If long periods such as months are used for the water budgets, a large part of the periods may contain flow or storage components with large errors associated with thunderstorm and snowmelt runoff. Thus, weekly periods are used because (1) small changes of flow pass through the study area within a few days, (2) only a few of the hydrologic data collected are excluded from the water-budget analysis, and (3) the amount of change in channel and bank storage for most periods of low flow is negligible. Also, for weekly periods, the potential for large changes of the quantity of ground-water inflow and outflow for the lake is small because the relative difference in head between the lake and the aquifer does not change greatly.

A few periods were excluded from the analysis because the potential for unsteady flow between the aquifer and the lake would adversely impact short-term (weekly) budget computation. The exclusion of these periods from the analysis is not considered to have a significant effect on the budget analyses as the quantity of water involved in these short time periods is small compared with the quantity of water moving between the aquifer and the lake in the stable flow periods.

METHODS OF OBTAINING KNOWN WATER-BUDGET COMPONENTS

Water-budget components defined for the conceptual model include major inflows and outflows for the spring and lake areas and the net change of storage in Lyman Lake for the 7-day periods (fig. 7). Data were collected to determine the values of the flow components for the water budget and to define the gradient of the potentiometric surface of the Coconino aquifer in the study area. The data also were used to determine if the potentiometric surface of the aquifer was changing with time. Locations of data-collection sites in the study area are shown in figure 8.

The overall accuracy of the water-budget method depends on the accuracy of each flow component used in the budget. If a single flow component cannot be measured with sufficient accuracy, the amount of error may completely mask the amount of the computed component (residual). Accordingly, the measurement of each flow component is described and the associated error is discussed. Errors for the flow components are assumed to be independent and distributed normally (table 1).

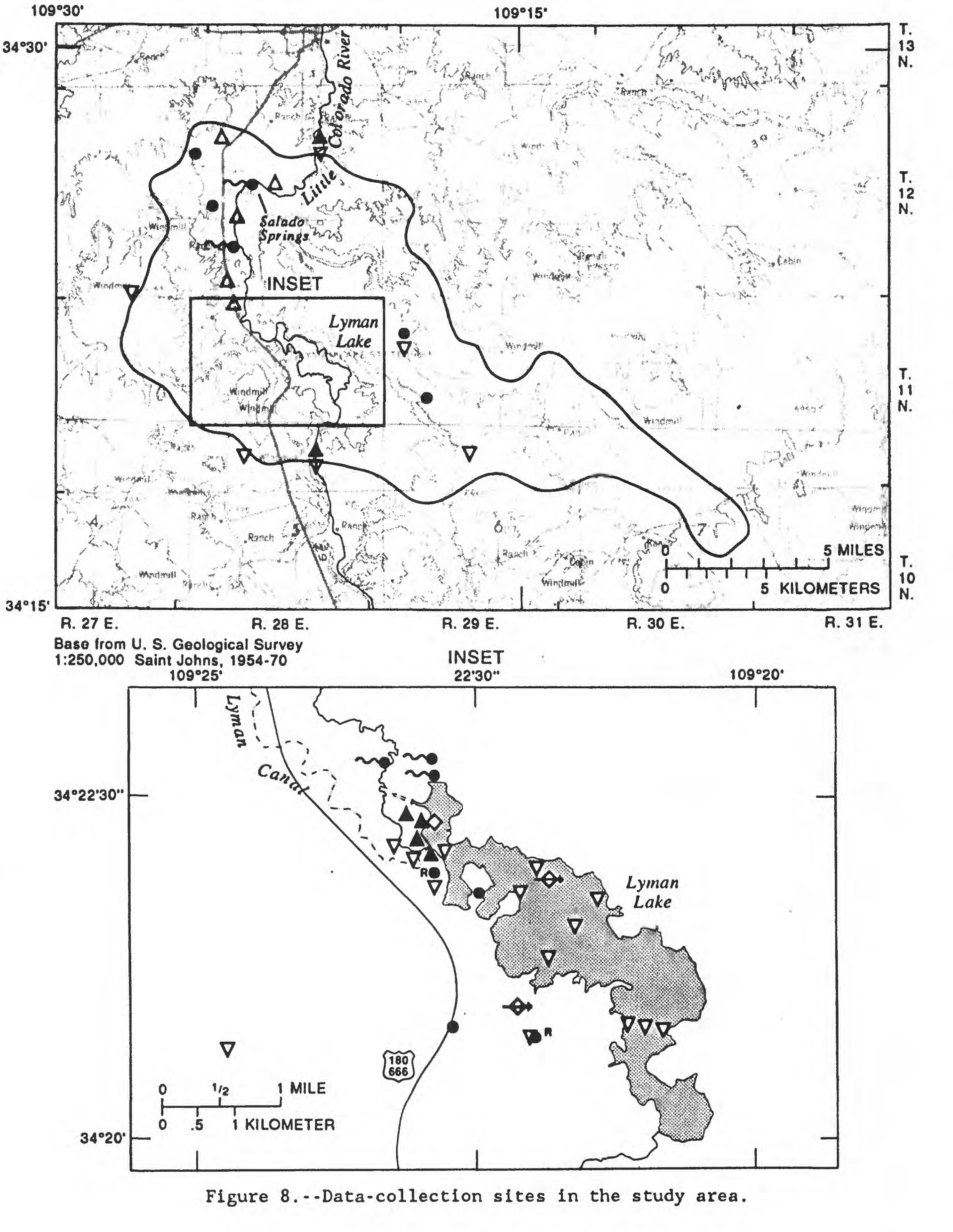


Figure 8.--Data-collection sites in the study area.

E X P L A N A T I O N

———	BOUNDARY OF STUDY AREA
●R	OBSERVATION WELL—R, indicates equipped with a recorder
~●	SPRING—Measured monthly
▲	CONTINUOUS-RECORD GAGING STATION
△	MISCELLANEOUS DISCHARGE-MEASUREMENT SITE
▽	MISCELLANEOUS WATER-QUALITY SITE
-◇→	EVAPORATION, TEMPERATURE, PRECIPITATION, HUMIDITY, AND WIND-VELOCITY MEASUREMENT STATION
◇	PRECIPITATION STATION

Figure 8.

Table 1.--*Components of the water budgets in the spring and lake areas*

Component	Symbol	Method of determination	Estimated standard error, in percent
		Streamflow components	
Inflow to lake at Little Colorado River	*Sℓ*	Standard stream gage (No. 09384000)	3.0
Ungaged inflow to lake	*Suℓ*	Miscellaneous discharge measurements and hydrograph analysis	10
Controlled outflow from lake to river	*Sr*	Standard stream gage (No. 09385500)	2.0
Controlled outflow from lake to Lyman Canal	*Sc*	Standard stream gage (No. 09385000)	2.0
Flow from lake to river at spillway	*Ss*	Standard stream gage (No. 09384600)	[1]2.0
Ungaged inflow to spring area	*Sus*	Hydrograph analysis	20
Outflow from spring area at river	*So*	Standard stream gage (No. 09385700)	2.0
		Meteorological components	
Evaporation from lake	*Eℓ*	Computed from meteorological measurements	[2]20
Evapotranspiration from upstream of lake	*ETℓ*	Blaney and Criddle	10 summer 50 winter
Evapotranspiration along river in spring area	*Es*	Blaney and Criddle	10 summer 50 winter
Precipitation on lake	*Pℓ*	Measured	[2]10
Precipitation on river in spring area	*Ps*	Assumed to be insignificant	---------

See footnotes at end of table.

Table 1.--*Components of the water budgets in the spring and lake area*--Continued.

Component	Symbol	Method of determination	Estimated standard error, in percent
		Storage components	
Change of storage in lake	Δs	Standard lake gage (No. 09384500)	Varies
Channel and bank storage in spring area	ΔS	([3])	
		Leakage components	
Leakage from lake to spring area	*Ld*	Periodic miscellaneous measurement of discharge	6
Leakage from Lyman Canal in spring area	*Lc*	Periodic miscellaneous measurement of discharge	5
		Ground-water components	
Flow to river between dam and Salado Springs	*Gr*	Computed from water budget	See table 2
Flow from Coconino aquifer to river between dam and Salado Springs	*Ga*	Computed from lake level-*Gr* relation	20
Flow from lake	*Go*	Computed from lake level-*Gr* relation	30
Flow to lake	*Gi*	Computed from water budget	See table 3

[1]Not applicable because periods with flow were not used.
[2]For most budget periods.
[3]Not applicable because periods with significant changes of storage were not used.

The amount of error for each component of the water budget is based largely on judgment and the true error is unknown. Some values are based on errors reported in literature for other studies. Reported errors, which often are not clearly defined, were converted to standard errors for this report. Standard errors for some other components are assumed to be one-half the estimated maximum likely error. Thus, the magnitude of the error used is judged to be the most reasonable on the basis of available information and experience. Because of the considerable judgment used to determine errors for evaporation and transpiration, the use of these errors for other studies is not recommended.

Streamflow Components

Discharge at all major streamflow gages that measure flows to and from the lake and spring areas was calculated using stage-discharge relations and continuous records of stage from January 1, 1985, to December 1, 1986. Standard U.S. Geological Survey techniques for streamgaging at sites with stable controls and standard stage-discharge relations were used throughout this period. The gage on the Little Colorado River below Salado Springs (09385700) is at the downstream end of the spring area. Virtually all the discharge from the Coconino aquifer to springs in the area occurs upstream from this gage. Any ground-water flow from Lyman Lake discharges to the river a few miles upstream from this gage, probably within a mile or two of the lake.

The streamflow components represent the largest fraction of the total flow for the water budgets of the lake and spring areas. Gaged flows to and from Lyman Lake are about 62 percent of the total flux into and out of the lake. Gaged flows to and from the Little Colorado River downstream from Lyman Dam are about 50 percent of the total flux of the spring area.

The estimated standard errors for weekly quantities of streamflow at the gages are shown in table 1. Flow from tributaries to Lyman Lake and the Little Colorado River downstream from Lyman Lake was not gaged. Periods of large quantities of flow from these areas were not used for this analysis because of the potential for introducing large errors. Inflow from these ungaged areas was assumed to be zero for periods when no precipitation or snowmelt occurred in the area. For periods of small quantities of ungaged inflow, the quantity was estimated by hydrograph comparison of the record of streamflow and lake contents. The standard error for these few periods was about 10 percent. Ungaged inflows to the lake and spring areas were about 1 and 2 percent, respectively, of the total flux of each area.

Meteorological Components

Meteorological data collected consist of precipitation, evaporation, and transpiration. Precipitation directly on Lyman Lake was recorded by continuous rainfall recorders at three sites on and around the lake from February 18, 1985, to December 1, 1986. Precipitation data were supplemented by National Weather Service data from St. Johns and Springerville from January 1 to February 18, 1985, and during periods when rainfall instrumentation on and around the lake malfunctioned. The Thiessen method (Thiessen, 1911) was used to calculate areal rainfall averages over the lake. The error associated with the collection of precipitation data is related mainly to the distribution and density of rain gages in the study area, techniques used to average the data collected by the rain-gage network, and storm type. Several periods of thunderstorm precipitation were not used for the water budgets because potential errors were large. For the few storms that were used in the analysis, a standard error of 10 percent was estimated for periods when data were available from sites on and around Lyman Lake and 30 percent when supplemental data from the National Weather Service were used. Precipitation directly on Lyman Lake accounts for about 3 percent of the flux of the lake area.

