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HYDROLOGY OF STOCK-WATER RESERVOIRS IN ARIZONA

By

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PREFACE

Many agencies and individuals have aided materially in the stock-pond investigations. Most of the gaging installations are located on Indian reservations or in grazing districts where official employees have helped locate suitable reservoirs for study, sometimes providing tools and labor, and often arranging for the gathering of gage readings. Among those who have been especially helpful are W. H. Berry, regional conservationist, and Bernard Hodgin, engineer, Bureau of Indian Affairs, Phoenix, Ariz.; Paul Buss, forest supervisor, and Keith Douglass, conservationist, San Carlos Indian Reservation; J. J. Schwarz, engineer, and William Fair, conservationist, Navajo Indian Reservation; Ward Kindred, conservationist, Fort Apache Indian Reservation; V. D. Smith, forester, Hualpai Indian Reservation; and Clarence Kinkor, conservationist, Papago Indian Reservation. The services of these men are greatly appreciated.

The field work was carried out in the Water Resources Division of the Geological Survey as part of the Soil and Moisture Conservation program of the Department of the Interior, under the supervision of H. V. Peterson, staff geologist, by C. H. Hains, hydraulic engineer, until 1949, and thereafter by R. C. Culler, hydraulic engineer. This report was prepared by W. B. Langbein, hydraulic engineer. G. B. Smith, hydraulic engineer, assisted in the observations at Juniper Lake on August 5-6, 1950.

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INTRODUCTION

The many thousands of stock-water reservoirs throughout the Western Range provide a large part of the watering facilities for the Nation's livestock industry. The individual stock-watering pond represents a small investment but the aggregate of all ponds is an investment of many million dollars.

Harvesting of the forage crop by stock on the Western Range depends on the accessibility of water. In general, cattle do not graze more than 3 miles from water. Where the water supplies are far apart, forage close to water is so intensively cropped that destructive erosion is induced, whereas valuable forage at a distance remains unharvested. Uniform and efficient utilization of the forage requires a large number of water supplies only short distances apart. For this reason, many thousands of reservoirs have been built. A recent survey in the 9,000-square-mile basin of the Cheyenne River in Wyoming shows that there are nearly 10,000 reservoirs, or about one per square mile. Although this density of reservoirs may not apply throughout the Intermontane Plateau, it is nevertheless indicative of a high state of development in some areas. Considering the construction under way and proposals for even greater construction, it is evident that the performance of stock-water reservoirs is a matter of great economic concern.

The availability of a dependable supply of stock water at the proper time or times during the grazing seasons is of extreme importance to the range-livestock industry. In humid areas, rivers, creeks, natural ponds, or lakes provide dependable waters and providing stock water is no problem. At the other end of the scale are the many arid ranges that do not contain any "live" waters. Between these two extremes there are still other ranges where seasonal water may be available or where water must be artificially provided. The arid or semiarid range areas present a unique problem in range management to livestock operators. Under these circumstances and conditions many and varied approaches to the solution of the water problem on such areas have been made.

Advantage is taken of the fact that water is a "key" resource on the arid range. Providing or withholding water for livestock permits better management of range and the livestock. For example, such use of water as a control in many instances limits the necessity for construction and maintenance of costly fencing projects. Water control, in lieu of fencing, is being used more and more to provide protection for areas that have been reseeded or are in other ways being rehabilitated under the departmental soil and moisture conservation program. Water control also permits range managers to provide for short-time water on lambing grounds, around loading stations adjacent to railroad shipping points, or at shearing pens, in holding pastures or roundup grounds.

For the best operating practices, yearlong water is not always desirable in the management of range and stock on western range areas. Some ranges, because of the character of the forage, are usable to advantage only in the spring; others only in the fall; whereas still others could be used for longer periods, and in some sections of the West many ranges are used the year long.

Attempts of stockmen and range managers to meet the problems that are frequently complicated during wet years or seasons of drought, have produced a varied pattern of stock-water developments and stock-water use. Lack of hydrologic and geologic data pertaining to water-supply possibilities has heretofore resulted in many unwise or impractical developments or attempts to provide water. Unfortunately some of these attempts that failed brought about considerable damage to the range or to values downstream. Better land and livestock management requires that improved practices be instituted. The Division of Land Utilization for the past several years has been sponsoring studies of the problems involved for the purpose of providing sound geologic and hydrologic data to the land management agencies to enable them to manage the range lands more effectively and at a reasonable cost.

Flow in the small drainage courses on grazing lands is infrequent and erratic. In order to provide carryover between storms, the tendency has been for the stockmen to make their reservoirs large, thus creating great surface areas and thereby increasing losses of water by evaporation and seepage. It seems significant that the amount of water consumed by stock from the ordinary reservoir is only a small fraction of the total flow in the washes; most of the water is lost by evaporation or disappears by seepage.

An important problem in water conservation is to minimize waste by permitting the surplus waters to flow downstream for the benefit of other users and for useful native vegetation. The solution of this problem depends largely on adequate data on runoff and sedimentation in the "dry" washes in the semiarid and arid parts of the country. Hydrologic information in the desert areas is needed not only for designing stock-water reservoirs but for determining source areas of flow in the major streams and of ground-water recharge. The flow in the dry washes is too erratic and the channels are too unstable to justify operation of stream-gaging and sediment stations. Gage-height records on dry washes can be obtained by "kickoff recorders" (triggered by a flow of water), but dependable discharge ratings are difficult to define on these ephemeral streams. Obtaining discharge measurements and sediment samples on washes of this kind would require the full-time residence of a hydrographer, entailing costs too high to warrant the work except perhaps on an intensive experimental scale.

In 1944 and 1945, in connection with reservoir performance studies, gages were installed on several stock-water reservoirs. The initial purpose was to learn when the reservoirs contained usable water, the rate of loss, and the frequency and amount of replenishment--the chief factors that determine the success or failure of a reservoir. Later it was found that the records of water level could also be interpreted in terms of the runoff into the reservoir. A group of reservoirs in Arizona, where they are commonly called "tanks" by stockmen, was selected for these initial studies (see fig. 1). Enameled gage plates graduated to 0.02 foot were installed on posts in the banks of the reservoirs. As most of these reservoirs are at locations remote from ranch houses or routes of frequent travel, the best that could be done was to obtain weekly readings. Nevertheless, readings were uncertain, and gaps of several weeks are numerous in the records. These gaps, although vexing, were not critical because for many months the reservoirs were slowly receding and it was not difficult to piece out the record. Spilling was more troublesome, except for those reservoirs with sufficient capacity for overflow to be infrequent. Experience in Arizona indicates that reservoirs with a capacity of 10 acre-feet or more per square mile of drainage area are best suited to stock-reservoir studies. Reservoirs of this size are also sufficiently large to trap all the sediment carried by the inflow.

It was found that records of this kind could yield considerable information in comparison with their cost. From the record of fluctuations of water levels, data on runoff, seepage, and evaporation can be obtained. Repeated capacity surveys provide information on volumes of sediment carried by the floods in the dry washes.

It is believed that the stock-reservoir studies begun in Arizona will help relieve the shortage in hydrologic data for the arid country. The studies have since been expanded to include a few basins in Wyoming, Colorado, and

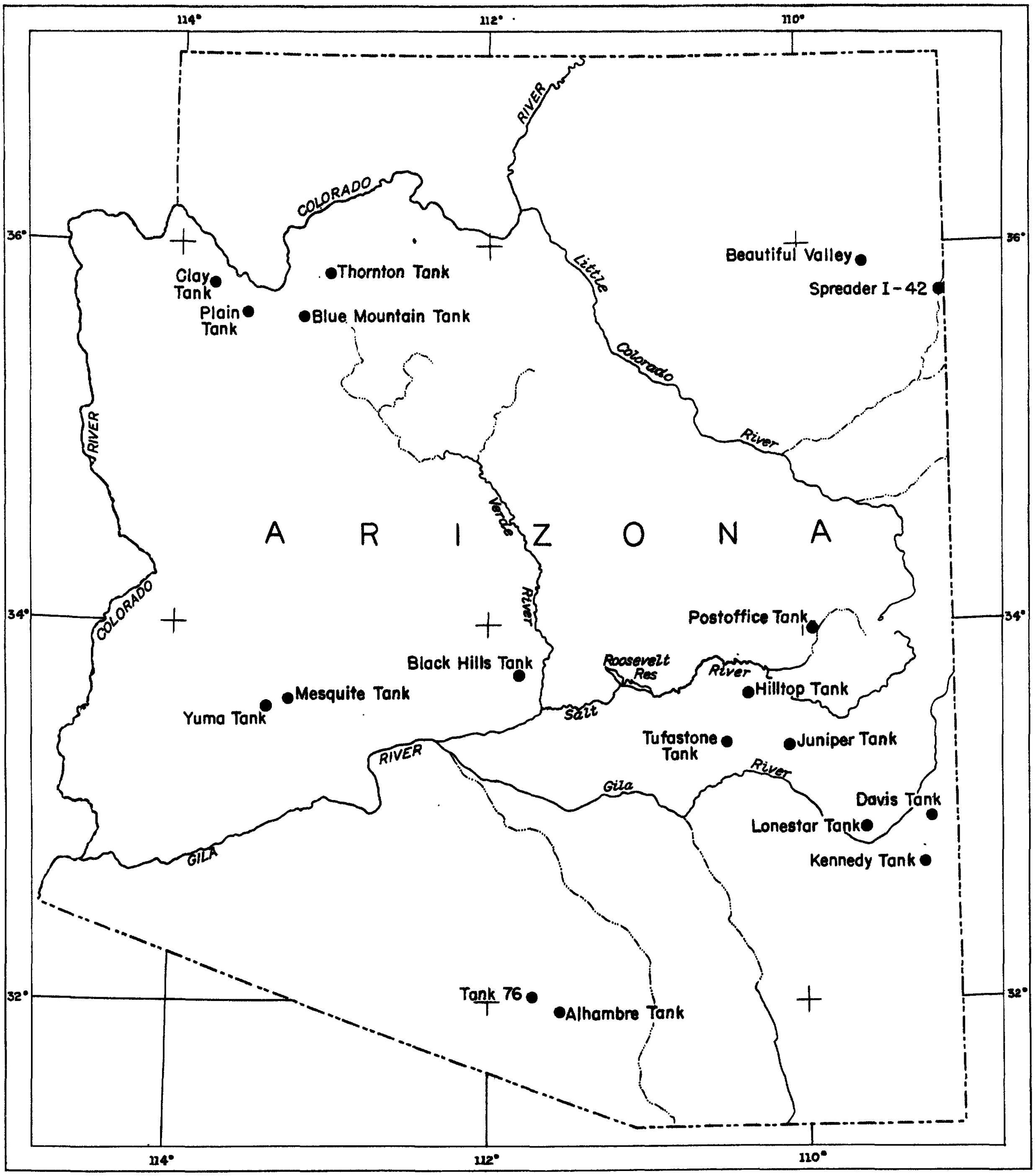


Figure 1.--Map of Arizona showing location of stock-water reservoirs investigated.

