WATER BALANCE IN UPPER LAKE MARY

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Upper Lake Mary is one of many sources of drinking water for the city of Flagstaff, Arizona, but it is the only surface water. The other sources are ground water in deep aquifers. On average, the amount of water withdrawn from Lake Mary has accounted for 46 percent of Flagstaff's water supply since its construction in 1941, but only 29 percent during the relatively dry period of the last 10 years. The lake also serves as a recreational facility for the people of Flagstaff and others coming from outside the city as well as a habitat for numerous wild animals in the area. Its proximity to town, good accessibility, water availability throughout the year, and suitable location make Lake Mary one of the best areas for viewing wildlife and birds (Coconino National Forest 1999).

Upper Lake Mary and its twin, Lower Lake Mary, are located in the lake Mary graben, a down-dropped block between the Anderson Mesa fault to the north and the Lake Mary fault to the south. Precipitation onto the surface and runoff from the surrounding watershed are the main inputs into the lake. Evaporation, seepage into the ground, and withdrawal for drinking water are the main outputs from the lake.

In this study, we use a water budget approach to characterize the hydrology of the lake and to determine the amount of water available, by month and by year, for various purposes. The basic assumption in the water budget calculation is that the total amount of water entering Lake Mary is equal to the total amount of output from the lake plus any change in the lake storage.

DESCRIPTION OF THE STUDY AREA

Upper Lake Mary is a long and narrow artificial lake located in the high plateau region of north-central Arizona, about 10 miles southeast of Flagstaff (see Figure 1). It was created in 1941 by constructing an earthen dam to provide a source of water for the city of Flagstaff. In response to increased population in the city, the height of the dam was raised in 1951 to double the capacity of the lake. The lake is 5 miles long, and a half mile and 300 feet wide at the widest and narrowest sections of the lake, respectively. The water surface level of the lake varies widely, depending on annual precipitation and surface runoff. At full capacity, when the water surface tops the spillway, the surface area of the lake reaches its maximum size of 876 acres, with 15,620 acre-feet of capacity. When full, the lake near the dam is 40 feet deep, and it averages 17.9 feet deep over the entire area.

Upper lake Mary has various environmental and resource functions. In addition to being a source of drinking water for Flagstaff, it serves as a recharge basin to the underlying aquifer and its surface water is used for fishing and boating. The lake is also a habitat for various wildlife species and an excellent area for picnicking, sunbathing, wildlife watching, and nature photography. However, this study is concerned only with estimating the water balance in the area.

WATER BALANCE COMPONENTS

A water balance analysis is one of the best ways to characterize the hydrology and water resources of an area, because the approach includes all aspects of hydrology and other important factors that affect the system (Warren et al. 2002). The water balance is expressed in the form of an equation that describes the relationship between inputs, outputs, and any change in storage. Furthermore, the input and output parts are expressed in terms of many variables representing the different factors that contribute to each part. For Lake Mary, the water balance equation is expressed as follows:

$$P + R - E - G - Q = \Delta S \qquad [1]$$

where

- P = the amount of precipitation falling on the surface of the lake
- R = the amount of runoff entering the lake from the surrounding watershed