Estimates of lake evaporation were calculated on the basis of the mass-transfer method as described by Harbeck (1962). Energy-budget data were not available to calibrate the mass-transfer coefficient for this method as suggested by Harbeck, but the method was checked against a functional relation also described by Harbeck (1962) with maximum differences of 10 percent. During periods when the mass-transfer method could not be used because of instrument malfunction, the free-water evaporation calculations described by Kohler and others (1955) were used. Data for the mass-transfer calculations were collected in the spring, summer, and fall from August 16, 1985, to December 1, 1986. The free-water method was used from June 4 to August 15, 1985. Evaporation during winter months of the study was estimated from U.S. National Weather Service Class A pan data at Many Farms, Arizona.

The accuracy of the computed or estimated evaporation varied depending on the technique used. The estimated standard errors for the mass-transfer and free-water methods and the Class A pan data were 20, 30, and 50 percent, respectively, for the budget periods. These errors seem to be consistent with values reported by Winter (1981) for evaporation. Annual evaporation for Lyman Lake as determined by this study was 18 percent greater than the annual estimate of evaporation for the Lyman Lake area as determined by the National Oceanic and Atmospheric Administration (Farnsworth and others, 1982). Standard errors for the lake evaporation were a maximum of 12 percent of the flow of the water budgets for the lake. Evaporation from Lyman Lake accounts for about 16 percent of the total water flux of the lake.

Evapotranspiration was estimated by an empirical technique described by Blaney and Criddle (1962) and modified by Rantz (1968). Evapotranspiration was estimated from January 1, 1985, to December 1, 1986. The standard errors associated with estimating evapotranspiration by this method (Cruff and Thompson, 1967) were about ±10 percent during the growing season and ±50 percent during the winter months. Evapotranspiration is about 1 percent of the total water budget for the lake area and about 10 percent of the total water budget for the spring area.

Evaporation and precipitation in the reach downstream from Lyman Dam could not be measured directly and therefore were estimated from evaporation and precipitation data for Lyman Lake and an estimate of the surface area for the river downstream from Lyman Dam. These components were estimated to be less than 1 percent of the total water budget during both summer and winter periods. To simplify the water budget, these components were excluded as relatively small and offsetting. Precipitation falling on areas other than the river in this reach is estimated as part of the ungaged inflow below Lyman Dam.

Storage Components

Changes in lake storage for the budget periods were determined from the net difference in storage at the end of each budget period. Lake storage was determined from a recent stage-storage relation established by the U.S. Soil Conservation Service for Lyman Lake (Sanders, 1984). Lake stage was recorded by a continuous-stage recorder from January 1, 1985, to December 1, 1986.

The greatest source of error for periods of unchanging lake storage was related to the precision of the measurement of lake stage. The maximum standard error for these periods was 0.02 ft of lake stage. For periods with large changes in stage, the standard errors are as small as 2 percent of the 7-day change of storage. For periods with small changes in stage, the standard errors can be a large percentage of the computed 7-day change of storage, but the amount of error, in acre-feet, introduced to most of the water budgets is small.

Bank and channel storage for the Little Colorado River in the spring area was not estimated or calculated. The brief periods in April and May 1985 and April 1986 when flow in the river was great enough to move water into storage were excluded from the water-budget analysis.

Leakage Components

Leakage from Lyman Lake and Lyman Canal was estimated from measurements of leakage generally made monthly. Leakage from the lake for the water-budget periods was estimated by prorating between leakage measurements. The change in amount of leakage from the lake was uniform because the lake level did not change rapidly or much during the study. Leakage from Lyman Canal was estimated using the periodic measurements of leakage and the amount of gaged discharge in the canal immediately downstream from the lake. Standard errors used during periods of leakage from Lyman Dam and Lyman Canal were 6 and 5 percent, respectively. Ungaged leakage for the lake and spring areas represents about 1 and 2 percent, respectively, of the total flux.

Observation-Well Data

Water levels in the Coconino aquifer were observed during the study using a network of wells (fig. 8). Two wells, (A-11-28)9acc1 and (A-11-28)22bda2, were equipped with continuous water-level recorders—one in operation from January 1, 1985, to December 1, 1986, and the other from May 22, 1985, to December 18, 1986. The remaining wells were measured monthly from January 1, 1985, to December 1, 1986. The errors associated with the measurement of water level depend on the method used to measure the well, the calibration of the device used, and the overall depth to water. The measured water levels were within 0.10 ft for shallow wells and 1.0 ft for deep wells.

Historical Data

Semiannual discharge measurements of the Little Colorado River have been made upstream and downstream from Salado Springs since 1975 (U.S. Geological Survey, 1975-86 and unpublished data). Also available since 1975 are records of discharge for the Little Colorado River below Lyman Dam and Lyman Canal (U.S. Geological Survey, 1975-86 and unpublished data), stage for Lyman Lake, annual and semiannual measurements of water level from U.S. Geological Survey well networks (U.S. Geological Survey, unpublished data), and weather conditions.

COMPUTATION OF GROUND-WATER FLOW COMPONENTS

The general water budget is used to compute ground-water flow into the spring and lake areas. The basic form of the budget that is used for 7-day periods is

$$\textit{Inflow} - \textit{outflow} = \textit{change in storage}. \qquad (1)$$

Flow to the Spring Area

The budget is used when changes in storage for 7-day periods in the spring area are not significant. Thus, periods of significant thunderstorm precipitation and of snowmelt or storm runoff in the area were not used. Using the components of flow shown in figure 7 and table 1, the budget is

$$(Gr + Sr + Ss + Sus + Ps + Ld + Lc) - (Es + So) = (\Delta S). \qquad (2)$$

For conditions of rather steady flow, the Ss, Ps, and ΔS components of equation 2 are negligible. Thus, by rearranging the components in equation 2:

$$Gr = (Es + So) - (Sr + Sus + Ld + Lc). \qquad (3)$$

The data used for equation 3 and the computed results are shown in table 2. Sixty-three 7-day budget periods could be reliably used.

The computed ground-water flow to the spring area, Gr, contains two components of flow as illustrated in figures 7 and 9—ground-water flow from the Coconino aquifer, Ga, and ground-water flow from Lyman Lake, Go. To determine ground-water flow from the lake, the quantity of ground-water flow to the spring area from the Coconino aquifer must be determined. The quantity of flow from the Coconino aquifer to the spring

Table 2.--*Flow components, lake elevation, and head difference for the spring area*

[For explanation of symbols see table 1. The number of significant digits for the flow components do not indicate accuracy]

	Components of flow for the 7-day period ending on the date indicated, in acre-feet								Elevation of the water surface of Lyman Lake, in feet above gage datum	Head difference between the lake and well (A-11-28)9accl, in feet
	Inflow				Outflow		*Gr*	SE^{1}_{Gr}		
Date	*Sr*	*Ld*	*Lc*	*Sus*	*So*	*Es*				
1985 water year										
May 27	33	8	3	0	157	62	174	7	56.78	40.06
Jun 10	73	7	0	0	175	74	168	8	56.35	39.69
Jun 17	76	7	10	0	167	74	147	8	55.88	39.30
Jun 24	77	7	29	0	194	74	156	9	55.38	39.60
Jul 01	79	6	29	0	196	74	156	9	54.95	39.29
Jul 08	83	5	25	0	188	76	151	9	54.47	37.93
Jul 15	81	5	20	165	355	76	161	20	54.22	37.72
Aug 19	75	3	17	6	173	69	140	8	52.62	36.44
Aug 26	75	3	20	4	171	69	137	8	52.14	35.90
Sep 02	80	3	17	4	171	65	132	7	51.44	35.33
Sep 09	74	3	20	0	167	56	126	7	50.81	34.75
Sep 16	61	3	17	0	165	56	139	7	50.26	34.27
Sep 23	10	3	0	6	116	56	153	6	50.27	32.00
Sep 30	8	3	0	63	174	56	155	9	50.31	31.54
1986 water year										
Oct 07	8	3	0	6	114	17	114	9	50.28	31.26
Oct 14	7	3	0	0	105	17	113	9	50.25	31.35
Oct 21	7	3	0	0	111	17	119	9	50.39	31.18
Oct 28	6	3	0	0	111	17	120	9	50.75	31.91
Nov 04	6	2	0	0	110	15	116	8	51.19	32.31
Nov 11	6	2	0	0	104	13	109	7	51.54	32.48

See footnote at end of table.

Table 2.--*Flow components, lake elevation, and head difference for the spring area*--Continued.

Date	Components of flow for the 7-day period ending on the date indicated, in acre-feet								Elevation of the water surface of Lyman Lake, in feet above gage datum	Head difference between the lake and well (A-11-28)9accl, in feet
	Inflow				Outflow		*Gr*	SE^1_{Gr}		
	Sr	*Ld*	*Lc*	*Sus*	*So*	*Es*				
Nov 18	6	2	0	0	110	13	114	7	51.81	32.88
Nov 25	6	2	0	0	111	13	116	7	52.01	33.10
Dec 02	6	2	0	0	122	12	126	6	52.30	33.45
Dec 09	6	2	0	0	117	10	118	5	52.48	33.52
Dec 16	6	2	0	0	116	10	117	5	52.61	33.58
Dec 23	6	2	0	0	116	10	118	5	52.74	33.72
Dec 30	6	2	0	0	120	10	121	5	52.83	33.72
Jan 06	6	3	0	0	121	11	123	6	52.95	33.81
Jan 13	6	3	0	0	119	11	122	6	52.99	33.91
Jan 20	6	3	0	0	123	11	126	6	53.05	34.03
Jan 27	5	3	0	0	123	11	127	6	53.12	34.12
Feb 03	5	4	0	0	126	12	130	7	53.29	34.13
Feb 10	5	5	0	0	133	13	137	7	53.38	34.28
Feb 17	5	5	0	0	126	13	130	7	53.50	34.40
Feb 24	5	5	0	0	116	13	119	7	53.63	34.71
Mar 03	5	5	0	0	116	14	120	7	53.97	35.07
Mar 10	5	5	0	0	113	16	120	8	54.35	35.60
Mar 17	5	5	0	0	128	16	134	8	54.89	36.10
May 26	82	7	3	0	179	62	149	7	54.20	35.93
Jun 02	87	7	17	0	181	66	136	8	53.68	35.52
Jun 16	54	5	17	0	153	74	150	8	52.81	34.88
Jun 23	90	5	15	0	169	74	132	8	52.14	34.38
Jun 30	100	5	5	8	183	74	138	8	51.80	34.05
Jul 07	123	3	0	0	183	72	128	8	51.41	33.87
Jul 14	99	3	3	6	179	72	139	8	50.83	33.35
Jul 21	103	3	13	14	190	72	129	8	50.42	32.86

See footnote at end of table.

Table 2.--*Flow components, lake elevation, and head difference for the spring area*--Continued.

Date	Components of flow for the 7-day period ending on the date indicated, in acre-feet								Elevation of the water surface of Lyman Lake, in feet above gage datum	Head difference between the lake and well (A-11-28)9accl, in feet
	Inflow				Outflow		*Gr*	SE_{Gr}[1]		
	Sr	*Ld*	*Lc*	*Sus*	*So*	*Es*				
Jul 28	84	3	0	0	153	72	137	8	50.28	32.85
Aug 04	88	3	2	0	155	71	132	8	49.57	32.27
Aug 18	83	3	3	30	178	70	129	8	48.41	31.34
Aug 25	80	3	20	4	161	70	124	8	48.03	30.96
1987 water year										
Oct 06	5	4	0	4	97	21	104	11	46.14	46.43
Oct 13	5	4	0	133	242	17	118	17	46.43	29.70
Oct 20	4	4	0	0	110	17	118	9	46.61	29.90
Oct 27	5	4	0	0	104	17	112	9	46.67	29.97
Nov 03	5	3	0	32	128	15	103	9	46.85	30.04
Nov 10	6	2	0	0	113	13	118	7	47.31	30.56
Nov 17	6	2	0	0	97	13	102	7	47.59	30.77
Nov 24	6	2	0	0	105	13	110	7	48.58	31.63
Dec 01	5	2	0	0	110	13	116	7	49.01	32.16

[1]Standard error.

area probably varied during the study, but the net change, if any, is insignificant because there was not a significant net change of average water level of the aquifer (fig. 6). Using the computed difference of stream-discharge measurements made upstream and downstream from Salado Springs since 1975 as an index to the total quantity of flow from the Coconino aquifer, the quantity of flow appears to vary with a maximum coefficient of variation of 0.24, but the average flow is nearly constant. The total quantity of ground-water flow to the spring area, *Gr*, is about 35 percent of the total flux of the area.