Utah. It is planned, at these new sites, to study sedimentation and erosion as well as runoff. This report, however, will be confined to performance at the original Arizona installations; but when longer periods of record are available, later reports will include the additional sites. This investigation was directed mainly toward evaluation of reservoir performance; problems of design or construction of dams were not included, nor were any studies made of flood discharges or spillway design.

DETERMINATION OF RUNOFF AND WATER LOSSES

The common type of dry wash in the arid country carries flows only as a result of the more intensive summer storms. The stream rise is rapid, sometimes as a wave front advancing downstream. The peak is sharp; the stream

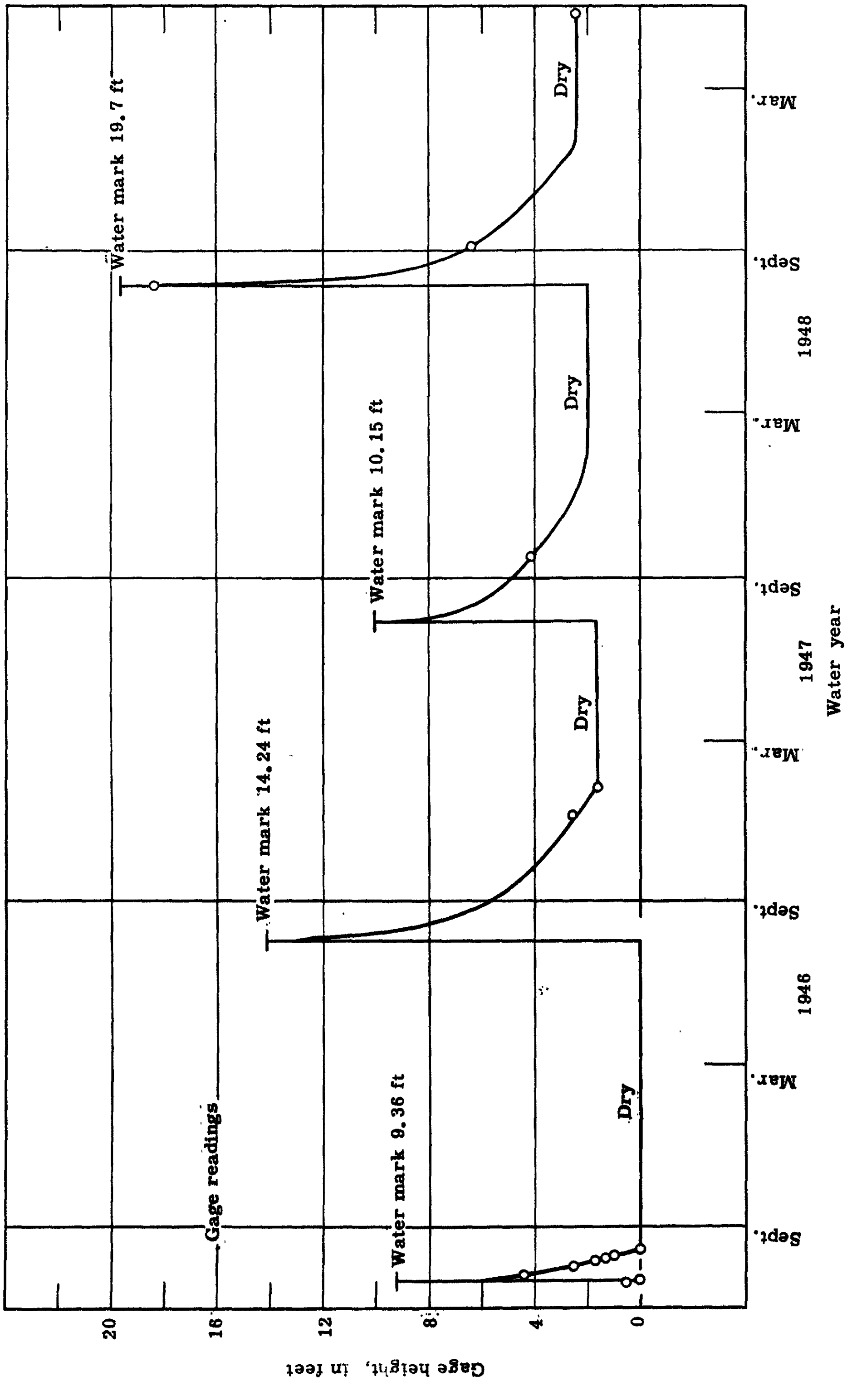


Figure 2.--Hydrograph of water surface at Black Hills Tank near Cave Creek, Ariz.

recedes quickly; and the channel may be dry again within a few hours.

When this flow is impounded by a stock-water reservoir, there is a rapid rise in stage until the inflow ceases. The duration of inflow is so short that seepage and evaporation losses from the reservoir may be assumed to be negligible during the period. Hence the total volume of flow may be closely determined by the increment in volume in the reservoir. After inflow ends, the stage in the reservoir begins to decline, rapidly at first and then more slowly as the seepage rate becomes less. If inflow does not recur for some time, the reservoir may go dry.

Records of water levels were obtained for 18 reservoirs in Arizona. The method of analysis is illustrated in this report by two examples; the first is typical of performance in the arid country and the second of the more humid mountainous country.

Black Hills Tank

Black Hills Tank near Cave Creek, Maricopa County, Ariz., is typical of a reservoir in the desert. The climate at this reservoir is similar to that of the valleys of the lower Gila Basin and west-central Arizona. Annual rainfall averages about 8 inches and annual temperature 70°F. A study of rainfall records obtained at Camelback, Ariz., 17 miles southwest of the reservoir, shows that rainstorms in excess of 0.5 inch per day average only 3 for a year.

The reservoir is formed by an earthfill dam, 28 feet high across a dry wash approximately 2½ miles long, and has a total capacity of about 65 acre-feet. The reservoir intercepts the runoff from an area of 1.56 square miles that is drained by a network of small washes 6 inches to 2 feet deep draining to the southeast on a slope of about 2 percent. The granitic rock that underlies the basin is capped by a thin mantle of coarse residual soil. Vegetation is of the mountain-brush type, consisting mainly of snakeweed, yucca, creosote bush, cactus, and small paloverde trees. Mesquite grows along the main drainage channels. The altitude (determined by aneroid barometer) ranges from 2,600 feet at the reservoir to 3,200 feet at the head of the basin.

The hydrograph of water levels in the reservoir, as constructed from gage readings and high-water marks, is shown on figure 2. Only one period of inflow occurred in each year of record. Because of the infrequency of rainstorms of sufficient volume and intensity to produce runoff, and particularly because of the perviousness of its bottom, the reservoir is dry more than half the year. The volumes of runoff associated with each rise in the reservoir, which occurred in August in every year listed, are as follows:

Date	Runoff in acre-feet
1945	7
1946	14
1947	7
1948	26

The 4-year average runoff is 13.5 acre-feet--8.5 acre-feet per square mile or 0.16 inch.

The results of capacity surveys are shown on figure 3. The original capacity in 1945 below a stage of 19 feet was 30 acre-feet. A resurvey in June 1949, when the reservoir was dry, showed a capacity of 26.5 acre-feet, indicating a 4-year deposition of 3.5 acre-feet, most of which was located below a stage of 10 feet. The original low point was at a gage height of zero, but in June 1949 the bottom was at a gage height of 2.4 feet. The year-to-year rise in the bottom is shown by the hydrograph on figure 2. About half of the sediment accumulated was produced by a small debris wave that accompanied the runoff of August 1948. A field examination shortly thereafter showed that this wave deposited 2-foot mud clods, 6-inch rocks, and whole mesquite trees in a fan at the entrance to the tank; but only fine sediments reached the bottom of the reservoir.

The record shows, therefore, that in addition to the average annual water runoff of 13.5 acre-feet, there was sediment amounting to 0.9 acre-foot per year (0.55 acre-foot per square mile per year), or 6 percent by volume of the runoff.

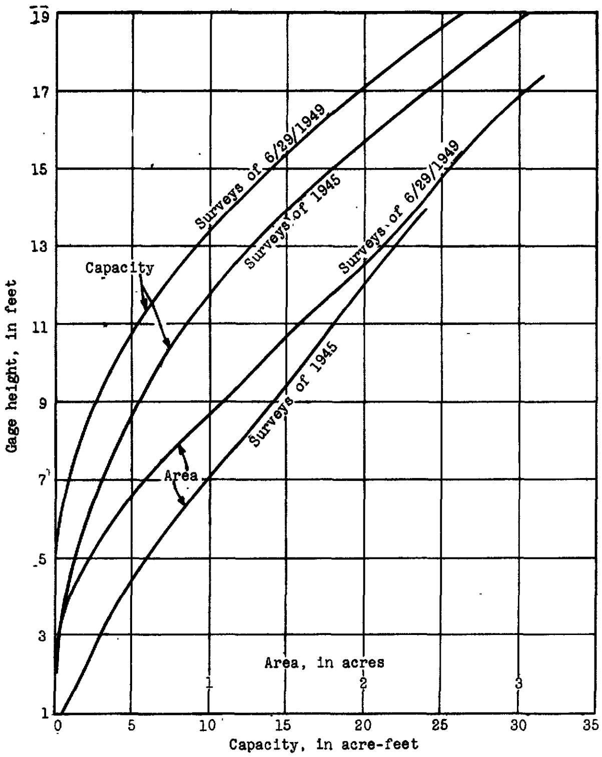


Figure 3.-- Area and capacity curves, Black Hills Tank near Cave Creek, Ariz.

