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WATER YIELD AND RESERVOIR STORAGE IN THE UNITED STATES

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INTRODUCTION

The capture and storage of water during high-water periods for use during low-water periods represents salvage of water which otherwise would be wasted and possibly would cause flood damage. The aggregate capacity of regulatory storage reservoirs in the United States (excluding those with capacities of less than 5,000 acre-feet) has increased from 33 million acre-feet in 1920 to 273 million acre-feet in 1953 (Thomas and Harbeck, 1956). The trend in reservoir construction for all purposes is still steeply upward. The amount of water that is now made available for use by reservoir storage and the amount that can be made available by additional storage are estimated in this paper.

RELATION BETWEEN STORAGE CAPACITY AND REGULATION

A reservoir regulates streamflow for beneficial use by storing water for later release. Changes in storage are the measure of the work done by a reservoir. The term "regulation" is here defined as the amount of water that is stored or released from storage in a period of time, generally a year. For calculation purposes, regulation is the sum of all gains in reservoir contents. Because any gain in storage eventually is offset by a loss, the sum of the gains tends to equal the sum of the losses; therefore, regulation could also be defined as the sum of all the drafts on storage.

The ability of a reservoir to regulate river flow depends on the ratio of its capacity to the volume of river flow. The ratio of the capacity in acre-feet to the mean annual flow in acre-feet per year is the detention period of the reservoir and has the dimension of years.

The total of the gains in storage during a period of years, divided by the number of years, gives the mean annual regulation. Dividing the mean annual regulation by the usable capacity of the reservoir gives the ratio of the regulation to the capacity (the regulation-capacity ratio), and dividing it by the mean annual flow gives the ratio to the mean annual flow (the regulation-flow ratio).

The regulation provided by existing storage facilities can be determined by studying the records of typical reservoirs. A representative group of reservoirs is listed in table 1 with the usable capacity, detention period, and annual regulation of each. Reservoirs were selected to cover detention periods ranging from about 0.01 year to 20 years.

The relation between the ratios of mean annual regulation to capacity and of capacity to annual flow for the reservoirs in table 1 is plotted on figure 1. This figure shows that reservoirs with capacities of about 0.17 of a

Table 1.—Capacity and regulation of some representative reservoirs

Reservoir and State	Usable capacity		Mean annual regulation[1]		
	Acre-feet[2]	Detention period (years)[3]	Acre-feet per year	Ratio to capacity	Ratio to mean annual flow
Piney, Pa	13,000	0.011	70,000	5.4	0.06
Great Falls, Tenn	49,400	.021	204,000	4.1	.089
Ocoee No. 1, Tenn	33,100	.035	204,000	3.6	.13
Claytor, Va	100,000	.04	150,000	1.5	.06
Mascoma Lake, N. H	7,744	.05	22,000	2.8	.14
Franklin D. Roosevelt Lake, Wash	5,072,000	.07	4,800,000	.95	.07
West Fork Bitterroot, Mont	31,700	.14	26,000	.82	.12
Hiwassee, N. C	1,376,000	.265	330,000	.90	.24
Green Mountain, Colo	146,900	.34	111,000	.75	.26
Gibraltar, Calif	7,731	.39	4,300	.55	.21
Stillwater, N. Y	106,000	.40	91,000	.86	.34
Sacandaga, N. Y	762,300	.51	560,000	.75	.38
First and Second Connecticut Lakes, N. H	88,106	.60	62,000	.70	.42
Norris, Tenn	2,281,000	.72	1,070,000	.47	.34
Shasta Lake, Calif	4,377,000	.80	1,530,000	.35	.28
Lake Alamanor, Calif	649,800	1.0	250,000	.38	.38
Salmon River Canal Co., Idaho	182,650	1.6	57,500	.31	.54
Henrys Lake, Idaho	79,351	2.1	20,600	.26	.54
Lake Mead, Ariz.-Nev	27,207,000	2.1	[4] 5,750,000	.21	.44