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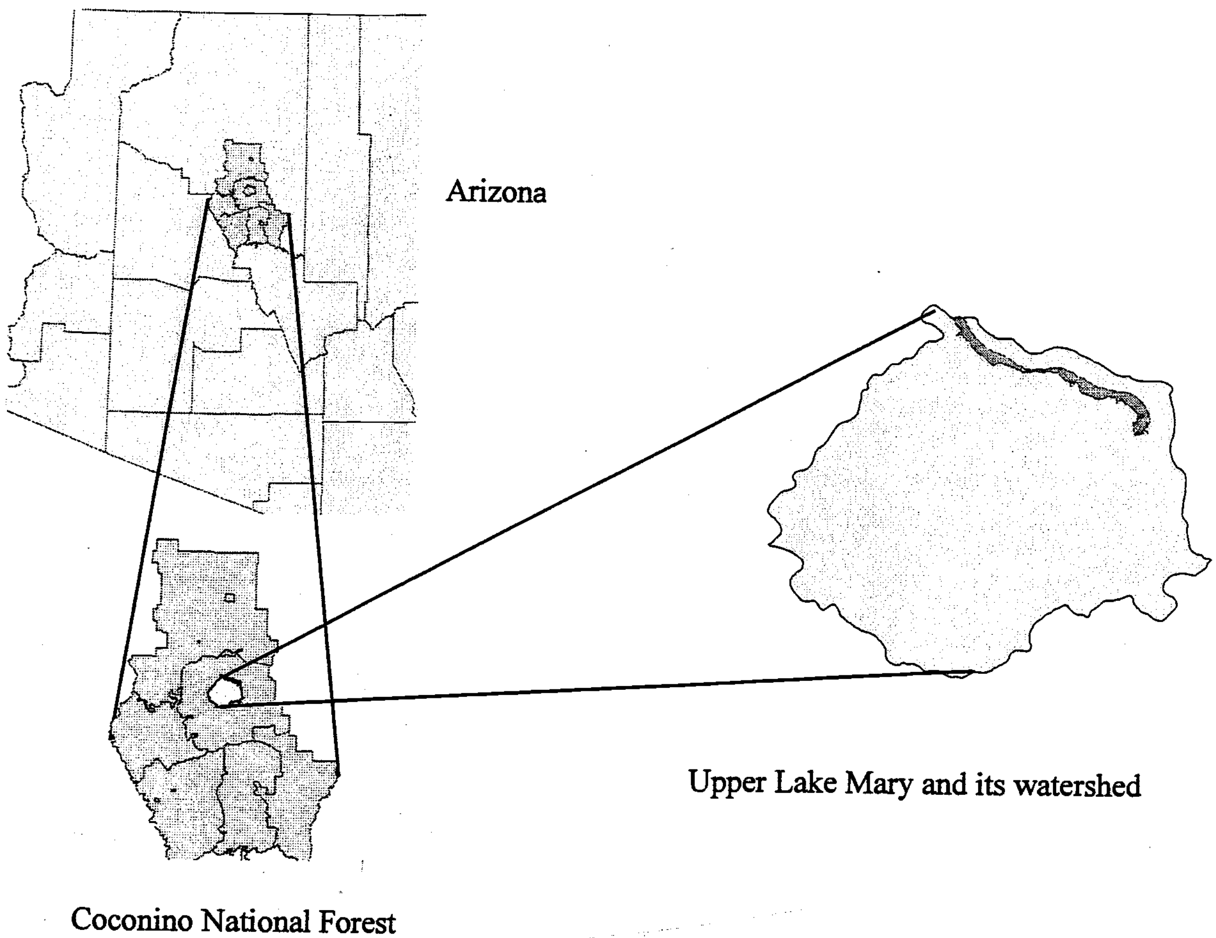

Figure 1. Location of Upper Lake Mary within the Coconino National Forest in Arizona.

E = the amount of evaporation from the lake surface

G = the amount of ground water seepage from the wetted surfaces of the lake

Q = the amount of lake water withdrawal for the city of Flagstaff

ΔS = the change in the lake storage.

Inputs

The inputs in the Lake Mary water balance equation are direct precipitation on the lake and surface runoff into the lake from the surrounding watershed. Most lakes have subsurface inputs that come in the form of springs. However, due to the unique geologic formation with offsets in the area, there is no significant subsurface contribution to Lake Mary.

Precipitation

Precipitation comes in the form of rain or snow that falls directly on the lake surface. The snowfall is converted to equivalent water in the water budget analysis. There are no specific precipitation data available for the Lake Mary area. The data used here reflect the 1950 to 2003 precipitation record obtained from the National Weather Service archive recorded at the nearby Flagstaff airport. The surface area of the lake for each month can be estimated from the stage versus area relationship curve shown in Figure 2 (Blee 1988; Ward et al. 1995). Then, we determined the monthly average amount of water from precipitation by multiplying the area of the lake by the corresponding precipitation depth, as shown in Table 1.