Postoffice Tank

A quite different analysis must be made of the records on reservoirs that contain perennial or more nearly perennial water. In general, the fluctuation in water level of a reservoir is given by the equation:

$$\Delta H = R/A + P - E - S - U/A$$

in which ΔH represents change in water level in feet; R is runoff in acre-feet; A is the water-surface area in acres; P is precipitation on the pond surface in feet; E is evaporation in feet; S is seepage in feet; and the term U/A represents the effect of use by livestock, expressed also in feet. The sum of the inflow terms $R/A + P$ is called recharge, and the sum of the terms $E + S$ is called water loss. The observed data are ΔH, P, and A; the problem is to determine the values of R, E, and S. For most reservoirs utilization of the water by stock is relatively small, amounting to 0.3 acre-foot or less per year.

Postoffice Tank near Whiteriver, Ariz., on the Fort Apache Indian Reservation, is an example of a perennial reservoir. This reservoir has a capacity of 3.5 acre-feet (see fig. 4) impounded by an earth dam about 11 feet high. The reservoir intercepts the runoff from a drainage area of 0.29 square mile on the Mogollon Rim. The drainage course lies in a canyon that runs parallel and adjacent to Postoffice Canyon and is separated from that canyon, as well as from the drainage area on the south, by ridges with side slopes of 25 percent. The altitude at the dam is 5,725 feet above mean sea level (by aneroid barometer) and the drainage basin heads on a mountain peak 500 feet higher. The sandstone that underlies the basin is mantled by a fairly thick sandy soil containing boulders and cobbles. The fill in the canyon bottom is fairly thick and consists of sandy loam. The basin lies in a dense pine forest with much litter. Very little evidence of recent erosion is noted, except for minor washing of the main channel near the reservoir.

The hydrograph of water levels in this reservoir, based on weekly readings on a staff gage, is shown on figure 5. It may be observed that the hydrograph consists, in the main, of abrupt rises in stage caused by runoff followed by slow depletions due to evaporation and seepage. However, recharge is frequent and the water supply is perennial. There are

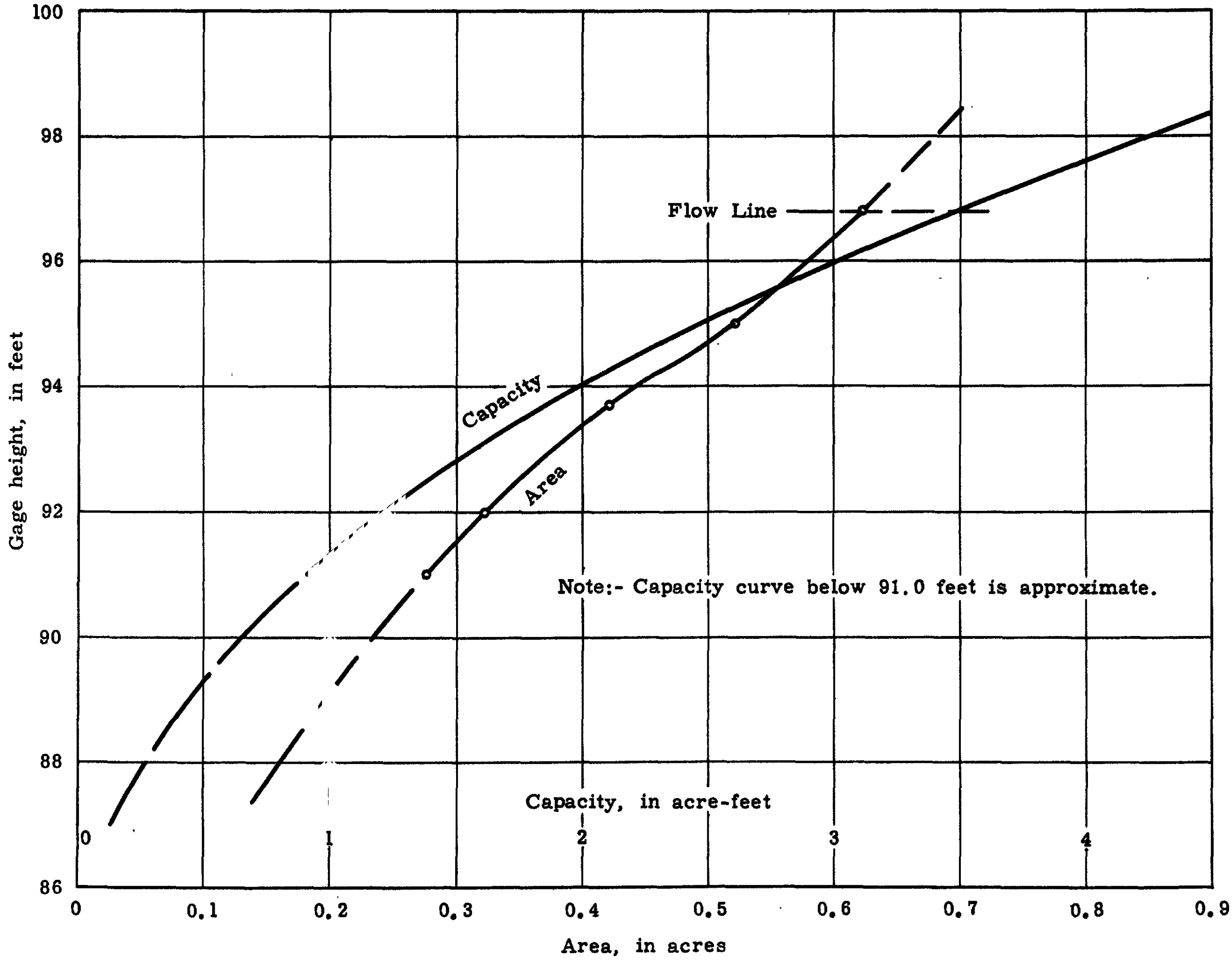


Figure 4.-- Area and capacity curves, Postoffice Tank near Whiteriver, Ariz.

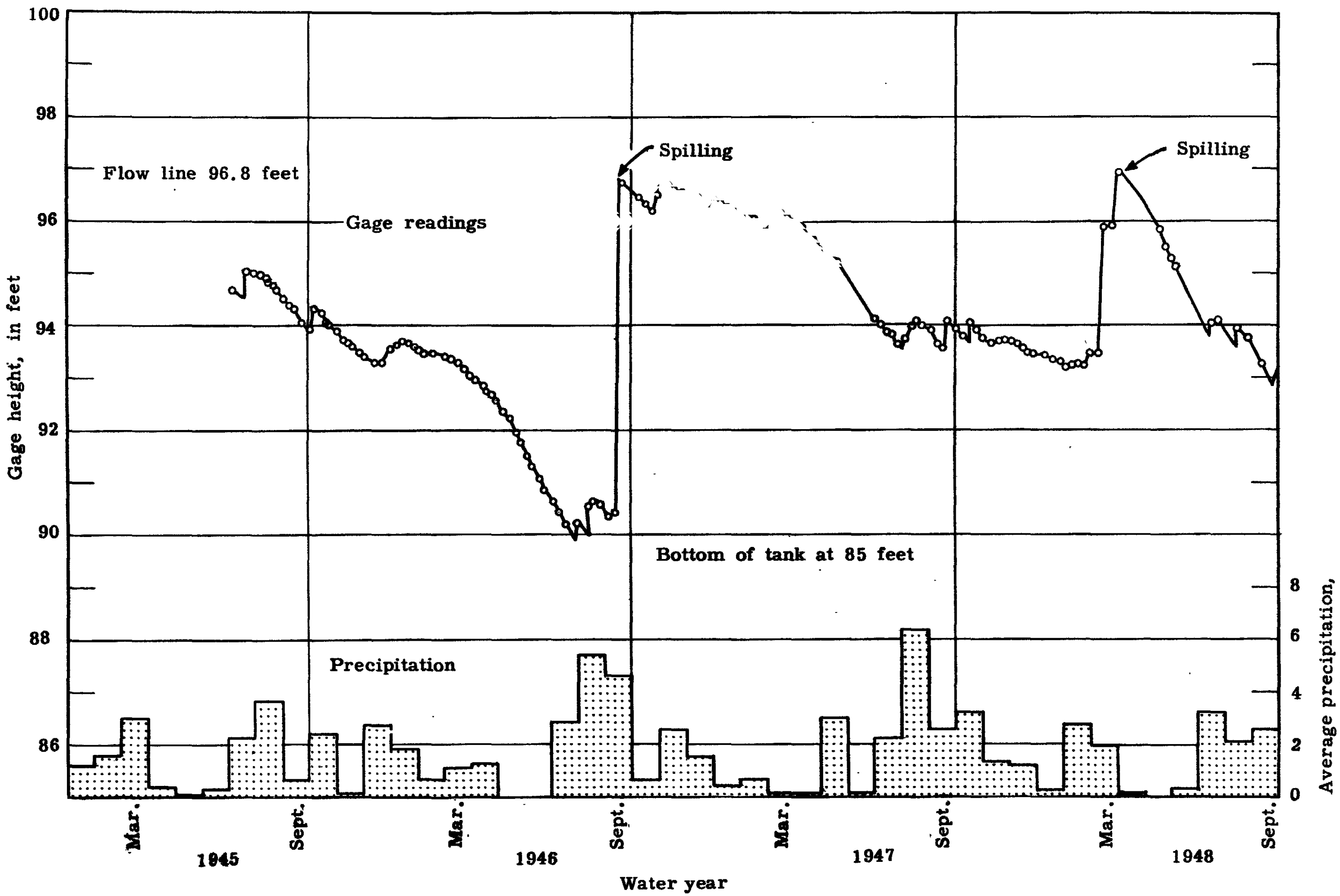
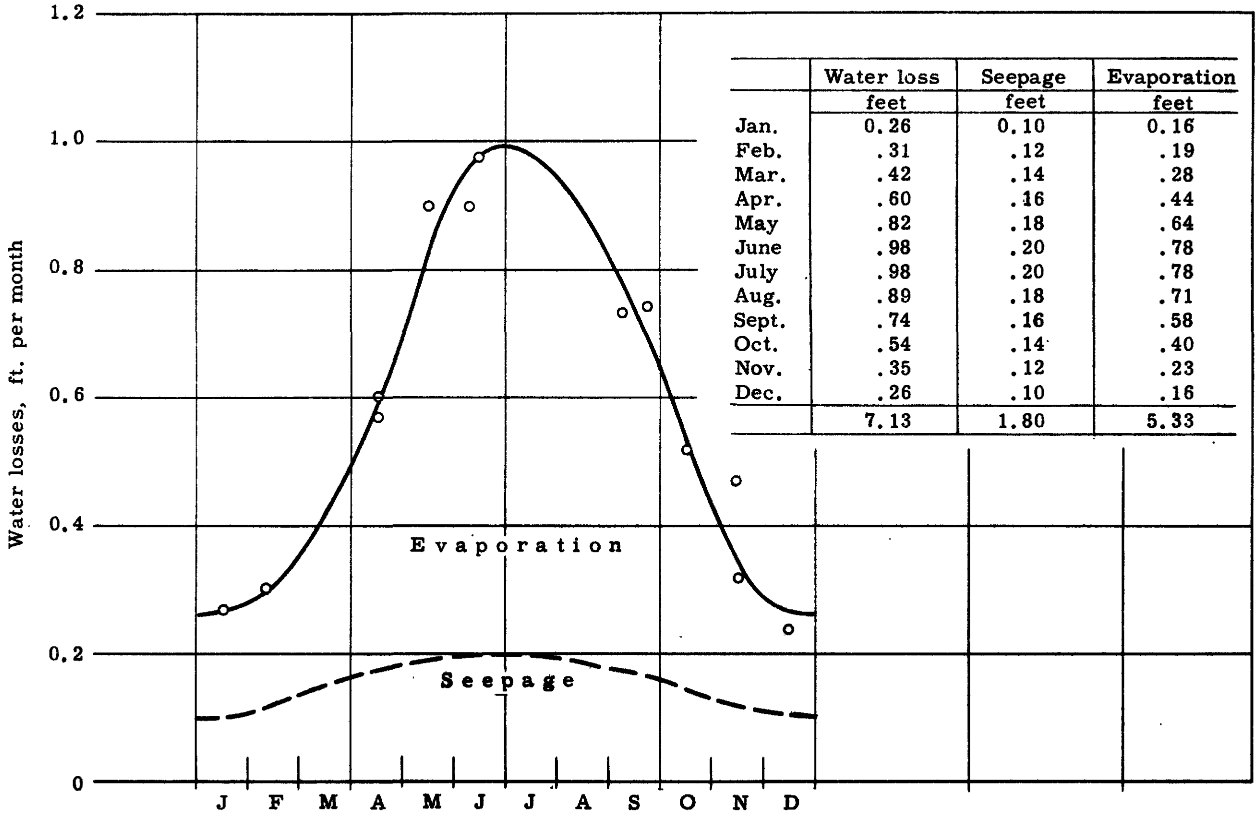