Table 1.—Capacity and regulation of some representative reservoirs—Continued

Reservoir and State	Usable capacity		Mean annual regulation[1]		
	Acre-feet[2]	Detention period (years)[3]	Acre-feet per year	Ratio to capacity	Ratio to mean annual flow
Lake Mead and Lake Mohave, Ariz.-Nev	29,000,000	2.3	[4] 6,500,000	0.22	0.51
Fort Phantom Hill, Tex	69,500	2.3	11,900	.175	.40
Lake Kickapoo, Tex	106,000	2.6	20,200	.19	.49
Elephant Butte, N. Mex	2,185,000	2.6	[4] 375,000	.17	.45
Elephant Butte and Caballo, N. Mex	2,526,000	3.0	[4] 470,000	.185	.55
Quabbin, Mass	1,279,000	6.0	119,000	.09	.56
San Carlos, Ariz	1,205,000	6.7	[4] 117,000	.097	.65
Lake Henshaw, Calif	194,320	21.8	8,170	.042	.91

[1] For reservoirs with detention periods greater than 0.1 year, regulation was computed from monthly changes in reservoir contents. For reservoirs with shorter detention periods, daily data were used.

[2] Thomas and Harbeck (1956).

[3] Ratio of usable capacity, in acre-feet, to mean annual flow, in acre-feet per year.

[4] Including evaporation losses.