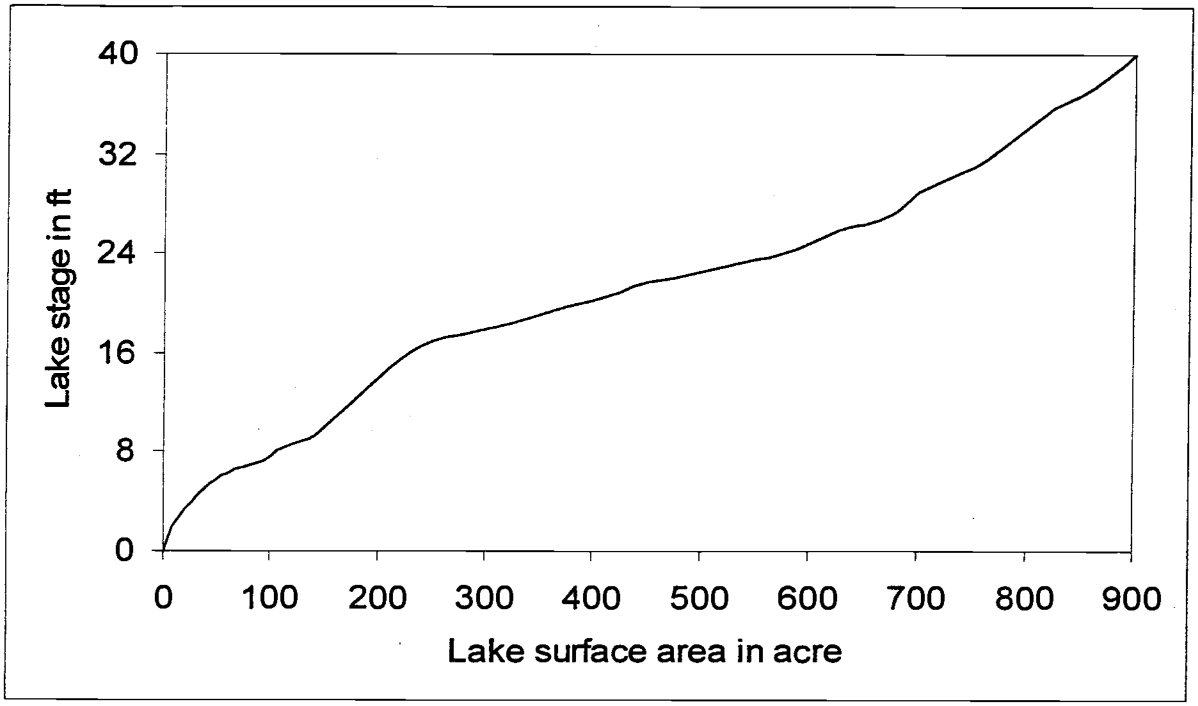

Figure 2. Relationship between lake stage and surface area (Blee 1988).

Table 1. Estimating the amount of water from direct precipitation falling on the surface of Lake Mary.

Month	Precipitation (inches)	Precipitation (feet)	Average Lake Stage (ft)	Lake Surface Area (acres)	Precipitation Voume (ac-ft)
January	1.99	0.166	24.12	560	92.87
February	2.09	0.174	24.42	565	98.40
March	2.24	0.187	27.00	650	121.33
April	1.28	0.107	30.22	730	77.87
May	0.70	0.058	30.18	728	42.47
June	0.50	0.042	29.45	725	30.21
July	2.48	0.207	27.86	693	143.22
August	2.83	0.236	26.75	648	152.82
September	1.96	0.163	25.70	610	99.63
October	1.59	0.133	24.97	595	78.84
November	1.72	0.143	24.47	566	81.13
December	1.93	0.161	24.02	558	89.75
Sum	21.31	1.776	—	—	1108.53

Surface Runoff

Surface runoff from the watershed area around the lake is the main input into the water budget equation for Lake Mary. The watershed area around the lake, which was determined using a Digital Elevation Model (DEM), is estimated to be about 34,043 acres. We used the USDA Soil Conservation Service's (SCS) curve number method in equation [2] to estimate the amount of runoff produced from precipitation events falling on the watershed.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad [2]$$

where

Q = the excess rainfall or direct runoff from a storm event (inches)

P = depth of precipitation (inches)

I_a = initial abstraction before ponding (inches)

S = potential maximum retention (inches).

The amount of the initial abstraction, I_a, is approximated by $0.2S$ for use in equation [2]. The result is shown in equation [3].

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad [3]$$

The value of S in turn is estimated from a curve number (CN) using equation [4]

$$S = \frac{1000}{CN} - 10 \quad [4]$$

where CN is a dimensionless curve number defined such that $0 \le CN \le 100$. For impervious surfaces, the value of $CN = 100$, whereas it is less than 100 for other surfaces.