Figure 5.-- Hydrograph of water surface at Postoffice Tank near Whiteriver, Ariz., and monthly precipitation for average of Whiteriver and McNary, Ariz.



	Water loss	Seepage	Evaporation
	feet	feet	feet
Jan.	0.26	0.10	0.16
Feb.	.31	.12	.19
Mar.	.42	.14	.28
Apr.	.60	.16	.44
May	.82	.18	.64
June	.98	.20	.78
July	.98	.20	.78
Aug.	.89	.18	.71
Sept.	.74	.16	.58
Oct.	.54	.14	.40
Nov.	.35	.12	.23
Dec.	.26	.10	.16
	7.13	1.80	5.33

Figure 6.--Seasonal variation in water loss, Postoffice Tank, Ariz.

periods when the water level in the reservoir rises slowly or is quite stable (as in January 1946 when it was indicative of slow contribution from snowmelt).

The analysis is begun by first considering those dry periods in which it is obvious that no runoff occurred. The quantity $P - \Delta H$ in such periods is equal to the water losses--i.e., seepage and evaporation (see table 1).

Figure 6 presents a hydrograph showing the seasonal variations in the water loss. The graph shows that water losses range from a high of 1 foot per month in midsummer to a low in winter of about 0.25 foot per month. The major cause of the seasonal variation in water loss is evaporation. Except for the effects of changes in viscosity due to changes in water temperature, seepage should be fairly uniform during the year in reservoirs with perennial water.

Figure 7 shows a graphic study of the water losses during dry periods taken from table 1 plotted against evaporation as measured in a class-A pan at Sierra Ancha (55 miles west), the nearest place where such observations are

Table 1.--Dry periods, Postoffice Tank
[T = trace]

Period	Mean gage height	Change in water level	Precipitation	Water losses	Pan evaporation at Sierra Ancha
	(feet)	(ft per month)	(feet)	(ft per month)	(ft per month)
Sept. 8-Oct. 2, 1945	94.3	-0.74	0	0.74	0.65
Nov. 1945	93.7	- .47	0	.47	.30
Apr. 1946	92.8	- .50	.10	.60	.60
May 1946	92.1	- .90	T	.90	.76
June 1946	91.2	- .98	T	.98	.94
Oct. 8-22, 1946	96.3	- .52	T	.52	.48
Nov. 1946	96.6	- .24	.08	.32	.22
Jan. 1947	96.3	- .26	.01	.27	.16
Jan. 30-Feb. 25, 1947	96.0	- .28	.02	.30	.22
Apr. 1947	95.7	- .56	T	.56	.57
Sept. 2-16, 1947	93.75	- .73	0	.73	.70
Dec. 2-24, 1947	93.6	- .24	0	.24	.18
May 15-June 9, 1948	95.5	- .90	.01	.91	.85

made. The points are fairly consistent and define a straight line that shows a water loss of 0.1 foot per month when pan evaporation is zero. This value very likely represents a minimal rate of seepage from Postoffice Tank during the winter season. To the extent that the rate of seepage would vary with the water viscosity, the maximal rate of seepage, in midsummer, should be about 1.8 times the minimal rate. Figures 6 and 7 show this suggested segregation of the water losses into evaporation and seepage. The total annual evaporation is shown as about 5.3 feet, 85 percent of that from the evaporation pan at Sierra Ancha.

The data in table 1 indicate no appreciable effect of reservoir stage or depth of water on water losses. This is not to be interpreted as a general conclusion, although it may be fairly true of reservoirs with perennial water supply and limited range in water-level fluctuation. It may be noted that the hydrograph of Black Hills Tank (fig. 2) shows a substantial lessening in the rate of water loss with drop in stage.

The graph on figure 7 is a basic relationship for computation of the recharge to Postoffice Tank. The sum of an observed change in stage and the rate of depletion as controlled by water losses, indicated by the graph, must be attributed to recharge; thus $\Delta H + L = R/A + P$, where L equals the water losses. When water level remains stationary ($\Delta H = 0$), then water losses are balanced by recharge; when water level drops at a rate equal to losses, then recharge is zero.

The computations of recharge and runoff to Postoffice Tank by months are given in table 2 for the period of useful record, August 1945 to September 1948. The items in this table are generally self-explanatory. The recharge to the tank is calculated from the formula $\Delta H + L$, where L is total water loss as determined from figure 7. The term ΔH is net change in water level as determined from the stage record. The recharge in feet multiplied by the mean water-surface area, corresponding to the monthly mean gage height (see fig. 4), equals recharge in acre-feet. The runoff into the reservoir is equal to the recharge minus the precipitation on the water surface. Figure 8, p. 11, shows precipitation as observed at McNary and Whiteriver (the nearest regular rain-gage stations) plotted against recharge to Postoffice Tank. It shows that the computed recharge in feet is always greater than the precipitation, the excess increasing with precipitation. The excess, of course, represents the runoff into the tank from the contributory drainage area. The amount of runoff is highly variable. A satisfactory definition of a rainfall-runoff relationship would require better rainfall data.

The reservoir overflowed on Sept. 17, 1946, and from March 31 to April 1, 1948. The volume of spill in acre-feet has been calculated from the following formula, based on normal shapes of flood hydrographs: Q times total lag divided by 6. Q is peak rate of outflow in cubic feet per second, as calculated from the peak stage used in a broad-crested-weir formula applied to the spillway cross section; thus $Q = 2.5\ LH^{3/2}$ where L is length of spillway in feet, and H is maximum depth of water over spillway, in feet. Total lag is the sum of the detention time, in hours, of the sur-

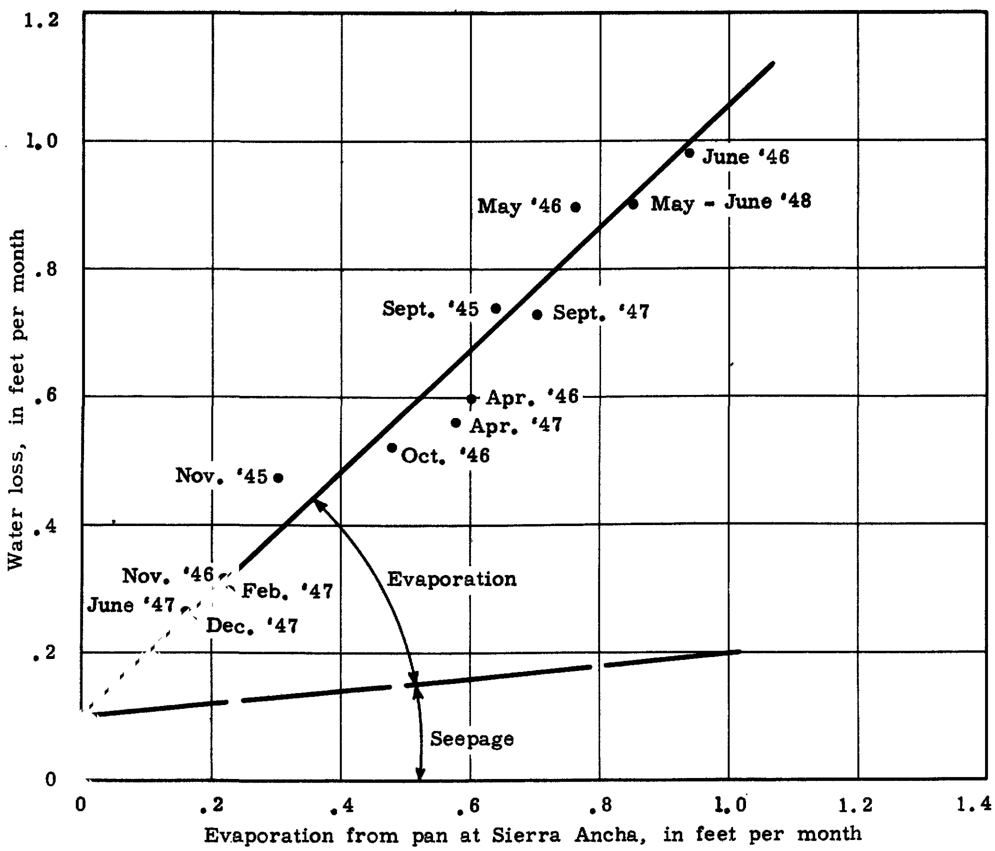


Figure 7.-- Evaporation and seepage from Postoffice Tank, Ariz.