Flow from the Lake Area

Any changes in ground-water flow from the Coconino aquifer are small relative to the changes in ground-water flow from Lyman Lake that result mostly from changes in lake level. When the level of the lake surface is equal to the potentiometric head of the aquifer near the dam, the ground-water flow from the lake is zero, or flow component *Gr* equals flow component *Ga*.

If a relation between the head difference, ΔH, of the lake and the Coconino aquifer and flow component *Gr* could be defined, the flow component *Ga* could be determined from the relation at $\Delta H = 0$. Because only large head differences occurred during the study period, the relation at $\Delta H = 0$ could not be reliably defined using the results of the water-budget computations. Values of *Gr* and ΔH were also computed for periods prior to this study; these values were used to supplement the data collected during the study period (fig. 9).

The historical data were used to determine ground-water flow to the spring area for periods when flow was steady and head differences between the lake and the Coconino aquifer were small. Ground-water flow was computed as the difference in measured flow in the Little Colorado River downstream from Salado Springs and the Little Colorado River below Lyman Dam gaging station as follows:

$$Gr = (MDs + DAs) - Sr, \qquad (4)$$

where

MDs = mean discharge of Salado Springs as determined from current-meter measurements and

DAs = instantaneous discharge above Salado Springs as determined from current-meter measurements.

The computed ground-water flow into the spring area using equation 4 is comparable to using equation 3 if the following conditions are met: (1) Periods of steady flow permit the use of current-meter measurements to approximate 7-day volumes of flow and (2) ground-water inflow between Salado Springs and the gaging station at the downstream end of the spring area is negligible. The first condition is assumed to be achieved as only current-meter measurements taken during sustained steady-flow conditions were used in this analysis. Available data and field observations support the second condition.

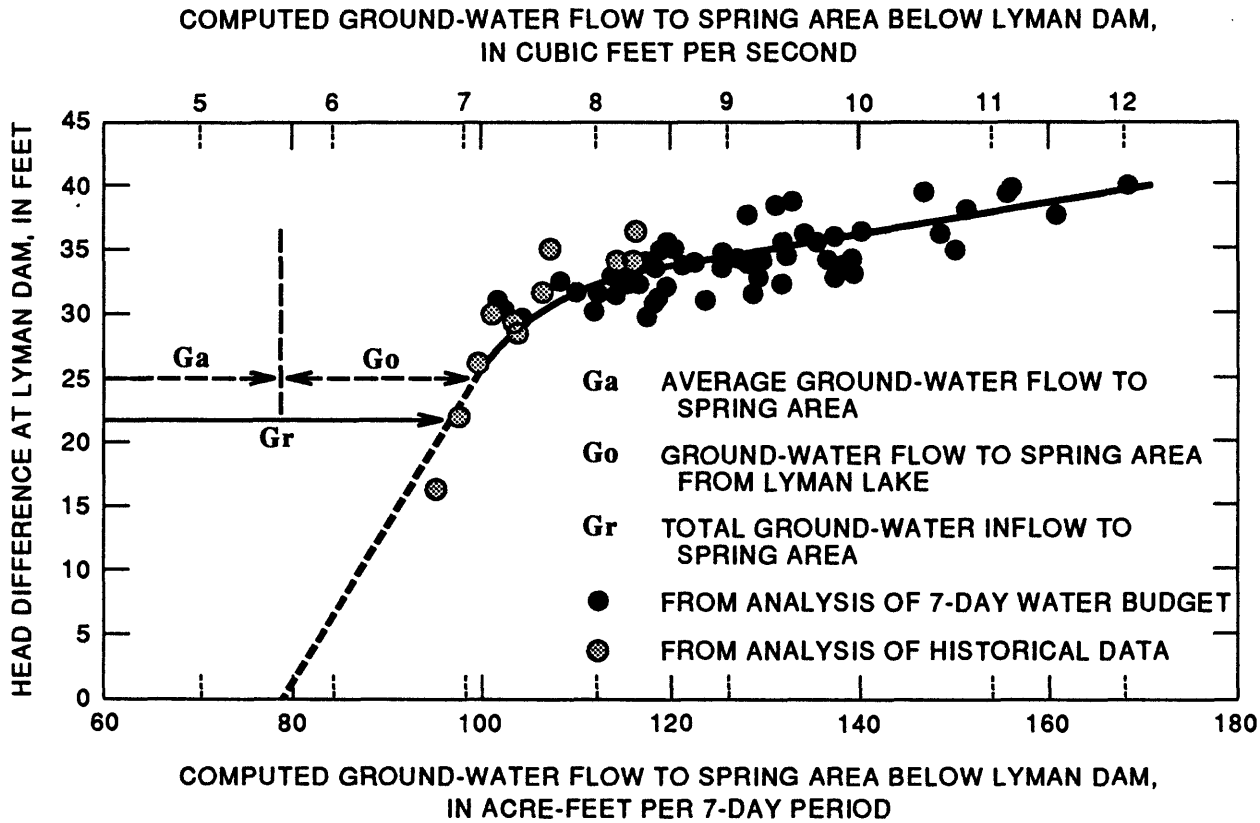


Figure 9.--Relation of head difference at Lyman Dam to computed ground-water flow to the spring area.

Twenty-four sets of data were available for the analysis using equation 4. Data sets that were influenced, or that may have been influenced, by significant amounts of evaporation, transpiration, precipitation, ungaged surface inflow, or changes in storage (unsteady flow) were excluded from the analysis. Eleven data sets met the necessary conditions and were used to compute the quantity of *Gr*. The computations are considered reliable but less precise than the water-budget computations.

The relation between the head difference of Lyman Lake and the Coconino aquifer at Lyman Dam and the ground-water flow to the spring area is shown in figure 9. The head in the aquifer is inferred from water levels at well (A-11-28)9accl near Lyman Dam (fig. 6). Thus, the computed head difference is an index of the head differences that force water through the ground over the lake-bottom area whenever the head in the lake is greater than the head in the Coconino aquifer. The relation is poorly defined for small head differences, but the estimate of about 80 acre-ft (5.8 ft^3/s) of ground-water flow to the spring area from the Coconino aquifer is considered reasonable. The break in the relation at a head difference of about 30 ft is the result of seepage at fractures and solution channels around the sides of the lake. Several seeps can be observed near the spillway. Also, the deposits of silt on the lake bottom retard the amount of seepage at low lake levels. The relation was used to determine the quantity of ground-water flow from the lake for the water budget (table 3).

Of the 100 7-day periods available for analysis, estimates of ground-water flow from Lyman Lake, *Go*, could be calculated for 63 periods (table 2). Estimated ground-water flow from Lyman Lake ranged from 23 to 94 acre-ft (1.7 to 6.8 ft^3/s) per 7-day budget period. The quantity of ground-water outflow is about 6 percent of the total water budget for Lyman Lake.

Flow to Lyman Lake

The water budget for Lyman Lake using flow components shown in figure 7 and table 1 is

$$Gi = (Go + Ld + E\ell + ET\ell + Ss + Sc + Sr) - (P\ell + Su\ell + S\ell) + \Delta s. \qquad (5)$$

For the budget periods used, the *Ss* component was negligible. The ground-water flow from the lake, *Go*, was determined from the relation in figure 9.

Ground-water flow to Lyman Lake, *Gi*, was calculated for 59 of the 63 7-day periods for which values of ground-water flow from the lake, *Go*, were available (table 3). The computed mean quantity of ground-water flow to Lyman Lake, *Gi*, for the 7-day periods was 84 acre-ft (6.0 ft^3/s) with an estimated average standard error of 69 acre-ft. The mean head difference was 31.0 ft. Ground-water inflow is about 10 percent of the total flux for the lake budget.

A statistically significant relation between the computed quantity of ground-water flow to the lake and the difference in head between the lake and observation well (A-11-28)22bda2 near the upstream end of Lyman Lake was not found (table 3). The range of head difference was less than 9 ft during the study, and the errors of the computed quantity of ground-water inflow are relatively large. Historical data are not available to further define the relation for low lake levels.

Analysis of Error

Errors associated with calculating and estimating flow components for water budgets have a significant effect on the interpretation of the results. Winter (1981) showed that the error for each flow component depends on the method of determining the component and the instrumentation used. Also, the error of the flow component computed using the water-budget equations (equations 2 and 3) is a summation of the errors for each flow component used in the equation if the errors are independent. The standard error of the flow component can be computed by the following equation:

Table 3.--*Flow components and head difference for the lake area*

[For explanation of symbols see table 1. The number of significant digits for the flow components do not indicate accuracy]

Date	Components of flow for the 7-day period ending on the date indicated, in acre-feet												Head difference between the lake and well (A-11-28)22bda2, in feet
	Inflow			Outflow						Δs	*Gi*	SE^{1}_{Gi}	
	Sl	*Sul*	*Pl*	*El*	*ETl*	*Sc*	*Sr*	*Ld*	*Go*				
1985 water year													
May 27	672	0	11	212	18	536	33	8	95	-163	55	129	26.40
Jun 10	478	0	0	284	20	440	73	7	92	-276	162	111	26.54
Jun 17	209	0	0	326	20	502	76	7	89	-763	47	120	26.89
Jun 24	200	0	0	346	20	575	77	7	92	-812	104	126	27.46
Jul 01	159	0	0	280	22	577	79	6	89	-698	197	109	27.76
Jul 08	103	0	0	342	22	573	83	5	77	-730	269	124	28.18
Jul 15	204	6	260	339	22	538	81	5	74	-460	129	145	28.44
Aug 19	160	0	0	191	21	524	75	3	64	-769	-52	68	29.47
Aug 26	98	0	22	121	21	565	75	3	59	-750	-25	61	29.92
Sep 02	79	0	25	182	20	548	80	3	54	-780	2	66	30.51
Sep 09	71	0	12	171	17	573	74	3	49	-817	-13	65	30.98
Sep 16	111	0	0	143	17	567	61	3	57	-712	24	63	31.38
Sep 23	111	1	60	127	17	0	10	3	31	13	29	59	31.73
Sep 30	89	2	81	118	17	0	8	3	28	51	52	58	32.09
1986 water year													
Oct 07	90	0	17	110	2	0	8	3	27	-39	3	57	32.29
Oct 14	102	0	4	106	2	0	7	3	28	-38	2	57	32.43
Oct 21	128	1	45	69	2	0	7	3	27	181	114	55	32.35
Oct 28	497	0	14	55	2	0	6	3	29	467	51	55	31.99
Nov 04	577	1	40	71	1	0	6	2	31	570	65	56	31.62
Nov 11	480	0	4	122	1	0	6	2	32	453	133	59	31.32

See footnote at end of table.

Table 3.--*Flow components and head difference for the lake area*--Continued.