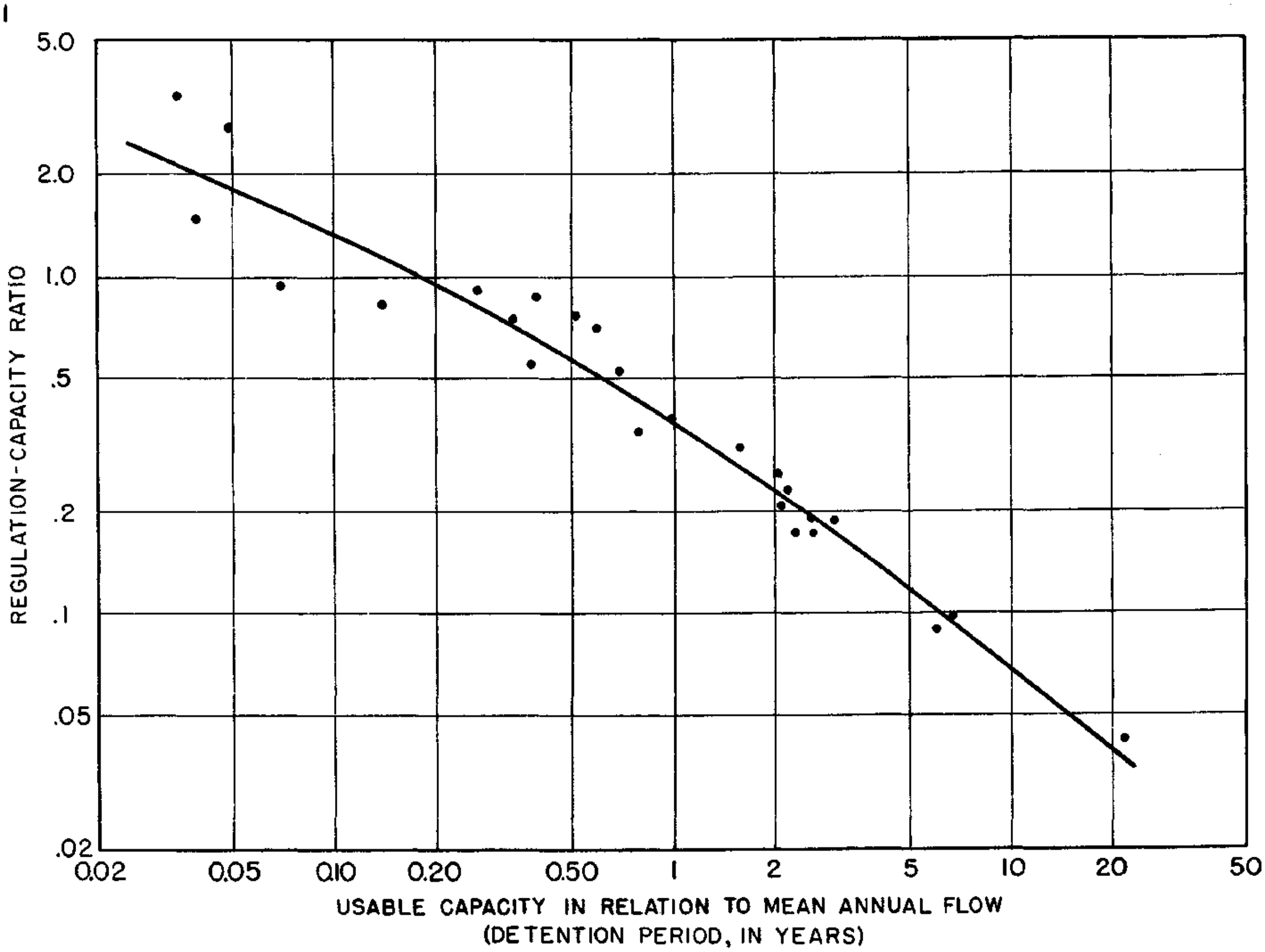

Figure 1.—Regulation-capacity ratio in relation to usable capacity.