Table 2.--Computations of recharge and runoff, Postoffice Tank near Whiteriver, Ariz.
[T = trace]

Date	Gage height end of period	Mean gage height	Change of gage height	Precipi-tation a/	Water loss	Mean sur-face area	Recharge		Runoff	
	(feet)	(feet)	(feet)	(feet)	(feet)	(acres)	(feet)	(acre-feet)	(feet)	(acre-feet)
1945										
July	95.00			0.19						
Aug.	94.62	94.8	-0.38	.31	0.83	0.52	0.45	0.23	0.14	0.07
Sept.	93.92	94.3	- .70	.05	.80	.47	.10	.05	.05	.02
Total								.28		.09
Oct.	93.89	94.1	- .03	.21	.52	.46	.49	.23	.28	.13
Nov.	93.42	93.7	- .47	0	.40	.43	0	0	0	0
Dec.	93.55	93.4	+ .13	.23	.28	.41	.41	.17	.18	.07
1946										
Jan.	93.55	93.6	0	.16	.24	.43	.24	.10	.08	.03
Feb.	93.40	93.5	- .15	.06	.34	.42	.19	.08	.13	.06
Mar.	93.08	93.3	- .32	.10	.46	.40	.14	.06	.04	.02
Apr.	92.58	92.8	- .50	.10	.70	.37	.20	.07	.10	.04
May	91.68	92.1	- .90	T	.86	.34	0	0	0	0
June	90.70	91.2	- .98	T	1.04	.29	.06	.02	.06	.02
July	90.26	90.3	- .44	.23	.93	.24	.49	.12	.26	.06
Aug.	90.42	90.5	+ .16	.45	.74	.26	.90	.23	.45	.12
Sept.	96.58	93.3	+6.16	.39	.68	.40	6.84	2.74	6.45	b/2.8
Total 1946 water year								3.82		3.35
Oct.	96.72	96.4	+ .14	.12	.52	.60	.66	.40	.54	.32
Nov.	96.48	96.6	- .24	.08	.32	.62	.08	.05	0	0
Dec.	96.38	96.4	- .10	.13	.30	.60	.20	.12	.07	.04
1947										
Jan.	96.14	96.3	- .24	.01	.26	.60	.02	.01	0	0
Feb.	96.20	96.0	+ .06	.10	.38	.58	.44	.25	.34	.20
Mar.	96.00	96.1	- .20	.01	.47	.59	.27	.16	.26	.15
Apr.	95.44	95.7	- .56	.01	.66	.56	.10	.06	.09	.05
May) June)	94.14	95.2	-1.30	.26	1.72	.53	.42	.22	.16	.09
July	93.64	93.9	- .50	.17	.99	.44	.49	.22	.32	.14
Aug.	93.94	93.9	+ .30	.53	.80	.44	1.10	.48	.57	.25
Sept.	93.96	93.9	+ .02	.22	.76	.44	.78	.34	.56	.25
Total 1947 water year								2.31		1.49
Oct.	93.78	93.9	- .18	.27	.55	.44	.37	.16	.10	.04
Nov.	93.71	93.7	- .07	.13	.30	.43	.23	.10	.10	.04
Dec.	93.47	93.6	- .24	.04	.28	.43	.04	.02	0	0
1948										
Jan.	93.22	93.4	- .25	.02	.31	.41	.06	.02	.04	.02
Feb.	93.50	93.3	+ .28	.23	.30	.40	.58	.23	.35	.14
Mar.	96.96	95.2	+3.46	.16	.33	.53	3.79	2.01	3.63	b/2.5
Apr.) May)	95.40	96.2	-1.56	.01	1.60	.59	.04	.02	.03	.02
June) July)	93.9	94.5	-1.50	.30	2.10	.48	.60	.36	.30	.14
Aug.	93.59	93.9	- .31	.18	.85	.44	.54	.17	.36	.16
Sept.	93.14	93.3	- .45	.13	.80	.40	.35	.14	.23	.09
Total 1948 water year								3.23		3.15

a Mean of Whiteriver and McNary precipitation. b Includes overflow.

charge (volume above the spillway crest) in the reservoir and that of the drainage basin. The detention time of the reservoir surcharge is computed from the formula 12 S/Q, where S is the maximum volume in temporary storage above the spillway-crest level in acre-feet, and Q is peak rate of outflow in cubic feet per second as computed previously. Detention time of the drainage basin in hours is estimated as equal to the square root of the drainage area in square miles.

For Postoffice Tank the detention time of the reservoir surcharge is estimated to be 12 hours and that of the drainage basin 0.5 hour. The spillage was therefore estimated to be 0.2 acre-foot in 1946 and 0.6 acre-foot in 1948. The annual runoff into Postoffice Tank was as follows:

Water year	Acre-feet
1946	3.35
1947	1.49
1948	3.15

The 3-year average runoff is 2.66 acre-feet, or 9.2 acre-feet per square mile. Because of the slow rate of sedimentation no repeat capacity survey was made.

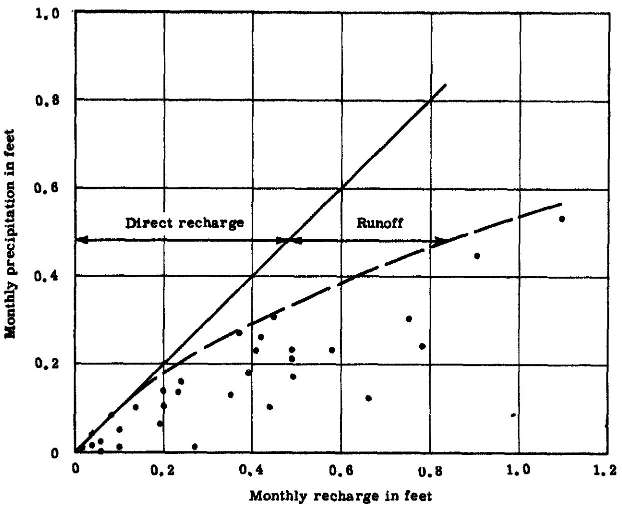


Figure 8.-- Relation of monthly recharge to precipitation, Postoffice Tank, Ariz

ANNUAL RUNOFF

The annual runoff at the reservoirs studied, as listed in columns 20 and 21 of table 3, ranged from 2 to 37 acre-feet per square mile, with a general average of about 9 acre-feet. The amount of runoff that a basin will produce depends on the amount and intensity of precipitation, the soil, the geology, and other aspects of the terrain. Adequate information is not at hand for evaluating the effects of each of these factors. An estimate of the runoff from a catchment area can be made from the range noted and by comparison with similarly situated drainage basins.

Ordinarily, for different drainage basins, one may associate the major part of the variations in mean annual runoff with variations in climate. The runoff values are typical of those that might be expected in semiarid and arid regions, but an examination shows that factors other than climatic are operative. For example, the climatic setting of Black Hills Tank is considerably more arid than that of Postoffice Tank, yet each reservoir has about the same annual runoff per unit of drainage area. In such cases the differences might be attributed to the geologic characteristics of the drainage basins. The runoff into Black Hills Tank appears high because of the large flow in 1948. The aridity at Black Hills Tank is evident in the year to year variability of the runoff, compared with that into Postoffice Tank.

The high runoff into Beautiful Valley Tank may be due in part to low-infiltration capacity of the shale bedrock underlying its drainage basin. The low runoff into Clay Tank in the Hualapai Indian Reservation may be due to the many cracks and fissures in the limestones that lie at the surface over most of this drainage basin.

Arizona had a general drought during the period of these investigations. Because of the drought, which seemed to be most intense in the Hualapai Indian Reservation, general storms were infrequent, but local convectional storms occurred sporadically. The chance occurrence of summer storms explains, it is believed, most of the diversity in runoff shown by the records. A continuation of these observations should average out most of the erratic effects of the desert climate, so that the influence of general climatic and terrain factors may be discerned.

Nevertheless, diversity in drainage basins as small as these is to be expected. The differences appear to be nearly as great between basins as between years. This diversity indicates that more meaningful information can be obtained from a large number of observations under widely different terrain and climatic conditions than from a few precise records for long periods at a few points.

Seasonal distribution of recharge

At reservoirs below 5,000-foot altitude, the records of water level show that recharge occurred in 2.25 months of the year on the average. The distribution of these months (fig. 9A) shows that periods of recharge are heavily grouped during July to October.

At reservoirs above 5,000 feet, the frequency of recharge averaged 3.0 months per year, somewhat greater than at the lower levels. However, as shown on figure 9B, there is less seasonal contrast between winter and summer. The frequency of summer recharge at these higher levels is not significantly less, but the major difference in recharge distribution is the added occurrence of winter rainfall and snowmelt.