Date	Components of flow for the 7-day period ending on the date indicated, in acre-feet												Head difference between the lake and well (A-11-28)22bda2, in feet
	Inflow			Outflow						Δs	Gi	SE^{1}_{Gi}	
	$S\ell$	$Su\ell$	$P\ell$	$E\ell$	$ET\ell$	Sc	Sr	Ld	Go				
Nov 18	411	0	26	126	1	0	6	2	37	350	85	59	31.02
Nov 25	357	0	0	68	1	0	6	2	40	260	21	64	30.87
Dec 02	311	0	0	62	1	0	6	2	42	375	177	62	30.65
Dec 09	292	0	0	45	1	0	6	2	42	234	38	58	30.58
Dec 16	238	0	0	45	1	0	6	2	42	168	27	58	30.30
Dec 23	170	0	0	45	1	0	6	2	43	169	96	58	30.14
Dec 30	110	0	0	45	1	0	6	2	43	116	104	58	30.14
Jan 06	183	0	0	41	1	0	6	3	43	172	83	57	30.05
Jan 13	175	0	0	41	1	0	6	3	44	100	20	69	29.92
Jan 20	122	0	0	41	1	0	6	3	45	98	71	69	29.91
Jan 27	110	0	0	41	1	0	5	3	46	113	99	72	29.93
Feb 03	185	0	39	56	1	0	5	4	46	276	163	71	29.77
Feb 10	181	2	78	77	1	0	5	5	47	146	21	76	29.58
Feb 17	181	0	13	77	1	0	5	5	47	195	136	80	29.41
Feb 24	250	0	0	77	1	0	5	5	49	211	98	76	28.96
Mar 03	542	0	0	88	1	0	5	5	52	552	161	83	28.52
Mar 10	603	0	0	102	2	0	5	5	56	517	183	87	28.23
Mar 17	663	0	93	103	2	0	5	5	62	877	297	86	27.73
May 26	66	0	5	188	19	508	82	7	60	-893	-100	77	29.02
Jun 02	91	1	6	188	20	532	87	7	56	-670	150	77	29.53
Jun 16	57	1	0	246	22	522	54	5	50	-815	27	74	30.23
Jun 23	45	1	13	171	22	581	90	5	47	-720	138	65	30.65
Jun 30	106	3	55	170	22	474	100	5	45	-520	132	65	30.90
Jul 07	78	2	37	158	22	417	123	3	44	-505	144	63	31.26
Jul 14	85	3	17	195	22	551	99	3	41	-752	54	67	31.90
Jul 21	174	8	63	199	22	530	103	3	37	-531	119	68	32.36

See footnote at end of table.

Table 3.--*Flow components and head difference for the lake area*--Continued.

Date	Components of flow for the 7-day period ending on the date indicated, in acre-feet													Head difference between the lake and well (A-11-28)22bda2, in feet
	Inflow			Outflow						Δs	*Gi*	SE_{Gi}[1]		
	Sℓ	*Suℓ*	*Pℓ*	*Eℓ*	*ETℓ*	*Sc*	*Sr*	*Ld*	*Go*				
Jul 28	150	3	18	178	22	117	84	3	37	-182	88	66	32.48
Aug 04	78	0	0	193	21	526	88	3	33	-830	-44	66	33.16
Aug 18	69	1	19	125	21	570	83	3	29	-630	113	49	33.94
Aug 25	46	2	68	120	21	577	80	3	28	-393	320	49	34.34
1987 water year													
Oct 06	56	3	88	93	4	0	5	4	26	-10	-25	46	35.14
Oct 13	152	3	155	79	2	0	5	4	26	290	97	46	34.85
Oct 20	176	0	2	88	2	0	4	4	27	180	127	45	35.02
Oct 27	121	0	0	80	2	0	5	4	27	60	57	44	35.15
Nov 03	185	4	116	41	2	0	5	3	27	180	-47	43	35.04
Nov 10	401	0	20	77	1	0	6	2	28	474	167	48	34.72
Nov 17	288	0	0	47	1	0	6	2	28	289	85	46	34.40
Nov 24	1,037	0	20	65	1	0	6	2	30	1,022	68	51	33.44
Dec 01	532	0	0	84	1	0	5	2	32	474	66	56	33.09

[1]Standard error.

$$SE = [(SE_1)^2 + (SE_2)^2 + (SE_3)^2 \text{ ------ } + (SE_n)^2]^{1/2}, \tag{6}$$

where the subscripts represent the flow components and $(SE)^2$ is the variance. For some of the flow components, such as the ungaged surface inflow, the standard error was estimated to be about half the maximum likely error. No error was used for a flow component for which no flow was determined during a 7-day period.

Sample computations of error for the spring and lake areas using the water budget for February 24, 1986, are as follows:

The water budget for the spring area, equation 3 (see table 2 for flow-component values), is

$$Gr = (So + Es) - (Sr + Sus + Ld + Lc)$$

and the absolute values of the component errors, in acre-ft per 7 days, are

$$SE_{Gr} = (2.3^2 + 6.48^2 + .05^2 + 0 + .28^2 + 0)^{1/2}$$

= 6.9 acre-ft per 7 days or about 6 percent of the computed ground-water flow to the spring area.

The water budget for the lake area, equation 5 (see table 3 for values of components of flow), is

$$Gi = (Go + Ld + E\ell + ET\ell + Sc + Sr) - (P\ell + Su\ell + S\ell) + \Delta s$$

and the absolute values of the component errors, in acre-ft per 7 days, are

$$SE_{Gi} = (14.7^2 + .28^2 + 38.5^2 + .13^2 + 0 + .05^2 + 0 + 0 + 5.0^2 + 64^2)^{1/2}$$

= 76 acre-ft per 7 days or about 78 percent of the computed ground-water flow to the lake area.

The computation errors for ground-water flow to the spring area, *Gr*, are relatively small and the computation is considered reliable. The computed quantity of ground-water flow from Lyman Lake, *Ga*, was determined using the relation shown in figure 9. The flow component *Ga* was determined by extending this observed relation of head difference between the index well and Lyman Lake water levels to the zero point, with sparse data below a 25-foot head difference and no data below a 15-foot head difference. There is a potentially large error in the value of *Ga*, and as it is the basis for deriving *Go*, and subsequently *Gi*, the effects of any error are carried through the entire analysis of the Lyman Lake water budget. For this study, a standard error of 30 percent was assumed for the *Go* component of the budget. The computed amount of ground-water flow to Lyman Lake is subject to large errors. Two sources of potential error are shown in the previous computation of error for February 24, 1986, in which the ground-water outflow and change of lake storage accounted for most of the error.

GEOCHEMISTRY OF SURFACE WATER AND GROUND WATER IN THE LYMAN LAKE AREA

By

Frederick N. Robertson

Water-chemistry and isotope data were used to calculate the flow of ground water to and from Lyman Lake and ground-water contributions to the downstream area. The data were used as an independent means of calculating a water budget. Data were collected from selected sites in Lyman Lake, from springs and wells in the Lyman Lake area, and from the Little Colorado River below Lyman Lake. Historical water-quality data for the Little Colorado River above Lyman Lake also were used. Samples were collected during August 9-20, 1985, and March 16-17, 1986. Water samples were analyzed for major ions and selected trace elements (table 4). Samples were also analyzed for the stable-isotope ratios of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$).

Chemical Composition of Surface Water and Ground Water

Water samples were collected from Lyman Lake in August 1985 for chemical and isotope analyses and for field measurements of pH, temperature, and specific conductance. During this sampling period, the lake levels were high. Dissolved-solids concentrations for five lake samples were calculated from specific-conductance measurements by use of a conversion factor of 0.633 derived from the four chemical analyses of the lake. Dissolved-solids concentrations were fairly uniform throughout the lake, ranging from 192 to 201 mg/L (milligrams per liter) and averaging 197 mg/L (fig. 10). The dissolved-solids concentrations of ground water, in contrast, were considerably larger and highly variable. Dissolved-solids concentrations ranged from 351 to 2,370 mg/L. The greater concentrations were attributed largely to dissolved sulfate and chloride.

Relative proportions of major ions in samples collected from Lyman Lake, wells and springs in the lake area, and the Little Colorado River below the lake and from historical data for the Little Colorado River above Lyman Lake are plotted on a trilinear diagram (fig. 11). The diagram shows distinct differences in relative proportions of ions among the sampling areas. The samples from Lyman Lake and the Little Colorado River above Lyman Lake, represented by triangles, generally are a calcium bicarbonate type and plot in a tight group on the diagram. Samples from the lake, in particular, plot in an extremely tight group. Water samples from wells and springs from the regional ground-water system (Coconino aquifer), represented by circles, contain considerably larger concentrations of dissolved solids than those from Lyman Lake or the Little Colorado River and are a sodium calcium sulfate chloride type. These samples also plot as a fairly well-defined group on the diagram but show more scatter than the surface-water samples. Average concentrations of constituents for ground water from the Coconino aquifer over those for lake water are increased by the following factors: Calcium (8), magnesium (5), sodium (14), potassium (9), sulfate (27), chloride (48), bicarbonate (3), fluoride (8), boron (18), and strontium (8). The smaller increases in calcium, magnesium, bicarbonate, and potassium may be due to

Table 4.--Chemical and isotope analyses of surface water and ground water

[Other identifier: L, C, R, indicates left, center, and right side of x-section indicated by triangle in figure 10. Site: SW, Surface water; LK, Lake; GW, Ground water; SP, Spring; µS/cm, microsiemens per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; dashes indicate no data; < indicates concentrations below detection limit for that analysis; E, estimate]

Local name or well number	Site identification	Other identifier	Type of site	Date	Time	Discharge, inst. cubic feet per second	Specific conductance (µS/cm)	pH (Standard units)	Temperature water (°C)	Hardness total (mg/L as $CaCO_3$)
Little Colorado River below Salado Springs near St. Johns	09385700	----------------	SW	08-15-85	1700	12	1,600	8.30	24.0	490
Little Colorado River above Lyman Lake near St. Johns	09384000	----------------	SW	08-23-83	1400	16	370	8.30	25.0	150
Little Colorado River below Lyman Dam (A-11-28)9bac	342215109231101	----------------	SW	08-15-85	0830	7.2	515	8.10	20.5	190
(A-11-28)10bdd	342159109220001	X-sec 9-11 R	LK	08-09-85	1030	-----	306	8.50	24.5	120
(A-11-28)9aca	342207109224701	X-sec 3-4 C	LK	08-09-85	1200	-----	310	8.50	25.0	130
(A-11-28)10cac	342150109220701	X-sec 9-11 L	LK	08-09-85	1030	-----	310	8.50	24.5	120
(A-11-28)10dda	342143109212801	X-sec 13-14 R	LK	08-09-85	0830	-----	303	8.50	21.5	-----
(A-11-28)10ddc	342134109213701	X-sec 13-14 C	LK	08-09-85	0830	-----	312	8.50	24.0	120
(A-11-28)14cda	342052109205701	X-sec 17-18 C	LK	08-09-85	1200	-----	318	8.40	21.5	-----
(A-11-28)14cdb	342052109210701	X-sec 17-18 L	LK	08-09-85	1200	-----	315	8.40	21.5	-----
(A-11-28)14dcb	342051109205001	X-sec 17-18 R	LK	08-09-85	1200	-----	318	8.40	21.5	-----
(A-11-28)15abc	342122109215001	X-sec 13-14 L	LK	08-09-85	0830	-----	312	8.50	24.0	-----
(A-11-28)9bda	342203109230601	Big Flowing Well	GW	08-15-85	1000	-----	2,050	6.70	18.5	740
(A-11-28)9dad	342148109222901	State Park Well	GW	08-20-85	1315	-----	2,800	7.00	18.5	890
(A-11-28)19aad	342030109243401	----------------	GW	08-16-85	1500	-----	690	7.70	15.0	-----
(A-11-28)22bda2	342024109220301	TEP M-6	GW	08-07-85	1500	-----	1,150	6.90	18.0	340
				08-07-85	1600	-----	1,150	6.90	18.0	330
(A-11-28)29dcd	341853109234701	----------------	GW	08-16-85	1430	-----	535	8.10	16.0	-----
(A-11-29)7dbb	342154109184001	Platt Well	GW	10-11-85	1200	-----	3,250	7.30	24.0	930
(A-11-29)28dbc	341913109163501	TEP P-14	GW	08-20-85	1130	-----	3,200	6.70	26.5	1,200
(A-12-27)35cda	342324109271601	Big White Corral	GW	08-20-85	1515	-----	880	7.30	18.0	340
				03-16-86	1200	-----	-----	----	----	-----
(A-11-28)4cbd	342240109231801	----------------	SP	08-15-85	1145	-----	3,000	6.80	17.5	1,000
(A-11-28)4dba	342247109225201	Coffer Dam-North	SP	08-15-85	1430	0.08	720	7.80	23.0	230
(A-11-28)4dbd	342241109225401	Coffer Dam-South	SP	08-15-85	1230	0.07	610	8.00	21.0	220
(A-12-28)17dca	342603109235501	Salado Springs	SP	08-16-85	1145	-----	3,220	7.90	20.0	1,000