The curve number is usually readily available in the form of tables for average antecedent moisture condition (*AMC II*). Then, either a conversion table (USDA Soil Conservation Service 1972) or equations [5] and [6] below (Chow et al. 1988) can be used to convert the *AMC II* values into antecedent moisture for dry conditions (*AMC I*) and for wet conditions (*AMC III*).

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} \quad [5]$$

$$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)} \quad [6]$$

The CN value for the average antecedent moisture condition (*AMC II*) for the study area is estimated to be 77. This assignment is made on the basis of the area having soil group C, described by clay loam and shallow sandy loam soils that have low organic matter content but usually are high in clay content and with a fair amount of wood or forest surface cover. Table 2 shows the amounts of surface runoff estimated using the SCS method described above.

Outputs

The output components of the water balance equation [1] are evaporation, groundwater seepage, and water withdrawal by the city of Flagstaff. Estimates for the values of these variables are obtained either from the literature, by using equations, or from real data obtained from the city of Flagstaff Water Treatment Plant.

Evaporation

According to Blee (1988), the evaporation loss from the water surface in Upper Lake Mary can be estimated using a mass transfer equation developed by Marciano and Harbeck (1952). The mass transfer value, which is directly proportional to the product of wind speed (U) and the vapor pressure gradient (e_o–e_a), is expressed in equation [7]:

$$E = NU(e_o - e_a) \quad [7]$$

where

E = evaporation loss (in inches)

N = mass transfer coefficient

U = wind speed at some height above the water surface (in miles per hr)

e_o = saturated vapor pressure that corresponds to the temperature of the water surface (in Hg)

e_a = vapor pressure of the air at some height above the water surface or shore (inches/Hg).

The constant N in equation [7] is related to other independent evaporation factors, such as energy or some other water budget component. For Upper Lake Mary, an empirical equation that was developed by Koberg and Ford (1965) was used to determine the amount of evaporation from the lake. To obtain the data necessary for estimating evaporation, a raft was anchored at each end of the lake, containing instruments to measure the mass transfer variables of vapor pressure and wind speed as well as temperature—an anemometer, a psychrometer, and a water temperature probe. A water temperature correction factor to correct fetch, the distance between the upwind shore and the point of measurement, and an atmospheric stability correction factor were used in constructing the mass

Table 2. Monthly average runoff from the Upper Lake Mary watershed (34,043 acres).

Month	Runoff Depth (ft)	Runoff Volume (acre-ft)
January	0.042	1418.44
February	0.022	737.59
March	0.029	992.91
April	0.003	85.11
May	0.000	0.00
June	0.006	198.58
July	0.017	567.37
August	0.025	851.06
September	0.019	652.48
October	0.017	567.38
November	0.038	1304.96
December	0.020	680.85
Sum	—	8056.73

transfer equation to determine the evaporation rate on each raft from May to October of 1969 and 1970, the time of year with the largest amount of evaporation occurrence. The evaporation rate computed for the lake was weighted by the lake surface area each raft represented, as shown in equation [8].

$$E_T = \frac{E_1 A_1 + E_2 A_2}{A_1 + A_2} \qquad [8]$$

where

E_T = average lake evaporation rate (inches/hr)

E_1 = evaporation rate at from raft 1 (inches/hr)

E_2 = evaporation rate at from raft 2 (inches/hr)

A_1 = lake surface area covered by raft 1 (acres)

A_2 = lake surface area covered by raft 2 (acres).

Figure 3 gives the average amount of monthly evaporation determined for Lake Mary. As shown above, the largest amounts of evaporation occur during the warm summer months of May through October.

Seepage Losses

Seepage losses from Upper Lake Mary were determined from several short-period water budget estimates; the periods ranged from 3 to 60 days. The water budgets were computed only for periods in which there was no surface flow into the lake. All the variables in the water budget of equation [1] were measured except seepage, which was computed as a residual using equation [9].

$$G = (H_1 - H_2) + P - E - Q \qquad [9]$$

where

G = ground water seepage from the lake (ft)

H_1 = lake stage (depth) at the beginning of the water budget period (ft)

H_2 = lake stage at the end of the water budget period (ft)

P = precipitation on the lake surface (ft)

E = evaporation rate (ft)

Q = water withdrawal from the lake(in feet).

The change in storage ($H_1 - H_2$) was determined from recorded changes in lake stage. The amount of evaporation (E) was measured at the rafts installed in Upper Lake Mary. The amount of water withdrawal (Q) was measured by the city of Flagstaff personnel at the water treatment plant. Precipitation depth (P) was measured by the rain gage at the upper end of the lake.