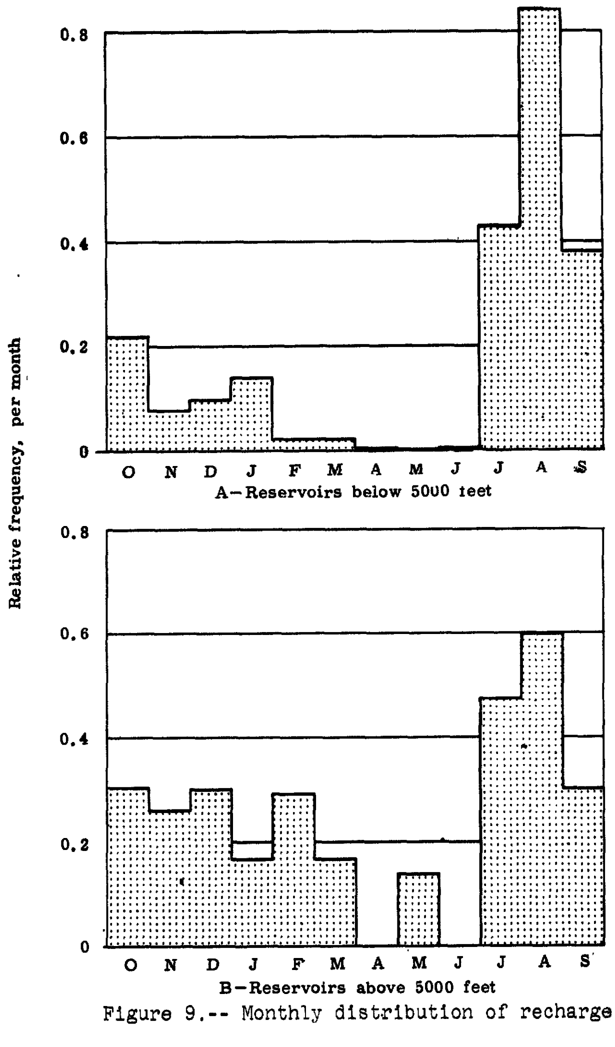


Figure 9.-- Monthly distribution of recharge.

Table 3.--Summary of data for reservoir gaging stations

Location Reservoir (Tank)	Drainage basin				Reservoir					Extreme water levels				Performance						Runoff	
	Area	Length	Relief	Altitude	Capacity	Depth	Area	v/ah (see p. 16)	Spillway elevation	Maximum Stage	Maximum Contents	Minimum Stage	Minimum Contents	Water loss (ft per month): Mean water-surface area	Water loss (ft per month): Total	Water loss (ft per month): Seepage	Water loss (ft per month): Mean evaporation	Mo per yr with water	Frequency of recharge		
	(sq mi)	(miles)	(feet)	(feet)	(acre-ft)	(feet)	(acres)		(feet)	(feet)	(acre-ft)	(feet)	(acre-ft)	(acres)					(mo per yr)	(acre-ft)	(acre-ft per sq mi)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
Ft. Apache Indian Res.																					
Postoffice	0.29	2.1	500	5725	3.5	11.8	0.62	0.48	96.8	97.0	3.5	90.2	0.7	0.46	0.6	0.15	0.45	12	7	2.6	9.2
Hualpai Indian Res.																					
Blue Mountain	.88	.75	450	5500	5.7	8.3	2.0	.34	95.0	91.7	2.5	86.4	0	.47	.7	-	-	4.2	1	1.5	1.7
Clay	22.9	7.5	900	5100	96	12.3	16.6	.47	95.0	93.45	80	82.7	0	4.2	-	-	-	7.3	2	36.6	1.6
Plain	13.6	6.5	400	4800	144	7.4	37.4	.52	95.0	93.2	89	87.6	0	10.0	.55	-	-	8	2.5	40.8	3
Thornton	.6	1.2	300	6550	15.7	11.5	3.7	.37	95.0	93.8	11.6	83.5	0	.9	.5	-	-	11	1	5.0	8.3
Navajo Indian Res.																					
Beautiful Valley	.52	1.76	500	5800	32.7	6.4	11.7	.44	81.2	79.6	17.5	74.8	0	3.5	.55	.05	.50	10.7	2.5	19.2	37
Spreader I-42	18.2	7	900	7000	a/100	a/22.9	11.0	.40	-	-	-	-	-	-	-	-	-	a/12-0	-	b/18.0	10
Papago Indian Res.																					
Alhambre	6.61	3	2960	3900	16	23	1.8	.39	-1.4	-1.0	16	-12.62	3	1.0	.75	.3	.45	12	2.7	b/10.6	1.6
Tank 76	1.17	1.9	1160	2900	9.4	10.1	3.3	.28	84.9	86.75	9.4	74.8	0	.95	1.5	-	-	9	2.5	b/11.0	9.4
San Carlos Indian Res.																					
Hilltop	10.6	5	1000	5300	130	18.4	18.6	.38	95.4	95.6	130	78.0	0.4	10	2.5	-	-	12	3	b/254	22
Juniper	2.0	1.75	650	4800	20	7.5	6.5	.41	94.2	95.2	20	90.98	6.1	4.5	.65	.25	.40	12	4	34	17
Tufastone	15.4	9.0	1000	2900	110	20.3	11	.49	29.0	-	-	-	-	-	-	-	-	12	-	-	-
Grazing Dist. No. 3																					
Mesquite	10±	6±	300	1300	8.7	16.2	1.3	.41	98.2	100.3	8.7	81.8	0	-	1.5	-	-	c/10	2.5	-	-
Yuma	-	-	-	1300	10	14.2	1.26	.56	89.0	89.9	11.2	75	0	.83	1.4	-	-	c/11.5	2.5	12.5	-
Grazing Dist. No. 4																					
Davis	d/.81	2.5	300	3900	2.5	8.7	.75	.38	91.9	92.5	2.5	83.5	0	.40	1.2	-	-	10	3	b/3.5	-
Kennedy	.97	2.6	1600	4150	4.7	8.9	1.52	.35	83.7	84.0	4.7	75	0	.50	1.4	-	-	8.5	2.5	b/4.9	5
Lonestar	.07	.5	1500	4270	2.1	11.2	.44	.43	86.2	86.2	2.1	75.0	0	.15	5.5	-	-	.5	.5	.5	6.5
Public Domain																					
Black Hills	1.56	2.5	600	2600	e/65	28.2	e/5	.46	28.2	19.7	25	0.0	0	.95	4	-	-	4	1	13.5	8.5

a Reduced to "0" by sedimentation.
b Additional runoff spilled.
c Probably higher since tank has sealed.
d 0.6 square mile regulated by upstream tanks.
e Estimated.

RESERVOIR WATER LOSSES

Evaporation and seepage are the two chief causes of depletion of the water in a stock-water reservoir. Collectively they are termed water losses. This term is quite apt as applied to the stock-water supply, although the water that seeps from a reservoir may reappear in part as stream flow to support stream-bank vegetation or in ways beneficial to downstream water users.

The methods of determining the rates of losses, as given in table 3, are explained in a previous section of this report. Rates of loss ranged from 0.5 foot to as much as 5 feet per month. Only four reservoirs had records of water level adequate for separation of water loss into evaporation and seepage. Evaporation rates averaged 0.4 to 0.5 foot per month (4.8 to 6.0 feet per year). These figures are probably representative, and seepage can be estimated from the difference between the total water loss and an evaporation rate of 0.45 foot per month. For most of the reservoirs studied, the rate of evaporation loss is the controlling factor in their performance, but as shown in table 3, there are several reservoirs for which the seepage rate greatly exceeds evaporation.

The rates of seepage as determined from analyses of the water-level records (table 3) are general averages. Detailed examination of recession hydrographs shows that seepage rates are variable. Some discussion has already been made of the effects of seasonal changes in water temperature upon possible changes in seepage rate. One of the most marked characteristics of hydrographs is the high initial rate of recession immediately after a rise in stage followed by a lessening in rate as the water level recedes. When recharge raises the water level in a reservoir, some water is absorbed in bank wetting. The rate of percolation is initially high while the dry soil absorbs water. On wetting, the clay particles of the soil swell and the rate of percolation diminishes. With recession of the reservoir level, the exposed land surface dries out, and the clays again shrink. The drying out represents a loss of the water that was absorbed in bank wetting. Those reservoirs that have large fluctuations in water level, separated by long periods of drying out, appear to have greater net seepage losses than those that have more stable water levels. These losses are particularly significant in reservoirs that have gently sloping sides. Such reservoirs are equally unsatisfactory because of evaporation losses.

The rate of seepage also varies for the following reasons which are related to position of water level: (1) Decreases in hydraulic head with recession in water level, and (2) the greater permeability of bed materials in the higher parts of a reservoir than of the thicker muds in the bottom of the reservoir.

In view of the still fragmentary nature of the records of water level in stock-water reservoirs, detailed investigation of variation in seepage losses does not appear feasible at this time. However, new techniques are being tried for determination of rate of seepage and evaporation.

The problem is to determine how much of an observed recession in water level during dry-weather periods is due to seepage and how much is due to evaporation. The principles employed in the separation are: (1) Evaporation varies in response to meteorologic controls, and (2) seepage is relatively uniform at a given stage and season. The relative proportions of evaporation and seepage are therefore variable.

In the annual cycle, loss by evaporation from shallow lakes reaches maximum in summer and minimum in winter. Figure 6 shows the seasonal variation in rate of water loss (rate of recession in absence of recharge) from Postoffice Tank. The rate of recession ranged from a maximum of 0.98 foot per month in June and July to a minimum of 0.26 foot per month in January. It is evident that evaporation is the dominant factor in this seasonal variation of water loss. The seasonal variation was used to estimate the monthly rate of seepage which was then deducted from the rate of recession to compute the rate of evaporation.

The diurnal cycle offers a comparable method for separating observed recession rates in seepage and evaporation. In the typical diurnal cycle, seepage (in or out) is uniform in rate but evaporation from shallow lakes is generally a maximum in midafternoon and a minimum sometime between midnight and sunrise. The minimum rate of recession approaches the rate of net seepage, according to a similar principle used by White (1932) to estimate rate of recharge from the diurnal transpiration cycle in ground-water level in an observation well.

A more refined technique that suggests itself is to measure the rate of recession in water level as precisely as possible during a 24-hour period and to correlate the rate of recession against an expression that combines the meteorologic and water-temperature factors that influence evaporation. Observations for this purpose were made at Juniper Tank on June 27-28, 1949, and August 5-6, 1950.

A series of hourly observations of water level, water temperature, wind speed, and wet- and dry-bulb temperatures were made during these two series. The methods used during the series of observations on August 5-6, 1950, are described below.

(1) Lake stage--measured by a vernier point gage, reading directly to thousandths of a foot. A gage well was provided by a 55 gallon oil drum, set offshore in the northern part of the lake in water about 2.5 feet deep. The intake was a quarter-inch hole about 18 inches below water surface.

(2) Wet- and dry-bulb temperatures--measured by standard Weather Bureau type sling psychrometer. Observations were made under the shade of a tractor umbrella, on the northern shore about 6.5 feet above water surface. Check observations showed no detectable difference between temperatures thus measured on the upwind and the downwind sides of lake.