Table 4.--Chemical and isotope analyses of surface water and ground water--Continued

Local name or well number	Silica, dis-solved (mg/L as SiO_2)	Solids, sum of consti-tuents, dis-solved (mg/L)	Nitro-gen, NO2+NO3 dis-solved (mg/L as N)	Phos-phorous ortho, dis-solved (mg/L as P)	Phos-phate, ortho, dis-solved (mg/L as PO_4)	Alum-inum, dis-solved (μg/L as Al)	Anti-mony, dis-solved (μg/L as Sb)	Arsenic, dis-solved (μg/L as As)	Barium, dis-solved (μg/L as Ba)	Beryl-lium, dis-solved (μg/L as Be)
Little Colorado River below Salado Springs near St. Johns	19	1,060	<0.100	0.020	0.06	30	<1	10	120	<0.5
Little Colorado River above Lyman Lake near St. Johns	22	247	<0.100	0.090	0.28	---	--	--	----	-----
Little Colorado River below Lyman Dam (A-11-28)9bac	20	323	<0.100	0.030	0.09	20	<1	3	91	<0.5
(A-11-28)10bdd	20	193	0.100	0.040	0.12	20	1	3	94	0.5
(A-11-28)9aca	21	198	0.120	0.030	0.09	---	--	--	----	-----
(A-11-28)10cac	20	195	<0.100	0.040	0.12	20	1	3	94	<0.5
(A-11-28)10dda	----	192E	------	------	----	---	--	--	----	-----
(A-11-28)10ddc	20	198	<0.100	0.050	0.15	---	--	--	----	-----
(A-11-28)14cda	----	201E	------	------	----	---	--	--	----	-----
(A-11-28)14cdb	----	199E	------	------	----	---	--	--	----	-----
(A-11-28)14dcb	----	201E	------	------	----	---	--	--	----	-----
(A-11-28)15abc	----	198E	------	------	----	---	--	--	----	-----
(A-11-28)9bda	13	1,370	<0.100	<0.010	-----	20	1	16	200	<10
(A-11-28)9dad	12	1,950	0.660	<0.010	-----	<10	<1	<1	<100	<10
(A-11-28)19aad	----	423E	------	------	-----	---	--	--	----	-----
(A-11-28)22bda2	5.9	688	<0.100	<0.010	-----	---	--	--	----	-----
	5.7	687	<0.100	3.60	11	---	--	--	----	-----
(A-11-28)29dcd	----	328E	------	------	-----	---	--	--	----	-----
(A-11-29)7dbb	11	2,220	<0.100	0.010	0.03	<10	1	11	<100	<10
(A-11-29)28dbc	15	2,370	<0.100	0.020	0.06	10	2	35	300	<10
(A-12-27)35cda	8.5	527	<0.100	<0.010	----	<10	<1	2	42	0.9
	----	------	------	------	----	---	--	--	----	-----
(A-11-28)4cbd	14	2,060	<0.100	<0.010	----	---	--	--	----	-----
(A-11-28)4dba	21	477	<0.100	0.070	0.21	---	--	--	----	-----
(A-11-28)4dbd	17	351	<0.100	<0.010	----	---	--	--	----	-----
(A-12-28)17dca	18	2,270	<0.100	<0.010	----	20	2	19	200	<10

Table 4.--Chemical and isotope analyses of surface water and ground water--Continued

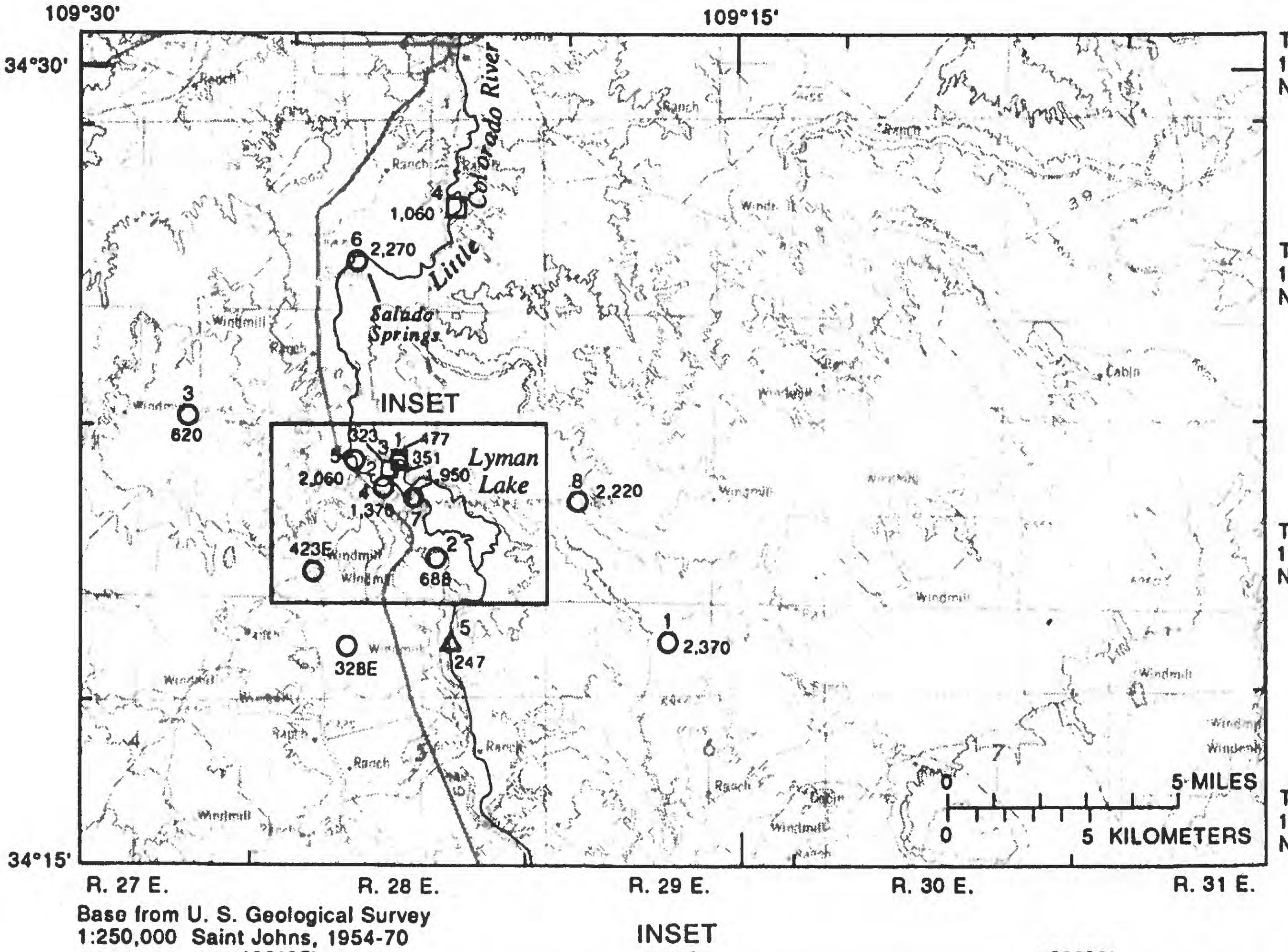
Local name or well number	Hardness noncarb Wh Wat Tot Fld (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity Wat Wh Tot Fet field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)
Little Colorado River below Salado Springs near St. Johns	220	140	34	180	4	14	274	310	200	1.3
Little Colorado River above Lyman Lake near St. Johns	0	35	16	30	1	2.8	200	11	10	0.30
Little Colorado River below Lyman Dam (A-11-28)9bac	23	50	16	42	1	3.8	169	57	31	0.60
(A-11-28)10bdd	0	31	11	20	0.8	----	139	19	7.2	0.30
(A-11-28)9aca	0	32	11	21	0.8	2.3	141	18	7.2	0.30
(A-11-28)10cac	0	31	11	20	0.8	2.4	139	19	7.2	0.30
(A-11-28)10dda	---	---	--	---	---	----	149	---	-----	----
(A-11-28)10ddc	0	29	11	20	0.8	2.4	149	19	7.0	0.30
(A-11-28)14cda	---	---	--	---	---	----	140	---	-----	----
(A-11-28)14cdb	---	---	--	---	---	----	140	---	-----	----
(A-11-28)14dcb	---	---	--	---	---	----	140	---	-----	----
(A-11-28)15abc	---	---	--	---	---	----	149	---	-----	----
(A-11-28)9bda	320	210	51	200	3	15	419	390	230	2.3
(A-11-28)9dad	550	230	77	320	5	20	350	690	380	0.40
(A-11-28)19aad	---	---	--	---	---	----	302	---	-----	----
(A-11-28)22bda2	110	94	26	110	3	19	229	120	170	2.8
	100	89	27	110	3	11	229	120	170	2.8
(A-11-28)29dcd	---	---	--	---	---	----	228	---	---	----
(A-11-29)7dbb	410	270	62	350	5	23	522	720	460	2.9
(A-11-29)28dbc	590	350	67	370	5	25	560	740	460	2.8
(A-12-27)35cda	70	86	30	53	1	14	271	95	71	2.8
	---	---	--	---	---	----	---	---	---	---
(A-11-28)4cbd	490	310	63	320	5	22	550	610	390	2.3
(A-11-28)4dba	5	56	22	76	2	5.0	226	140	19	2.1
(A-11-28)4dbd	0	59	17	41	1	6.8	218	69	8.9	1.6
(A-12-28)17dca	590	300	65	400	6	26	430	720	480	2.5

Table 4.--Chemical and isotope analyses of surface water and ground water--Continued