The stage/seepage relationship in Figure 4 was established to estimate the long-term seepage loss from the lake (Blee 1988). It was constructed by plotting the results obtained from the short-term water budgets. The average seepage loss volume from the lake for each month of the year can be estimated from this graph.

Water Withdrawal by the City of Flagstaff

According to the data on the monthly amount of water pumped from Lake Mary by the city of Flagstaff during the years 1949 through 2001, the amount of water pumped varied with the amount of water coming into the lake and the seasonal water demand. The data show that, on average, 2363.38 acre-feet of water per year has been pumped from the lake during the last 52 years. Table 3 shows the amount of water pumped each month during the last 5 dry years, indicating the effect of drought on the demand for Lake Mary water (City of Flagstaff Utility Department 2002).

RESULTS AND CONCLUSION

Annual inflows and outflows have been determined using several methods and the available data. The water balance for each month—that is, the change in the lake volume—is determined by subtracting the total average outputs from the total inputs into the lake. Table 4 shows the monthly average values of the different hydrologic conditions contributing to the water balance in Upper Lake Mary. The last column in Table 4 and Figure 5 show the monthly changes in the amounts of water in Lake Mary.

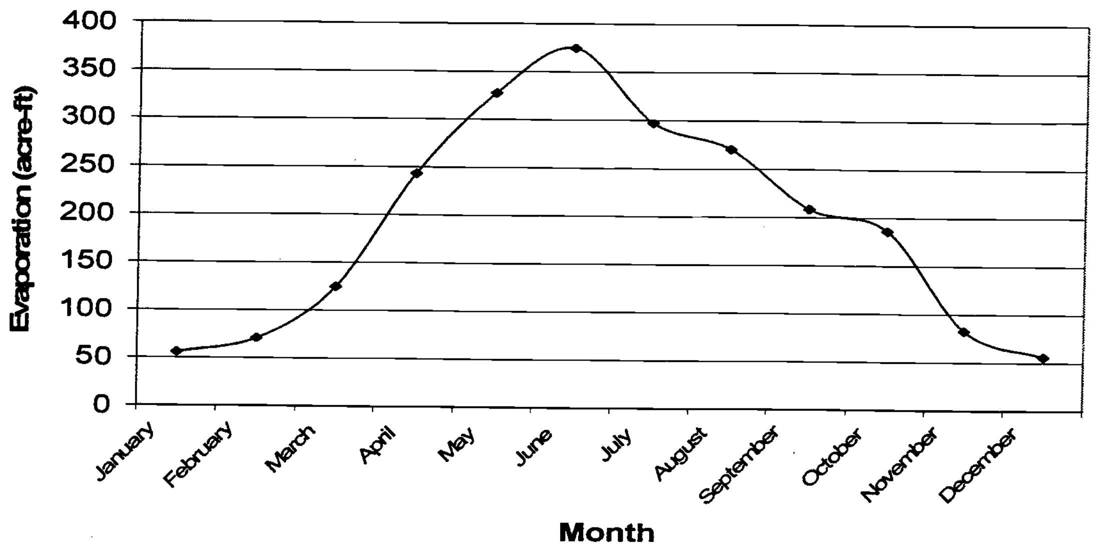

Figure 3. Monthly evaporation loss (in acre-ft) from Upper Lake Mary (Blee 1988).