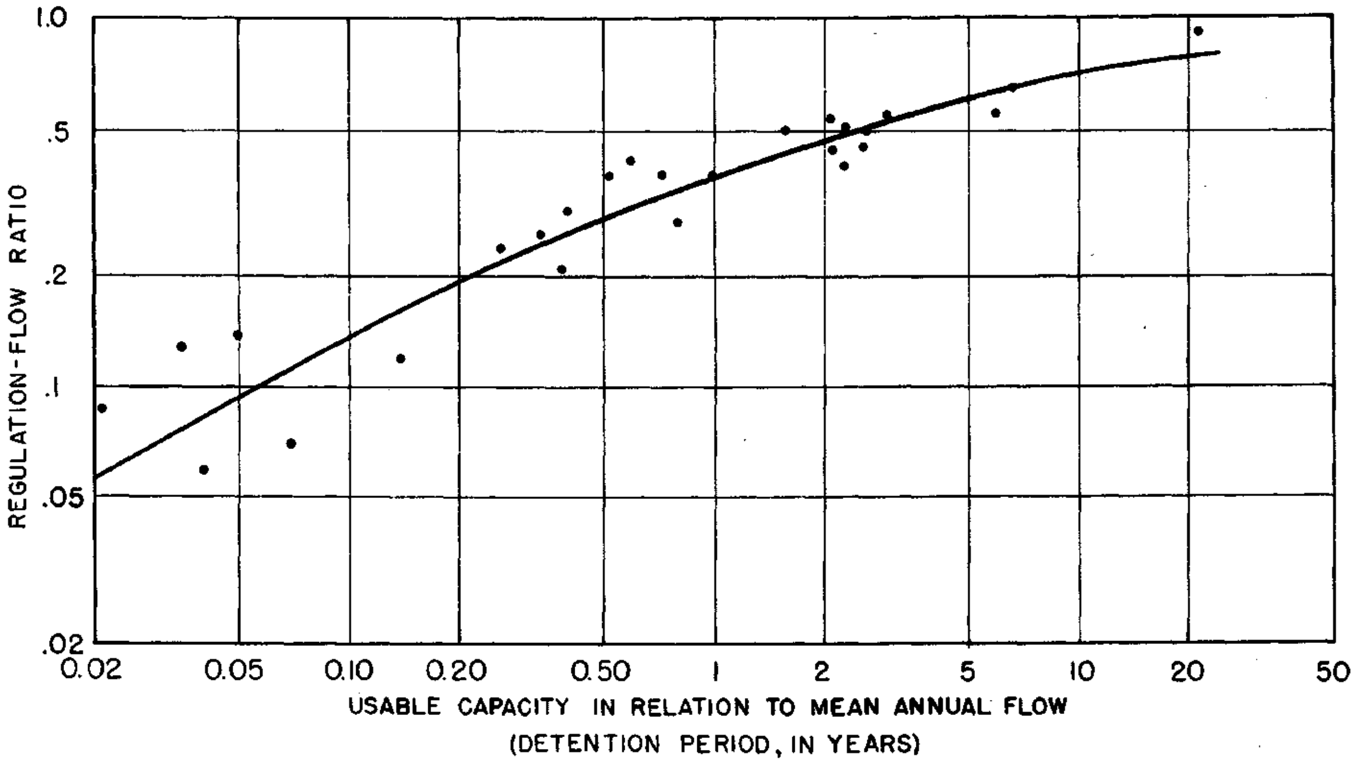

Figure 2.—Regulation-flow ratio in relation to usable capacity.

year's flow have their full capacity utilized once each year. The total of the changes in contents of reservoirs with capacities of less than 0.17 of a year's flow exceeds the capacity; in other words, their capacity is used more than once each year. Reservoirs with usable capacities equal to a year's mean flow have an average annual utilization of about 37 percent of their capacity.

Figure 2 shows how reservoir capacity influences regulation expressed as a ratio to mean annual flow. The regulation increases with the detention period, approaching 80 percent of the annual flow for large-holdover reservoirs. The annual regulation cannot, of course, exceed the annual runoff. The graph on figure 2 is defined by the following equation:

$$\frac{C}{Q} = 2.5\left(\frac{\frac{R}{Q}}{1-\frac{R}{Q}}\right)^{1.6}$$

in which R is the mean annual regulation, Q is the mean annual river flow, and C is usable capacity. The form of this equation parallels that of the equations for storage, based on analogy with queues (Langbein, 1958). The equation indicates that usable capacity would go to infinity if regulation, R/Q, were to approach unity. The equation may also serve as a guide for determining the capacity needed to obtain a specific amount of regulation.[1]

[1]The regulation, R/Q, can be computed from a comparison of the duration curve of the inflows into the proposed reservoir with the duration curve of the desired outflow from reservoir.

The relations illustrated by figures 1 and 2 seem to be well defined despite the substantial differences in stream regimen and in manner of operation.

EXISTING CAPACITY

Taking the reservoirs in the United States reported by Thomas and Harbeck (1956) (excluding those built solely for flood control) and classifying them by capacity (in terms of detention periods), results in the following:

Detention period (years)	Number of reservoirs	Aggregate usable capacity (million acre-feet)	Regulation-capacity ratio[1]	Total regulation (million acre-feet)
less than 0.05	415	19.0	2.00	38
0.05–0.19.....	343	55.0	1.20	66
0.20–0.49.....	210	61.0	.70	43
0.50–0.99.....	167	45.7	.45	21
1.0–1.49......	68	43.5	.31	13
1.5 and over..	64	49.0	.20	10
Total or average....	1,267	273.2	0.70	191

[1]From figure 1.

Thus, the computed annual water supply made available by existing reservoirs is about 190 million acre-feet. This quantity, reduced by an estimated net-evaporation loss of 10 million acre-feet (mostly in the Western States), is 13 percent of the total flow of the rivers of the United States (1,400 million acre-feet). The percentage of regulation varies in different river basins. The figures for some typical major drainage basins are:

Drainage basin	Regulation, in percent, of total flow[1]
Ohio River (excluding the Tennessee and Cumberland Rivers)	1
Tennessee and Cumberland Rivers	17
Colorado River[2]	50

[1]Excluding flood-control reservoirs.
[2]Not including Glen Canyon Reservoir, now under construction.