Local name or well number	Boron, dissolved (μg/L as B)	Cadmium, dissolved (μg/L as Cd)	Chromium, dissolved (μg/L as Cr)	Cobalt, dissolved (μg/L as Co)	Copper, dissolved (μg/L as Cu)	Iron, dissolved (μg/L as Fe)	Lead, dissolved (μg/L as Pb)	Manganese, dissolved (μg/L as Mn)	Mercury, dissolved (μg/L as Hg)
Little Colorado River below Salado Springs near St. Johns	330	<1	<1	2	4	12	<2	17	<0.1
Little Colorado River above Lyman Lake near St. Johns	50	--	--	--	--	27	<1	6	----
Little Colorado River below Lyman Dam (A-11-28)9bac	70	<1	<1	<1	2	11	3	11	<0.1
(A-11-28)10bdd	30	1	1	1	8	5	1	48	0.1
(A-11-28)9aca	30	--	--	--	--	26	--	32	----
(A-11-28)10cac	30	<1	1	<1	8	5	<1	48	<0.1
(A-11-28)10dda	---	--	--	--	--	-----	--	---	----
(A-11-28)10ddc	30	--	--	--	--	<3	--	41	----
(A-11-28)14cda	---	--	--	--	--	-----	--	---	----
(A-11-28)14cdb	---	--	--	--	--	-----	--	---	----
(A-11-28)14dcb	---	--	--	--	--	-----	--	---	----
(A-11-28)15abc	---	--	--	--	--	-----	--	---	----
(A-11-28)9bda	360	<1	1	<1	3	480	2	30	<0.1
(A-11-28)9dad	410	<1	<1	<1	3	110	3	70	<0.1
(A-11-28)19aad	---	--	--	--	--	-----	--	---	----
(A-11-28)22bda2	210	--	--	--	--	3,000	--	230	----
	220	--	--	--	--	2,900	--	220	----
(A-11-28)29dcd	---	--	--	--	--	-----	--	---	----
(A-11-29)7dbb	730	1	<1	1	1	20	<1	40	----
(A-11-29)28dbc	710	<1	<1	<1	<1	2,600	3	50	<0.1
(A-12-27)35cda	480	<1	<1	<1	3	1,500	6	36	<0.1
	---	--	--	--	--	-----	--	--	----
(A-11-28)4cbd	610	--	--	--	--	180	--	30	----
(A-11-28)4dba	200	--	--	--	--	13	--	20	----
(A-11-28)4dbd	130	--	--	--	--	11	--	34	----
(A-12-28)17dca	750	<1	<1	<1	<1	30	4	<10	<0.1

Table 4.--Chemical and isotope analyses of surface water and ground water--Continued

Local name or well number	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Selenium, dissolved (µg/L as Se)	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Zinc, dissolved (µg/L as Zn)	Cyanide, dissolved (mg/L as Cn)	O-18/O-16 Stable isotope ratio per mil	H-2/H-1 Stable isotope ratio per mil
Little Colorado River below Salado Springs near St. Johns	1	4	<1	<2.0	1,400	8	<0.01	-8.69	-69.4
Little Colorado River above Lyman Lake near St. Johns	-	--	--	----	-----	---	-----	------	-----
Little Colorado River below Lyman Dam (A-11-28)9bac	1	1	<1	<1.0	480	31	<0.01	-7.73	-64.0
(A-11-28)10bdd	1	2	1	1.0	310	21	0.01	-7.64	-66.3
(A-11-28)9aca	-	--	--	----	-----	---	-----	-7.70	-62.4
(A-11-28)10cac	1	2	<1	<1.0	310	21	<0.01	-7.65	-64.0
(A-11-28)10dda	-	--	--	----	-----	---	-----	-7.52	-62.4
(A-11-28)10ddc	-	--	--	----	-----	---	-----	-7.61	-65.3
(A-11-28)14cda	-	--	--	----	-----	---	-----	-7.70	-67.1
(A-11-28)14cdb	-	--	--	----	-----	---	-----	-7.55	-65.3
(A-11-28)14dcb	-	--	--	----	-----	---	-----	-7.63	-64.5
(A-11-28)15abc	-	--	--	----	-----	---	-----	-7.65	-64.0
(A-11-28)9bda	2	1	<1	<1.0	1,700	30	<0.01	-10.83	-76.4
(A-11-28)9dad	4	3	12	<1.0	2,700	50	<0.01	-8.18	-68.0
(A-11-28)19aad	-	--	--	----	-----	---	-----	-7.70	-59.3
(A-11-28)22bda2	-	--	--	----	-----	---	-----	-10.43	-77.3
	-	--	--	----	-----	---	-----	------	-----
(A-11-28)29dcd	-	--	--	----	-----	---	-----	-9.37	-70.7
(A-11-29)7dbb	2	5	<1	<1.0	2,400	10	-----	------	-----
(A-11-29)28dbc	3	<1	<1	<1.0	2,800	30	<0.01	-11.04	-83.7
(A-12-27)35cda	3	2	<1	<1.0	1,600	520	<0.01	-11.65	-92.1
	-	--	--	----	-----	---	-----	-11.75	-86.5
(A-11-28)4cbd	-	--	--	----	-----	---	-----	-10.69	-80.3
(A-11-28)4dba	-	--	--	----	-----	---	-----	-6.99	-61.7
(A-11-28)4dbd	-	--	--	----	-----	---	-----	-6.29	-57.5
(A-12-28)17dca	1	1	<1	<1.0	2,800	20	<0.01	-10.46	-79.6



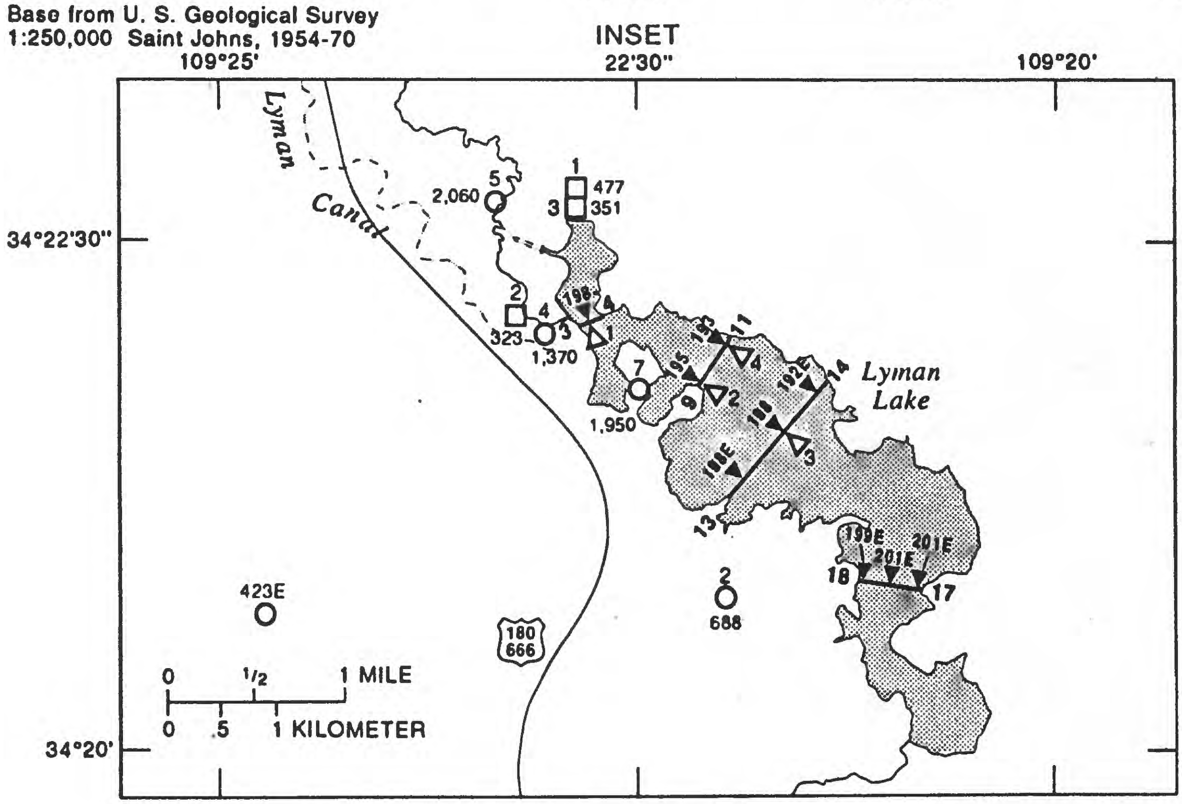


Figure 10.--Dissolved-solids concentrations in surface water and ground water, 1985-86.

EXPLANATION

△ 5 247 — SURFACE-WATER SITE—Number, 5, indicates site on the trilinear plot. Number, 247, is dissolved-solids concentration, in milligrams per liter

○ 6 2,270 — GROUND-WATER SITE—Number, 6, indicates site on the trilinear plot. Number, 2,270, is dissolved-solids concentration, in milligrams per liter; E, estimated from conductance measurements of the Coconino aquifer

1,060 4 □ — SITE OF POSSIBLE MIXTURE OF SURFACE WATER AND GROUND WATER—Number, 4, indicates site on the trilinear plot. Number, 1,060, is dissolved-solids concentration, in milligrams per liter

201E 18 —▼— 17 — LAKE CROSS SECTION—Numbers at ends of cross sections, 18 and 17, are reference points from Sanders (1984). Triangle indicates site where lake was sampled. Number, 201E, is dissolved-solids concentration, in milligrams per liter; E, estimated from conductance measurements of Lyman Lake

Figure 10.

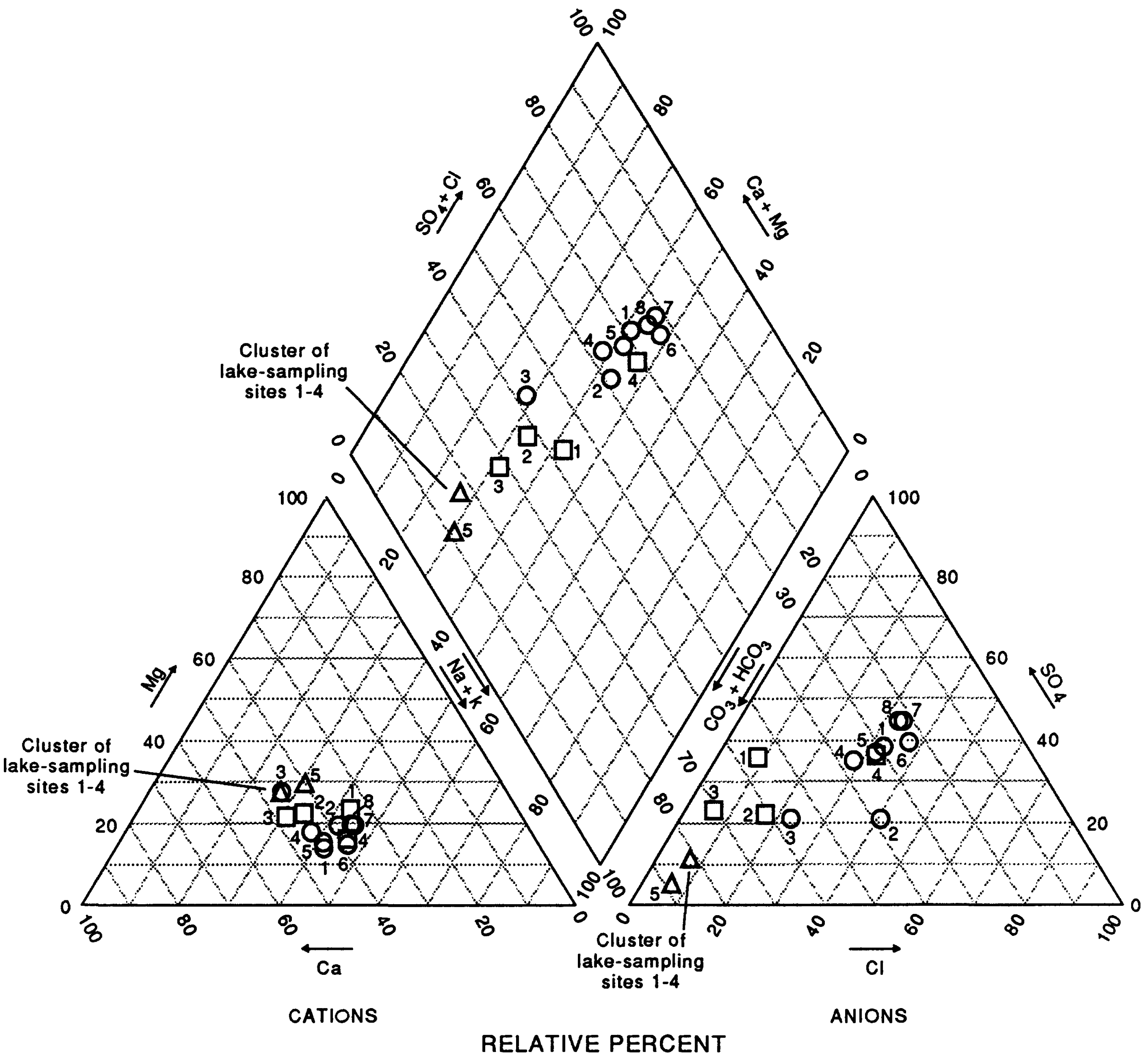


Figure 11.--Relative proportions of major ions in surface water and ground water.