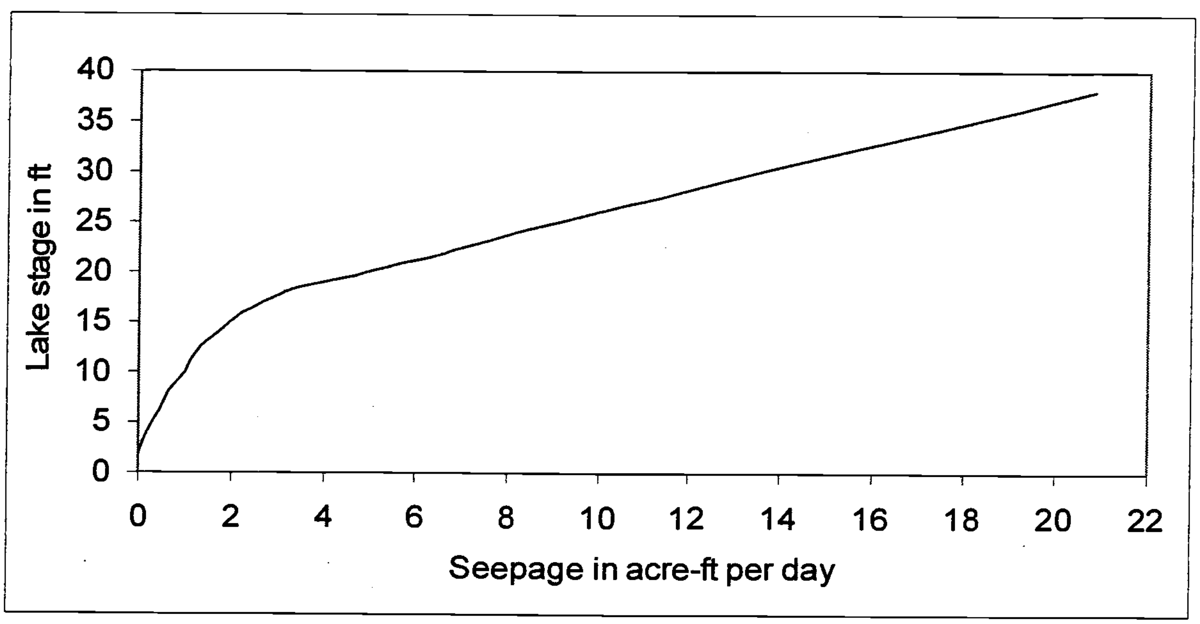

Figure 4. Relationship between lake stage and seepage loss developed from a short-term water budget (Blee 1988).

Table 3. Average monthly water withdrawal from Upper Lake Mary during 1999–2003.

Month	Average Withdrawal (1999–2003) [2]	Percentage from Total [3]	Actual Annual Avg Water Pumped 1941–2001 (ac-ft) [4]	Actual Average Monthly Volume = [3] * [4]
January	266.17	4.37		103.23
February	93.81	1.54		36.38
March	246.67	4.05		95.72
April	269.30	4.42		104.49
May	1125.60	18.47		436.70
June	1299.78	21.33		504.31
July	913.07	14.98	2363.38	354.12
August	687.22	11.28		266.53
September	421.12	6.91		163.33
October	190.69	3.13		73.96
November	262.18	4.03		101.73
December	318.13	5.22		123.43
Sum	6093.73	—		2362.93

Table 4. Average monthly values of the different water balance components in Lake Mary.

Month	Precip. on Lake Surface (ac-ft)	Evap-oration (ac-ft)	Seepage (ac-ft)	With-drawal (ac-ft)	Runoff Using SCS Method (in)	(ft)	Runoff Volume (ac-ft)	Change in Storage (ac-ft)
January	92.87	56.00	263.5	103.23	0.50	0.04	1418.44	1088.58
February	98.404	70.60	255.2	36.39	0.26	0.02	737.59	473.80
March	121.33	124.60	341.0	95.72	0.35	0.03	992.91	552.92
April	77.87	243.30	420.0	104.49	0.03	0.01	85.11	–604.81
May	42.47	327.60	427.8	436.70	0.00	0.00	0.00	–1149.63
June	30.21	374.60	396.0	504.31	0.07	0.01	198.58	–1046.12
July	143.22	297.40	372.0	354.27	0.20	0.02	567.37	–313.08
August	152.82	270.00	334.8	266.62	0.30	0.03	851.06	132.46
September	99.633	208.40	294.0	163.39	0.23	0.02	652.48	86.323
October	78.838	185.90	285.2	73.99	0.20	0.02	567.38	101.13
November	81.127	82.50	267.0	101.73	0.46	0.04	1304.96	934.86
December	89.745	55.80	260.4	123.43	0.24	0.02	680.85	330.97
Annual	1108.53	2296.80	3916.9	2364.27	—	—	8056.73	587.29