(3) Wind speed--measured by a 3-cup Friez anemometer, mounted about 6.5 feet above water surface.

(4) Water temperature: (a) Surface water--measured at a point near the well, with bulb just under the surface and shaded from the sun. Check measurements of surface-water temperatures at various points in reservoir showed temperatures varying as much as 2° higher or lower from that measured at index point. (b) Bottom water--measured by obtaining a sample of bottom water in a 12-ounce bottle with a slow air leak. Duplicate samples were taken to assure equilibrium between bottle and water. Observations were made in water 4 feet deep. Greatest depth is probably 5.5 feet.

The observations are given in table 4. Averages for 4-hour periods are given for the June 1949 series and 2-hour periods for that of August 1950 when more precise data were obtained.

Generalized hydrographs of rates of change in water level are shown on figure 10. The diurnal cycle is well developed in both series of observations, although more marked in the June 1949 series. The minimum rate in each case was reached during the hours after midnight.

The minimum rate approaches the rate of seepage to the extent that evaporation during the early morning hours was zero and might be taken as close approximation of the seepage rate, were it not that consideration must be given to the possibility of negative evaporation, i.e., condensation. A closer estimate of seepage might be calculated if allowance is made for the rate of evaporation or condensation, small as the rate might be.

There are several formulas for combining the meteorological factors into an expression for evaporation. A review of these formulas and the theories upon which they are based is given in a recent report by the U. S. Navy Electronics Laboratory (Anderson et al., 1950). We are not concerned with a formula for evaporation but rather with an expression that is proportional to evaporation; or more specifically one that will reduce to zero when evaporation is zero. For this purpose, use can be made of the expression: $E \quad u^{3/4} (e_w - e_a)$, where u is wind speed in miles per hour; e_w is vapor pressure in inches of mercury, corresponding to temperature of the surface water in the reservoir; and e_a is the vapor pressure of the air, corresponding to the dew point.

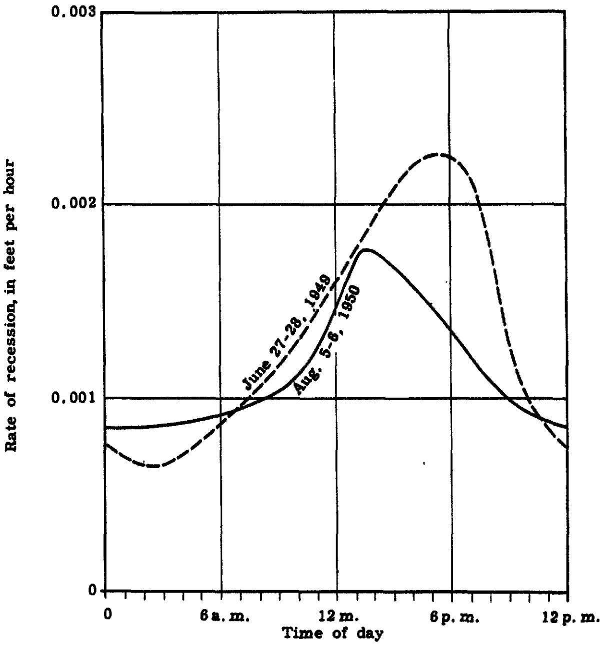


Figure 10.--Diurnal variation in rate of recession in water level.

An examination of the data in table 4 shows that dew points were generally stable during the periods of observation. Water at the surface showed significant amounts of cooling at night, but rates of wind movement showed the major diurnal change. Most of the variation in rate of recession in water level was associated with changes in wind speed. This association is somewhat unfortunate because comparatively little is known about the effect of wind speed upon the rate of evaporation under differing conditions of atmospheric stability, whereas experiments generally confirm that, except for molecular diffusion in the absence of wind, evaporation is proportional to $e_w - e_a$, the so-called "Dalton difference." Rough calculation, however, indicates that molecular diffusion is of the order of 0.00005 foot per hour, an amount too small to be considered in this analysis. Therefore, it is permissible to presume that under field conditions evaporation is zero when wind is zero, a condition that is satisfied by the foregoing expression.

The value of the exponent of the wind speed, 3/4, as originally proposed by Millar (1937) for average atmospheric stability, is confirmed by these observations to the extent that a value of about this size yields the maximum correlation with the rate of recession in water level. Although a more general analysis would permit variation in the value of the exponent of wind speed in accordance with the degree of stability, a constant exponent is considered sufficiently satisfactory for this study.

The values of the expression $u^{3/4} (e_w - e_a)$ are given in the final column of table 4 and are plotted against the observed rate of recession on figure 11. The points satisfactorily define two graphs of equal slope but different intercepts for the two series. We are concerned primarily with these intercepts because they presumably represent the rate of recession when evaporation is zero. The rate of recession then represents seepage. The intercepts on the axis of zero evaporation are 0.00038 foot per hour for the series of June 1949 and 0.00064 foot per hour for the series of August 1950. The greater seepage in the August 1950 series is due largely to the fact that the water level then stood just at the spillway, 2.3 feet higher than in June 1949.

The water budget for 24-hour periods in these two series is as follows:

Date	Stage	Surface area	Total fall in 24 hours	Seepage	Evaporation, by difference
	(feet)	(acres)	(feet)	(feet)	(feet)
June 27-28, 1949	91.92	5.6	0.032	0.009	0.023
Aug. 5-6, 1950	94.22	6.5	.028	.015	.013

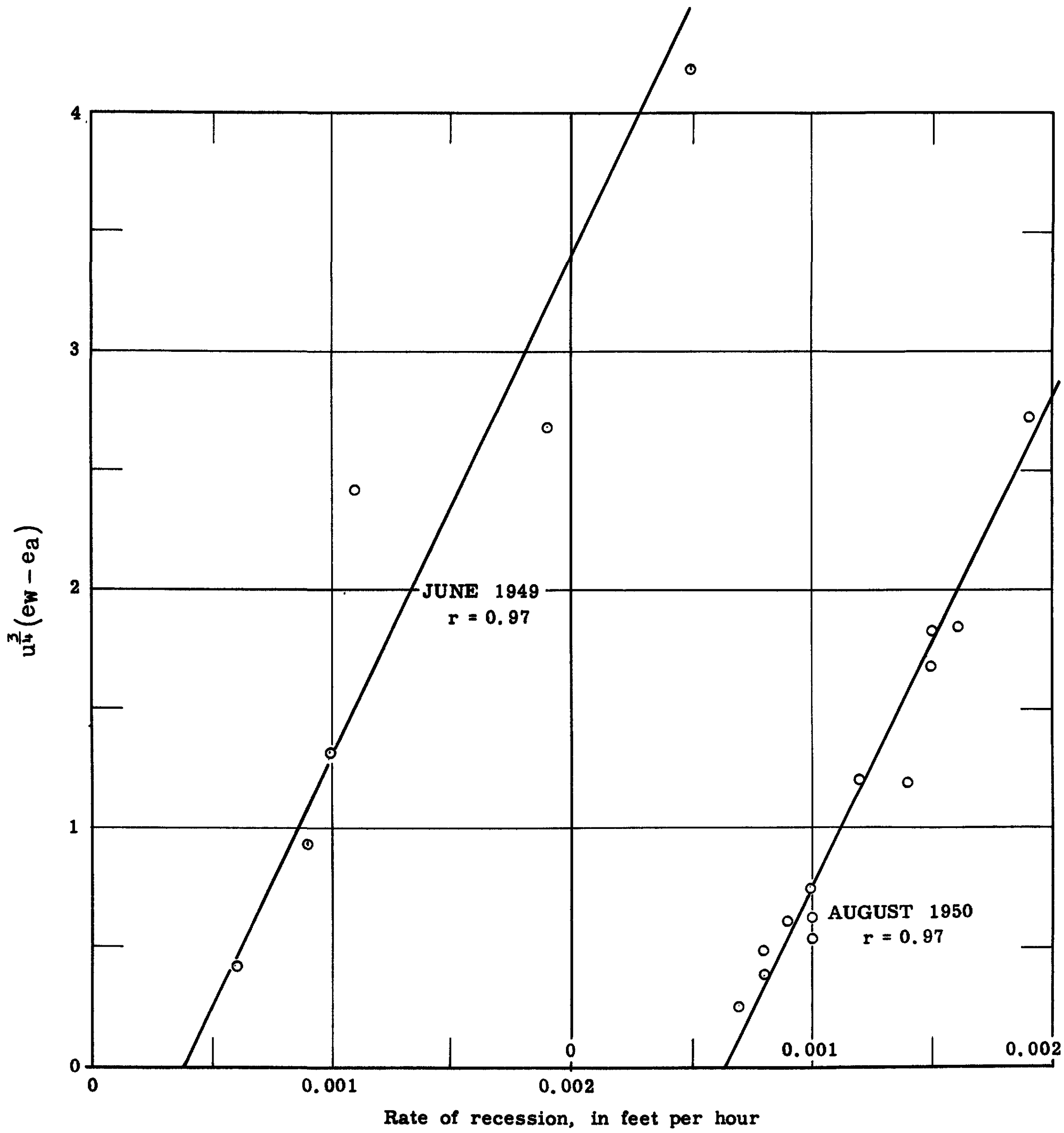


Figure 11.-- Variation in rate recession with $u^{\frac{3}{4}}(e_W - e_a)$.

The quantities in acre-feet can readily be determined, if desired, by multiplying the depths by the surface areas in acres on the respective days, as given in the table at the bottom of page 14.

The analysis of the seasonal variation in the rate of recession for Juniper Tank, by the methods explained in the Postoffice Tank illustration in this report, indicates that the mean rate of seepage of Juniper Tank during the summer months is about 0.32 foot per month, or 0.01 foot per day. This value is within the range indicated by the above analysis of the diurnal cycle. By detailed analysis of the diurnal cycle several times during the year, it should be possible to define the influence upon seepage of stage, water temperature, and other factors.