Water control by storage follows a law of diminishing returns. Each successive increment of control requires a larger amount of reservoir storage space than the preceding increment. The net effect is illustrated by figure 2. Storage capacity equal to a year's flow can regulate almost 40 percent of the flow, but doubling the capacity increases regulation only by about one-third. There is, therefore, a limit to the amount of storage that it is feasible to build with prospect of useful return.

Although in the East a considerable increase in usable water supply can be obtained by additional reservoir storage, some drainage basins in the West may already be approaching the limit.

For example, the capacity of existing reservoirs in the Colorado River basin is nearly 35 million acre-feet. Most of this capacity, which is in Lake Mead, is used to regulate the flow of the main stem. The regulatory capacity soon will be nearly doubled by the construction of Glen Canyon Reservoir, which will have a usable capacity of about 20 million acre-feet. But evaporation imposes a ceiling on potential river regulation in an arid climate. If, as in Lake Mead and as computed for the Glen Canyon Reservoir (U. S. Bureau of Reclamation, 1954), annual evaporation averages about 27,000 acre-feet per million acre-feet of usable capacity, one can construct from figure 2 the following relation between storage capacity and net regulation for the Colorado River system:

Detention period (years)	Capacity of reservoirs in system (million acre-feet)[1]	Annual regulation (million acre-feet)	Annual evaporation (million acre-feet)	Net annual regulation (million acre-feet)
1.0	13	4.7	0.4	4.3
2.2	[2] 29	6.3	.8	5.5
3.0	39	6.8	1.1	5.7
4.0	52	7.2	1.4	5.8
5.0	65	7.6	1.8	5.8
6.0	78	7.9	2.1	5.8

[1]Based on annual flow of 13 million acre-feet.
[2]Approximate present main-stem development.

Selected detention periods are listed in the first column. The capacity was obtained by multiplying the detention period by the mean annual flow of the Colorado River. The annual regulation was obtained from figure 1, as shown in the following example: The regulation-capacity ratio for a detention period of 1 year is 0.37. Thus, 0.37 multiplied by the capacity required for a detention period of 1 year, 13 million acre-feet, equals 4.7 million acre-feet. The annual evaporation is based on the evaporation rate of 27,000 acre-feet per million acre-feet of capacity. The net annual regulation is the annual regulation minus the annual evaporation.

The net regulation indicates, insofar as main-stem regulation of the Colorado River is concerned, that the capacity of existing reservoirs and of those under construction (total nearly 50 million acre-feet) is near a theoretical optimum—the minimum capacity necessary to provide the maximum obtainable regulation—and that any increase in capacity will not increase the supply. Furthermore, this optimum is insensitive. There is no significant gain in net regulation between 29 and 78 million acre-feet of capacity. The gain in regulation to be achieved by increasing the present 29 million acre-feet to nearly 50 million acre-feet of capacity appears to be largely offset by a corresponding increase in evaporation.

These conclusions, based on figure 2 and reservoir evaporation as reported under operating conditions, reflect practical gains or losses in regulation of water by reservoirs. The present analysis deals only with the problem of water supply and is intended only to convey a principle. Appraisal of the benefits of such operations in power or irrigation is a separate problem.

FUTURE CAPACITY

Woodward (1957) estimated that an annual increment of 9 to 10 million acre-feet of storage will be needed to meet anticipated increases in water use. This rate of increase will about double the present storage over the next 25 to 30 years, a rate that about parallels the rate of increase in the use of surface water. The estimated future development of storage in the United States is shown in figure 3. The actual increase will depend on how strategically the reservoirs are installed.

The present reservoir capacity of 273 million acre-feet is equal to 0.195 of the annual flow of the rivers of the country. The total regulation is 190 million acre-feet. These data correspond to point A on figure 3. If, as indicated by the present rate of increase in use of surface water for all purposes, the need for regulated supply of water will double in the next 25 years, the regulated annual supply a quarter of a century hence will be 380 million acre-feet. If the storage facilities to effect this development are located most strategically, that is so as not to duplicate present or future installations, the capacity needed would correspond to point B on figure 3. This capacity would be twice the present capacity. However, if the new installations are in basins which already are intensively developed, the total capacity needed would be that corresponding to point C on figure 3, the line A—C being parallel to the curve on figure 2. This capacity would be 1,200 million acre-feet, or about 4.5 times the present capacity.