EXPLANATION

△ 1	Site (A-11-28)9aca	Lake-water sample
△ 2	Site (A-11-28)10cac	Lake-water sample
△ 3	Site (A-11-28)10ddc	Lake-water sample
△ 4	Site (A-11-28)10bdd	Lake-water sample
△5	Site 09384000	Little Colorado River above Lyman Lake sample
○ 1	Site (A-11-29)28dbc	Well-water sample, Coconino aquifer
2○	Site (A-11-28)22bda2	Well-water sample, Coconino aquifer
3 ○	Site (A-12-27)35cda	Well-water sample, Chinle(?) Formation
4○	Site (A-11-28)9bda	Well-water sample, Coconino aquifer
5○	Site (A-11-28)4cbd	Spring-water sample, Coconino aquifer
○6	Site (A-12-28)17dca	Salado Springs sample, Coconino aquifer
○7	Site (A-11-28)9dad	Well-water sample, Coconino(?) aquifer
8○	Site (A-11-29)7dbb	Well-water sample, Coconino(?) aquifer
1□	Site (A-11-28)4dba	Coffer Dam Spring north sample
□ 2	Site (A-11-28)9bac	Little Colorado River below Lyman Dam sample
3□	Site (A-11-28)4dbd	Coffer Dam Spring south sample
□ 4	Site 09385700	Little Colorado River below Salado Springs sample

NOTE: Symbols and numbers correspond to locations of sites on figure 10.

Figure 11.

precipitation and sorption reactions and larger increases in sulfate and chloride to dissolution reactions not controlled by mineral equilibrium solubilities or sorption reactions. This difference in chemistry between the surface-water and ground-water groups can be interpreted as different evolutionary paths from the point of recharge in the White Mountains to discharge near Lyman Lake. The samples represented by squares and positioned between these two groups (fig. 11) may be mixtures of ground water and surface water or simply waters that have different geochemical histories as related to a particular flow path.

Ground-Water Flow to Lyman Lake

The Little Colorado River below Lyman Lake at Lyman Dam has a water chemistry that appears to be a mixture of lake water and ground water from the Coconino aquifer. The sample shows an increase in dissolved-solids concentrations and plots in figure 11 on a mixing line between the surface water and ground water, suggesting that some ground water has entered the lake. This sample is particularly critical because it reflects the composition of the lake water immediately below the dam. Mass-balance constraints and average concentrations of major and trace elements in water from the Coconino aquifer (defined below in the isotope hydrology discussion) and concentrations in Lyman Lake at cross-section 9-11 were used to determine the quantity of ground water that appears to have entered the lake. The relation of the surface-water and ground-water components is given in the following equation:

$$C_m = C_1 \times Q_1 + C_2 \times Q_2, \tag{7}$$

where

C_m = concentration of constituent in mixture of spring, well, or river water;

C_1 = concentration of constituent in ground water;

C_2 = concentration of constituent in lake water;

Q_1 = percentage of ground water in mixture; and

Q_2 = percentage of lake water in mixture.

Using the trace elements of boron and strontium, the ground-water contribution was calculated to be 8.02 ±0.01 percent. Using the elements of sodium, chloride, and sulfate as the most conservative species, a contribution of 7.71 ±0.7 percent was calculated. Examination of the saturation state of the ground water (Ball and others, 1980) indicate that the above species should act conservatively. The ground water from well TEP P-14 and Salado Springs, which contain the largest concentrations of bicarbonate, calcium, magnesium, chloride, and sulfate, are saturated to oversaturated with respect to calcite, aragonite, and dolomite and undersaturated with respect to gypsum, halite, celestite, and strontianite. Lyman Lake water is saturated with respect to aragonite, calcite, and dolomite and highly undersaturated with respect to halite, gypsum, celestite, and strontianite. The lower Colorado River below Salado Springs, which contains a mixture of the two waters, is oversaturated with respect to aragonite, calcite, and dolomite, and also is highly undersaturated with respect to halite, gypsum, celestite, and stronianite. Thus, these constituents should behave conservatively in all waters. Boron and strontium were used in a separate calculation because they are constituents that are particularly strong indicators of ground water and also tend to act conservatively (Robertson, in press). The presence of about 8 percent ground water in the Little Colorado River at this location supports the conceptual model, and the percentage is close to the estimate of 10 percent for ground-water flow into Lyman Lake as determined by water-budget computations.

Ground-Water Flow to the Spring Area

Chemical data also were used to examine mixing of ground water and surface water downstream from Lyman Dam. Using dissolved-solids and chloride concentrations of water from the Little Colorado River below Salado Springs and from Salado Springs as conservative elements, the inflow of ground water to the Little Colorado River between Lyman Dam and the Little Colorado River below Salado Springs gaging station was calculated using equation 7. The calculated inflow of ground water to the river using dissolved-solids and chloride concentrations were 37.8 and 37.6 percent, respectively. Thus, the chemical data, supported by the isotope data discussed next, does indicate that significant ground water is discharging from the Coconino aquifer to the Little Colorado River between the dam and the gaging station or at least along the reach near Salado Springs. Because the potentiometric surface of the Coconino aquifer is slightly above the land surface near Lyman Dam and at Salado Springs, a ground-water contribution to the Little Colorado River in the spring area is expected.

A similar mass balance to calculate ground-water inflow to the lake between the Little Colorado River above Lyman Lake gaging station and Lyman Lake was indeterminate. The most recent analysis shows that the concentrations of the dissolved constituents in the Little Colorado River above Lyman Lake were very near those of the lake, with most values being slightly larger (table 4). Calcium, magnesium, potassium, and chloride had differences of less than 5 mg/L and sodium and sulfate of less than 10 mg/L. These differences are close to the precision of the analytical method for some of these constituents. Historical data also show that these values, although variable, tend to be small. The smaller dissolved-solids concentrations in the lake compared to those in the river indicate that a dilution of the river water apparently has occurred. Depending on the dissolved-solids content of the precipitation and runoff entering the lake, the dilution factor could be significant. For example, if a diluting water contained 2 mg/L, the river would be diluted by about 20 percent. Until more is known about the composition of the inflow water, particularly the isotope content of the Little Colorado River above Lyman Lake, any determination is difficult. Because of these small differences, which require additional data, and the uncertainties in change in storage of the lake caused by precipitation, evapotranspiration, and inflow and outflow, a mass-balance calculation with the inflow value was not attempted.

Deuterium and ^{18}O Content of Surface Water and Ground Water

Water samples were analyzed for $^{18}O/^{16}O$ ratios (^{18}O) and $^{2}H/^{1}H$ ratios (deuterium). The locations of sample sites are shown in figure 8. The isotopic compositions presented in this paper are reported by δ (delta) notation:

$$\delta = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 10^3, \qquad (8)$$

where R is either the $^{2}H/^{1}H$, or $^{18}O/^{16}O$, isotope ratio and all values are reported in per mil (°/₀₀). Positive values show the sample to be enriched in the heavy isotope species, and negative values show the sample to be depleted in the heavy isotope species relative to the standard. δD and $\delta^{18}O$ are reported relative to the Standard Mean Ocean Water (SMOW).

Water from Lyman Lake has a distinctive isotopic composition that is enriched in deuterium and ^{18}O relative to the ground water. Although the lake water has a distinctive composition, the isotope data could not be used with any certainty to calculate inflow, outflow, or mixing. The lake water shows an enrichment of the heavier isotopes that can be derived from those of the regional ground-water system through evaporation. The δD and $\delta^{18}O$ values of the ground water, surface water, and lake water are shown in figure 12. An evaporation line of slope 5 corresponds to evaporation lines determined in other parts of the State (Robertson, 1984). Water that has not undergone evaporation since its origin as precipitation normally falls along the meteoric water line with a slope of about 10 (Craig, 1961). The evaporation effect can be seen from the waters that plot along the line with a slope of 5 between the ground waters and surface waters. The evaporation trend along this line departs from the meteoric water line expressed by the equation $\delta D = 8\delta^{18}O + 10$. A local ground-water line established for the Basin and Range physiographic province in Arizona parallels the meteoric water line but falls slightly to the right with a smaller deuterium excess (Robertson, 1984; in press).

The δD and $\delta^{18}O$ values of the nine samples from Lyman Lake plot in a relatively tight group: δD, -64.59 ±1.60°/₀₀ and $\delta^{18}O$, -7.63 ±0.06°/₀₀. Because the mean and the standard deviation of the individual sample groups from various parts of the lake fall within this range, any difference is difficult to discern, particularly in view of the precision of the analytical method, which is about ±2.0 for δD and ±0.15°/₀₀ for $\delta^{18}O$.

A small but noticeable evaporation effect can be observed in the δD of the lake water being enriched in the heavier isotope from inflow to

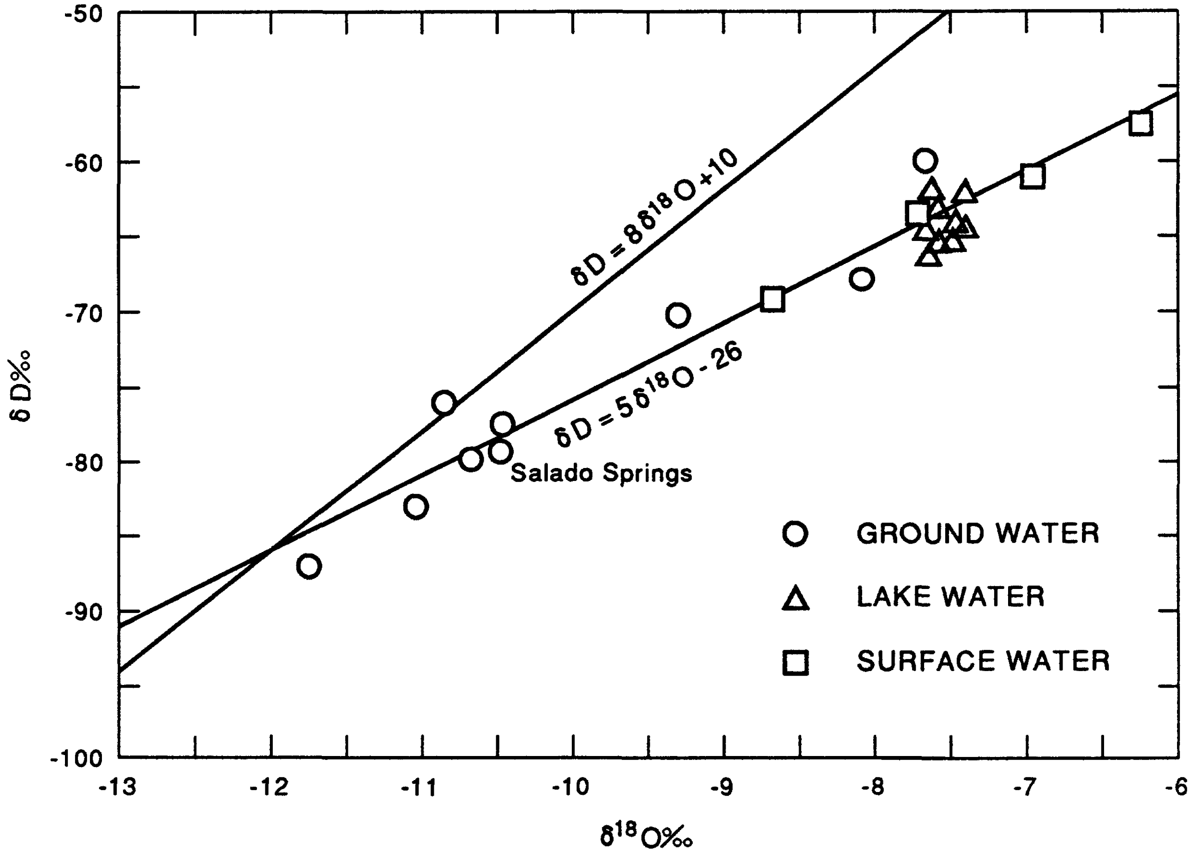


Figure 12--δD and $\delta^{18}O$ values of surface water, ground water, and lake water.

outflow. δD is used for the comparison because it is less affected by evaporation. Samples taken in the lake nearest the inflow point of the Little Colorado River at cross-section 17-18 (fig. 10) have a mean δD content of -65.63 ±1.33°/₀₀ ($\delta^{18}O$, -7.63 ±0.06°/₀₀). Samples taken at midpoint of cross-section 13-14 have a mean content of -63.90 ±1.45°/₀₀ ($\delta^{18}O$, -7.57 ±0.06°/₀₀). A sample taken near the outflow of Lyman Lake at cross-section 3-4 has a content of -62.40°/₀₀ ($\delta^{18}O$, -7.7).