Table 4.--Observations at Juniper Tank

Time	Average rate of recession in water level	Average air temperature	Average dew point	Average water temperature		Average wind speed	$u^{3/4}$ (e_w - e_a)
				surface	bottom		
	(ft per hour)	(°F)	(°F)	(°F)	(°F)	(mph)	(see p. 14)
	Series of June 27-28, 1949						
June 27, 1949:							
4 - 8 p.m.	0.0025	83	30	78.5	-	9	4.18
8 - 12 p.m.	.0009	70	30	74.0	-	1.5	.94
June 28, 1949:							
12 p.m. - 4 a.m.	.0006	56	32.5	69.4	-	0.5	.41
4 - 8 a.m.	.0010	60	33	67.5	-	3.8	1.32
8 a.m. - 12 m.	.0011	77	34.5	74	-	5.8	2.41
12 m. - 4 p.m.	.0019	87	34.8	79	-	5	2.69
Average	.00133						1.99
	Series of August 5-6, 1950						
Aug. 5, 1950:							
12 m. - 2 p.m.	.0016	74.6	53.5	72.2	-	8.2	1.85
2 - 4 p.m.	.0015	78.4	49.1	79	71.2	4.0	1.83
4 - 6 p.m.	.0015	79.5	52.5	79	-	4.0	1.68
6 - 8 p.m.	.0014	73.1	57.1	77	-	3.5	1.18
8 - 10 p.m.	.0007	67.8	58	75.1	-	0.6	.26
10 - 12 p.m.	.0010	64.0	57	73.6	-	1.7	.54
Aug. 6, 1950:							
12 p.m. - 2 a.m.	.0008	60.5	57	72.5	-	1.2	.38
2 - 4 a.m.	.0010	60.0	56.5	71.5	-	2.5	.62
4 - 6 a.m.	.0008	59.8	55.2	70.9	70.0	1.75	.48
6 - 8 a.m.	.0009	65.0	57.2	70.2	-	2.9	.60
8 - 10 a.m.	.0010	75.0	56.5	73.4	-	2.6	.75
10 a.m. - 12 m.	.0012	79.9	51.9	79.8	-	3.8	1.70
12 m. - 2 p.m.	.0019	82.5	52.4	83.0	70.8	5.7	2.73
Average	.00118						1.12

PERFORMANCE

The results obtained at the reservoir gaging stations as summarized in table 3 are, in general, self-explanatory. The capacities of the reservoirs studied ranged from 2.1 to 144 acre-feet. In relation to size of drainage area the capacities averaged about 9 acre-feet per square mile. Reservoirs with less capacity than this generally spilled one or more times during the period of gage readings.

Reservoir shape is indicated by the ratio v/ah (see column 9 of table 3), where a is the area in acres at spillway level (column 8), h the depth in feet from spillway level to bottom of the reservoir (column 7), and v the total capacity in acre-feet to spillway level (column 6). This ratio averages about 0.4 and suggests a rough rule for estimating capacity of a reservoir--capacity = 0.4 x area x depth.

Table 3 includes a summary of the maximum and minimum water levels and contents during the period of observation, generally 1945-48. About half the reservoirs overflowed and, with few exceptions, every reservoir listed was dry at least once during the period of observation. Reservoirs are built to hold water between rains. The ideal reservoir contains usable water all year, although in cases of seasonal use of the range the reservoir need contain water only during seasons when the surrounding range is grazed. As measured by the average number of months per year during which they contained water, the reservoirs included in this study were fairly successful. Only three had water for less than 6 months, whereas five contained water the year long.

Depth of water is well recognized as a major criterion in governing performance of a reservoir; but it is important not to confuse depth of water with depth of reservoir, as many high dams impound only shallow pools of impermanent water.

The depth of water in a reservoir, and therefore its performance, is the result of several factors: Volume of inflow; frequency of inflow; rate of loss; and depth-area relation of reservoir. A study of these factors in relation to the performance of the reservoirs is shown on figure 12. The ordinate represents the average number of months per year that the reservoirs contain water, as given in column 19 of table 3. In the quantity R/aL, R represents the annual runoff in acre-feet (column 21 of table 3), a the mean water-surface area in acres (column 15), and L the mean rate of water loss in acre-feet per month (column 16). The plotted numbers on figure 12 indicate the average number of months per year in which recharge occurs (column 20). For most of the reservoirs studied the value of a averaged about 60 percent of the area at the spillway (column 8 of table 3) for reservoirs with yearlong supply, and 30 percent for others. The relationship shown on figure 12 can be approximated by the following formula: $p = (F - 1) + R/aL$. The value of F (average frequency of recharge) ranged from 1 to 3 months per year, so that the carry-over term R/aL is the major criterion as to performance. In humid regions, where recharge occurs more frequently, high performance can be achieved even though the quantity R/aL is low.

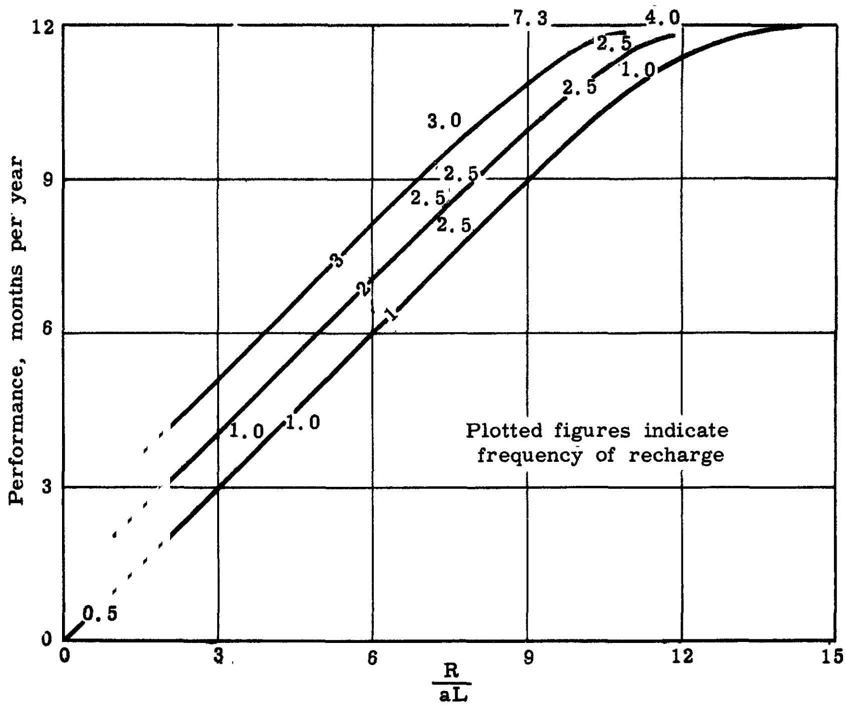


Figure 12.-- Relation of performance to runoff, water area, water loss and frequency of recharge.

PRINCIPLES OF RESERVOIR DESIGN

Unlike an irrigation reservoir, the performance of a stock-water reservoir is dependent on depth of water rather than on capacity. The records demonstrate that there is generally little need for a reservoir to have a capacity greater than that necessary to store the mean annual runoff. Providing additional capacity to store the water that would spill in years of extraordinary runoff, according to the evidence obtained, does not thereby provide water during extended dry periods. Rates of loss are great at high, infrequent stages and losses at such stages may be at the expense of downstream users without necessarily benefiting the stock-water supply. Increasing capacity is generally an uneconomical method of obtaining depth. For example, doubling the capacity in most reservoirs adds only about 35 percent to the depth. Nor does placing reservoirs in tandem, in lieu of a single large reservoir, seem to help; to the contrary, it even increases losses without providing water during dry years. Rate of losses imposes a limit on the amount of carry-over water that can be provided.

The problem is to get sufficient water depth to carry over a reasonably long dry period. For economic reasons, this need not be the longest dry period on record, but it must be one that is fairly representative of the dry periods that are likely to occur. The water-level records indicate that this dry period in Arizona is rarely longer than 15 months and is less where recharge occurs more than once a year. For purposes of design, the dry period in months may be roughly estimated from the formula $15\,[2/(F + 1)]$, where F is the average frequency of recharge per year. This leads to the important criterion that depth should be at least equal to $15\,[2/(F + 1)]\,L$, where L is average rate of water loss in feet per month--provided that the capacity at this depth does not greatly exceed annual runoff.

Consider the following as an example. Given: R = 15 acre-feet per year, L = 0.6 foot per month, and F = 2 months; required: depth for 12-month performance. Depth needed is $15\,[2/(F + 1)]\,L = 6.0$ feet. The area-capacity curves for this site shows a surface area of 2.5 acres and a capacity of 6 acre-feet at a 6-foot depth. The mean surface area exposed to loss may be taken as 0.6 of the area at the 6-foot depth. Annual losses would therefore be (0.6 x 2.5 acres) x 0.6 foot per month x 12 months = 11 acre-feet. Since there is ample runoff to supply this loss, a 6-foot reservoir should provide 12-months water per year, on the average, until this depth is depleted by sedimentation. Excess water will be spilled.

If runoff were only 3 acre-feet per year there would be some question whether a 6 acre-foot reservoir would be economical at this site, inasmuch as it would be rarely filled. Yearlong water supply could be obtained at this site only through supplementation of depth by excavation of a charco (pit reservoir) such that total capacity at a depth of 6 feet does not exceed the annual runoff, about 3 acre-feet in this example.

The design of a stock-water reservoir requires information that is not generally available in advance. The data obtained in this investigation, nevertheless, do indicate certain limits that might be observed in order to minimize expense without detracting from performance. Some rough rules might be as follows: Depth not less than about 7 feet for a capacity of not more than 5 to 10 acre-feet per square mile of drainage area. Where this depth cannot be obtained within the specified limit of capacity at a natural site, charco pits are necessary. Charco pits constructed by building the dam from materials excavated from the reservoir bottom are desirable in every case provided excavation does not extend into permeable materials. Enough is known (Holtan, 1950) about soils to show that seepage losses may be minimized by compacting the bottom materials prior to filling the reservoir. The best material for compaction is a well-graded mixture of not more than 30 percent or even as little as 5 percent of clay. The bottom should be loosened to a depth of at least 6 inches and then brought to a moisture content of good tilth. The loosened and moistened soil should be compacted by heavy machinery or cattle. The process is about the same as might be followed in building a tight dam. In important jobs, the method can be refined and the material made nearly water-tight.

For practical reasons reservoirs should have at least 3 acre-feet capacity, which entails a drainage area of at least 0.6 square mile. Exceptions might be made in regions of high runoff provided seepage is very low. As reservoirs on large drainage areas tend to involve troublesome amounts of sediment as well as other expensive factors, it appears inadvisable to impound a wash with a drainage area of more than 15 square miles for a stock-water supply.

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