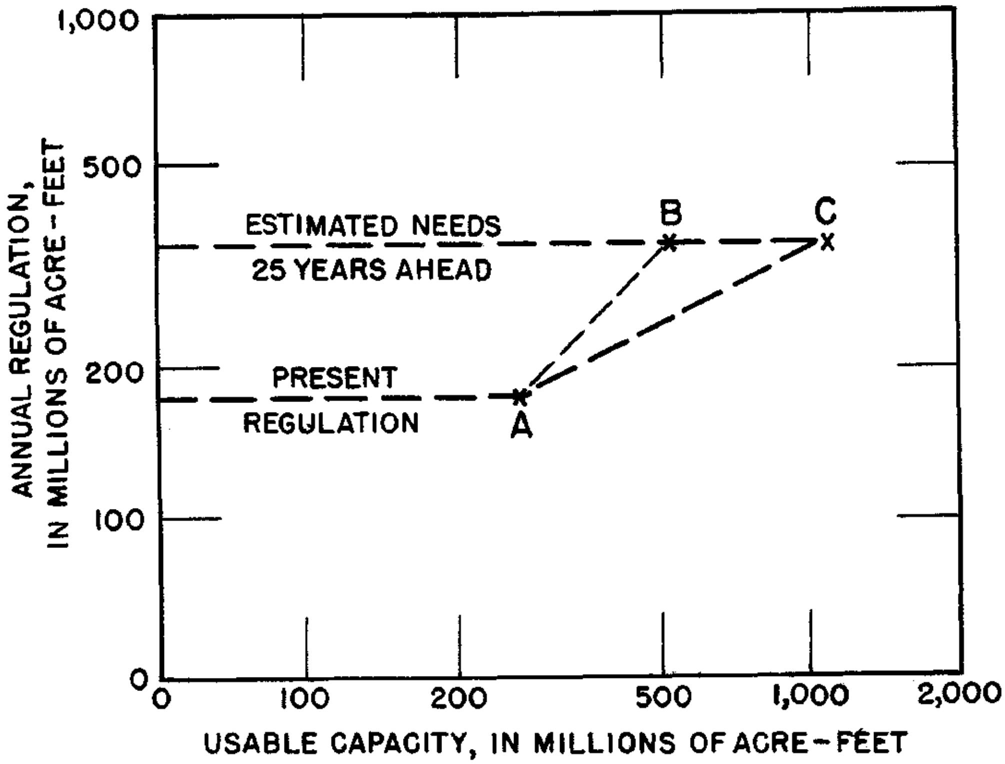

Figure 3.—Estimated future development of storage in the United States.

Thus, there is a wide range to challenge ingenuity in achieving efficient location of reservoirs.

CONCLUSIONS

Reservoir-storage development in the United States has made available for use about 190 million acre-feet of water or about 13 percent of the total river flow. The degree of storage development is highly variable. It is relatively greatest in the sparsely populated Colorado River basin and least in the populous Ohio River basin. The trend in construction of reservoirs in the United States is still steeply upward, but, as observed in Engineering News-Record (1958), the point of ultimate development for hydroelectric power, irrigation, flood control, and navigation may be seen on the horizon. Water supply and pollution control may become the dominant objectives of water storage.

Although in the United States as a whole, substantial increase in water supply can be obtained by additional storage development, water control by storage follows a law of diminishing returns. There is a limit to the amount of storage that can be useful. The Colorado River basin is an example of a river basin where storage development may be approaching, if not exceeding, the useful limit. The prospect of a shift in emphasis toward water supply for towns and factories sharpens the need for added development of storage in the populated regions of the country. Future needs for storage capacity to meet anticipated demands for water challenge ingenuity in achieving efficient location of the added storage.

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