The δD value of -67.1°/₀₀ from the center sample in cross-section 17-18 is of special interest. The sample is slightly more depleted in the heavier isotope than the lake average and is isotopically the lightest sample from the lake. It is of interest because, in addition to the evaporation process just discussed, an inflow of ground water to the lake could have caused the same effect because the δD content of the Coconino aquifer is depleted about 15°/₀₀ relative to the lake. The sample was taken at the upstream end of the lake, thus a ground-water inflow interpretation would be in accordance with the conceptual model as the potentiometric surface of the Coconino aquifer is above the lake at this point. More isotopic data from the lake, particularly the deeper parts, and from the Little Colorado River above the lake would be needed to determine if the difference was due to ground-water inflow or to evaporation or to analytical precision. Analytical aspects are critical because the small percentages in question would require a δD difference of only 1 or 2°/₀₀ for the lake.

Although application of the isotope data was not successful in determining the ground-water component of Lyman Lake, the data were essential in defining the ground water of the Coconino aquifer that was used in the chemical interpretations and in determining mixing of surface water and ground water below Lyman Dam. The δD and $\delta^{18}O$ values of the samples from Salado Springs (A-12-28)17dca; unnamed spring (A-11-28)4cbd; and wells (A-11-29)28dbc, (A-11-28)9bda, and (A-11-28)22bda2 form a tight group in the lower left part of figure 12 and appear to adequately represent the stable-isotope content of the Coconino aquifer. Calculated mean and standard deviation for δD and $\delta^{18}O$ for the two springs and three wells are -79.46 ±2.86°/oo and -10.68 ±0.24°/oo, respectively. The samples, which were collected from locations about 5 to 6 mi north and northwest of Lyman Lake, adjacent to the lake, 2 mi south of the lake, and about 6 mi to the southeast (fig. 10), should adequately represent the regional aquifer system. The isotope content of Salado Springs (δD, -79.60°/oo and $\delta^{18}O$, -10.46°/oo), a major ground-water discharge point in the area for the Coconino aquifer, also indicates that this mean value is representative of the regional system. The two samples to the southwest from wells (A-11-28)29dcd and (A-11-28)19aad are enriched in their heavier isotope content relative to the Coconino aquifer and probably represent mixtures of water from the regional aquifer and from locally recharged waters. The dilution through local recharge is also apparent by the large bicarbonate concentration and small dissolved-solids concentrations relative to the regional aquifer. Coffer Dam Spring south and Coffer Dam Spring north, although classified as springs, are essentially lake water that emerges to the land surface below Lyman Dam. The heavier isotope content of these two samples probably was caused by additional evaporation since leaving the lake.

The isotope data were used analogously to the chemical data to calculate mixing of surface water and ground water between Lyman Dam and the Little Colorado River below Salado Springs. Using the average δD and $\delta^{18}O$ values determined for the Coconino aquifer and Lyman Lake and the value of the Little Colorado River below Salado Springs, percentages of 32.4 and 34.7 were determined for δD and $\delta^{18}O$, respectively, for ground-water inflow to the river. These values are lower but are in good agreement with the values determined by the water chemistry and thus indicate that about 36 percent (35.6 ±2.6 for the four calculations) of the water in the Little Colorado River along this reach is being supplied by the Coconino aquifer.

Relation to the Conceptual Model

The geochemical data are in general agreement with the conceptual model as idealized in figure 7. The potentiometric surface of the Coconino aquifer is above the lake level at full pool at the upstream end of the lake but is at a point just above the land surface near Lyman Dam. During the study, the lake was not always at full pool and the surface at the upstream end was below the head of the Coconino aquifer, thus causing ground-water flow from the aquifer into the lake, at least at the upstream end, as illustrated in the model. The chemical data indicate that about 8 percent of the surface water leaving Lyman Dam is derived from ground water.

The isotope data and the chemical data show that ground water is discharging from the Coconino aquifer to the Little Colorado River below Lyman Dam. The potentiometric surface of the Coconino aquifer is above the land surface at Lyman Dam and at Salado Springs, supplying the driving force for ground-water flow into the river. The computed 35.7 percent of the ground-water inflow to the spring area is in good agreement with the 35 percent computed from the water budget and with the conceptual model. The calculated contribution of the water from the Coconino aquifer is based on the isotopic and chemical composition of the aquifer as defined by the stable isotopes and on the isotopic and chemical composition of the Little Colorado River at the gaging station. The calculations specify only the ground-water contribution to the river between the dam and the gaging station. Total ground-water contribution measured at the gaging station represents the sum of two components—ground-water flow from the lake above the dam and ground-water flow to the river below the dam.

The percentage of ground-water flow to the river calculated by use of the isotope data represents the sum of these two components. The ground-water component of the lake was not determined by the isotopes because of the similarity of the isotope values of the lake. Mass-balance calculations made using chemical constituents of the lake water and of the waters downstream infer that about 5 percent of the ground water is supplied by the lake and the rest is contributed below the dam. Using chloride and dissolved-solids concentrations of water from the lake, at the gaging station, and from Salado Springs, percentages of 40.8 and 41.6, respectively, were calculated. The chemical data may be more reliable in this case because calculations can be made using more than one constituent. A similar percentage of 40.7 for the ground-water contribution between the lake and Salado Springs can be derived using the single δD value of $-62.4^{\circ}/_{\circ\circ}$ that was taken at the downstream end of the lake. The downstream part is where inflow to the ground-water system would be anticipated as the potentiometric surface of the aquifer is below the lake elevation at this point. Thus, using the chemical data and the single deuterium value, the ground-water contribution to the Little Colorado River would be about 36 percent from the Coconino aquifer below the dam and about 5 percent from ground water from the lake.

In general, the chemical and isotope data support the conceptual model. Ground water in the amount of the previously calculated 8 percent appears to enter the lake somewhere, probably near the upstream end. A small ground-water component from the lake, as much as 5 percent, also appears to flow to the river at some point, presumably near the dam. Finally, the chemical data and the isotope data show that the Coconino aquifer supplies about 36 to 41 percent of the flow to the Little Colorado River between Lyman Lake and the gaging station below Salado Springs.

SUMMARY AND CONCLUSIONS

Surface-water and ground-water resources of the area were defined quantitatively by the use of water budgets and geochemical data. Ground-water flow to and from Lyman Lake was computed using water budgets. The computations were subject to errors associated with each of the flow components used in the water budget. Results of the computations support the conceptual model for the spring area; the conceptual model for the lake area could not be confirmed or disputed.

One hundred 7-day budget periods were available for analysis from January 1, 1985, to December 1, 1986. Computed ground-water flow from Lyman Lake was from 23.0 to 94.0 acre-ft per 7-day period for 63 budgets that could be used for this analysis. The estimated standard error associated with the computed quantity of ground-water outflow was about 30 percent. During the study period, the estimated quantity of ground-water flow from Lyman Lake accounted for about 6 percent of the total water budget of the lake. The mean quantity of ground-water flow to Lyman Lake was 84 acre-ft (6.0 ft^3/s) for the budget periods that were used for this analysis and the mean head difference at the upstream end of the lake was 31.0 ft. The estimated standard error associated with the computed ground-water flow to Lyman Lake was from 43 to 145 acre-ft and averaged 69 acre-ft. During the study period, estimated ground-water flow to Lyman Lake accounted for about 10 percent of the total water budget of the lake. Water levels in the Coconino aquifer, as measured at observation wells around Lyman Lake, had only minor seasonal fluctuations. Changes in lake elevation varied through a range of about 10 ft. This combined effect resulted in a range of head difference of about 9 ft at the upstream end of the lake. A relation between ground-water inflow to the lake and the head difference between the Coconino aquifer and the lake level could not be defined because of (1) the limited range of head difference, (2) possible differences between the conceptual and actual behavior of the complex relation between surface-water and ground-water flow in the area, and (3) the relatively large errors of the computed ground-water flow to Lyman Lake. A poorly defined relation between ground-water flow from the lake and the head difference between the Coconino aquifer at the downstream end of the lake and lake level was determined, and the shape of the relation agrees with observations of seepage from the lake.

The stable-isotope data could not be used to distinguish between surface water and ground water in the lake because both waters apparently originated in the same geographic area. The calculations using concentrations of dissolved constituents of Lyman Lake and of the Little Colorado River below Lyman Lake show that about 8 percent of the flow leaving the lake is ground water. This percentage is within the range of the water budget for the lake. Chemical and deuterium data indicate that as much as 5 percent of ground-water flow to the little Colorado River between Lyman Dam and Salado Springs may originate as lake seepage. The chemical and isotope data clearly show that the Coconino aquifer contributes about 36 to 41 percent of the water in the Little Colorado River in the spring area. This percentage includes the ground-water component above and below Lyman Dam. These results are in agreement with the conceptual model of the interactive flow system of ground water and surface water.

The ability of the water-budget method as applied in this study to determine ground-water flow to and from Lyman Lake is largely dependent on the range of lake stage that occurred during the study. The results were severely limited because less than one-third of the potential range of lake level occurred with only high lake levels for a 10-foot range. Water-budget and geochemical data tend to confirm the conceptual model for the spring area but neither confirm nor dispute the conceptual model for the Lyman Lake area. Only an estimate of mean ground-water flow to Lyman Lake at an average head difference was made, and a relation between ground-water flow to the lake and the difference in head between the lake and the Coconino aquifer could not be defined. Additional data collection and water-budget computations when the lake level is low perhaps would be useful in defining a relation. If the water levels and hydraulic gradient of the Coconino aquifer remain stable, the results of a future study could be used to enhance the results of this study.

Additional water-chemistry and isotope data would be useful in a future study. Increased sampling of δD and $\delta^{18}O$ of Lyman Lake at depth and in upstream and downstream parts and, most importantly, of the Little Colorado River above Lyman Lake may aid in quantifying the ground-water inflow and outflow of the lake. Sampling at lower lake levels also would be useful. At lower lake levels, different amounts of mixing of ground water and surface water may occur and may be reflected in the water chemistry or the isotope content. Ground-water flow into the lake would be less diluted by surface water, and the ground-water geochemistry would play a larger role in the quantification of flow components.

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