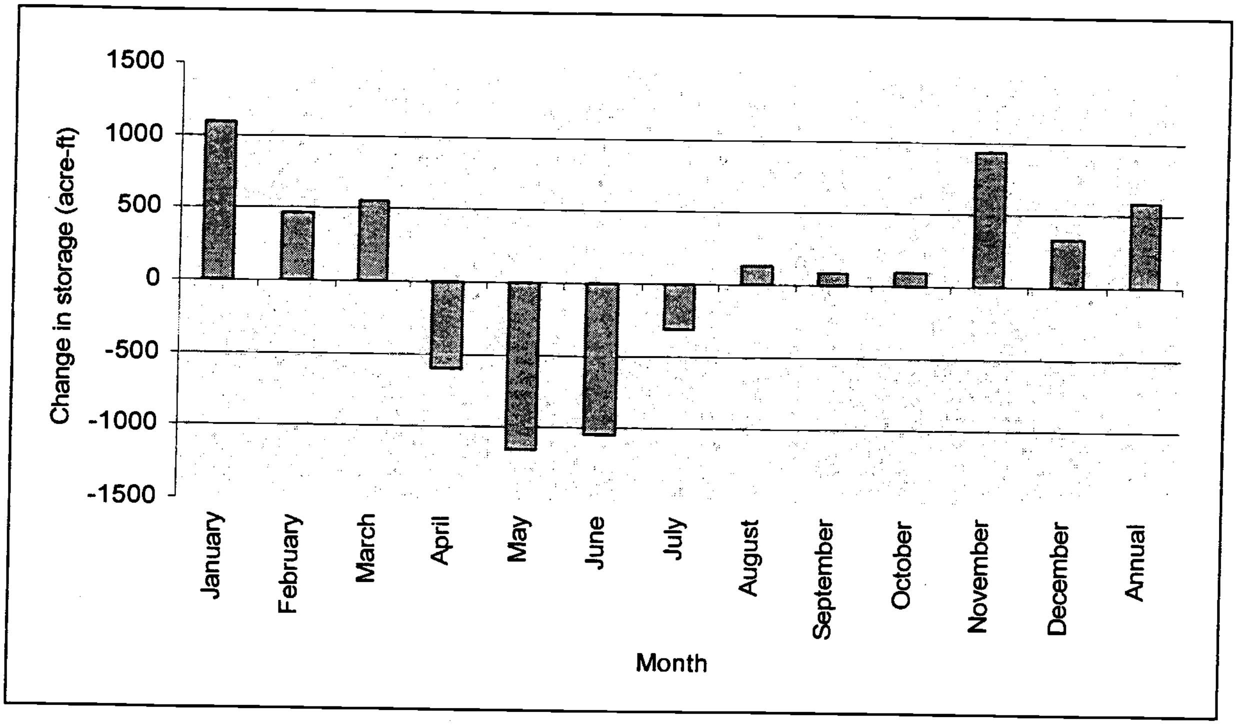

Figure 5. Monthly change in storage in Lake Mary obtained using the water balance method.

The water balance calculation shows that the annual average amount of water in Upper Lake Mary is 587.29 acre-feet. This is only about 3.76 percent of the maximum capacity of the lake. This amount is so small that it is not adequate even to satisfy the supplementary drinking water needs of the city of Flagstaff. Under this kind of situation, it would be unwise to pump any water from the lake. Because of this the amount of water withdrawn from the lake varies from year to year depending on weather conditions in the area. In some years, little or no water is pumped from the lake to avoid total loss of the lake during severe drought periods. Table 4 shows that the largest amount of water losses from the lake are through evaporation and seepage. Both types of losses amount to 72 percent of the total output. The rest is withdrawn for drinking water by the city of Flagstaff. However, the withdrawal does not occur when the lake is low during dry periods. Hence further studies to find ways to reduce the amount of evaporation and seepage are appropriate. Reducing the loss will save water that can be used for the increasing population in the city of Flagstaff and to prevent the lake from drying up during drought.

Deepening the lake by at least 17 ft, which is the average depth, and sealing 64 percent of the lake bottom would avoid 50 percent of the evaporation loss and 81 percent of the seepage loss. Since the lake is located within the USDA's Coconino National Forest and was built by the city of Flagstaff, it is managed jointly by both the Forest Service and the city. There is an agreement between the two not to lower the lake depth below 18.3 ft. This helps to avoid overwithdrawal while ensuring its continuous availability for recreational activities, wildlife habitat, and other benefits. This water balance study estimates the average water availability in Upper Lake Mary for domestic and other uses. However, the results do not show the water balance characteristics during wet and dry periods. Evaluating the water balance on a yearly basis can help estimate the amount of water availability for withdrawal under different climate conditions.

ACKNOWLEDGMENTS

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