DAMS, RESERVOIRS AND WITHDRAWALS FOR WATER SUPPLY -- HISTORIC TRENDS

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METRIC EQUIVALENTS

Multiply	by	to obtain
acre-ft	1237.	cubic meters
acre-ft per sq. mile	476.	cubic meters per square kilometer
billion gals per day	3.78×10^6	cubic meters per day
square miles	2.59	square kilometers

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INTRODUCTION

The U.S. Geological Survey (USGS) from time to time has published an inventory of major reservoirs and controlled natural lakes. The latest available USGS report (Martin and Hanson, 1966) indicated that as of 1963 usable capacity in major reservoirs[1/] (those having 5,000 acre-feet of usable capacity[2/]) totaled 359 million acre-feet which approximates the 320 million acre-feet indicated as of that date in a recent provisional inventory of dams prepared by the U.S. Army Corps of Engineers (COE, March 1981).

GROWTH IN CAPACITY OF RESERVOIRS

Figure 1 shows the growth in capacity of major reservoirs in the United States according to USGS and COE sources. The growth rate for total capacity averaged about 80 percent per decade until the early 1960's. Since then reservoir capacity has increased at a markedly slower rate, the effects of approaching an asymptotic limit on capacity in some areas, compounded, perhaps, by increasing public aversion towards reservoir construction (Holmes, 1979).

Reservoirs serve many purposes, such as flood control, irrigation, municipal water supply, or hydroelectric power generation. Much of the growth in capacity, especially after 1930, took place in multipurpose reservoirs that provided economies of scale and of combination. This trend was made possible by a change in technology that increased the number of practical damsites. Early dam builders sought a stream that cut through a narrow or "box" canyon of hard rocks, or a broad lake with a narrow stream outlet, so that a small dam could impound a large volume of water. Over the years, however, less favorable sites (those having a smaller capacity per unit volume of dam) have been developed, as indicated by the following data for the 100 largest reservoirs in the U.S. listed by Mermel (1958).

[1/]This study follows previous USGS practice of excluding reservoirs having usable capacity of less than 5,000 acre-feet. As reservoirs become smaller, the numbers increase greatly. The number of major reservoirs (exceeding 5,000 acre-feet) totals about 2,600. The COE lists tens of thousands of dams 25 feet or more in height or impounding 50 acre-feet or more. However, the capacity in these smaller impoundments is a small fraction of the total usable capacity - of the order of 2 percent.

[2/]Or "normal" capacity used by the COE. This is the total capacity less flood capacity and thus includes dead storage which is excluded from the "usable" capacity as defined by the USGS.

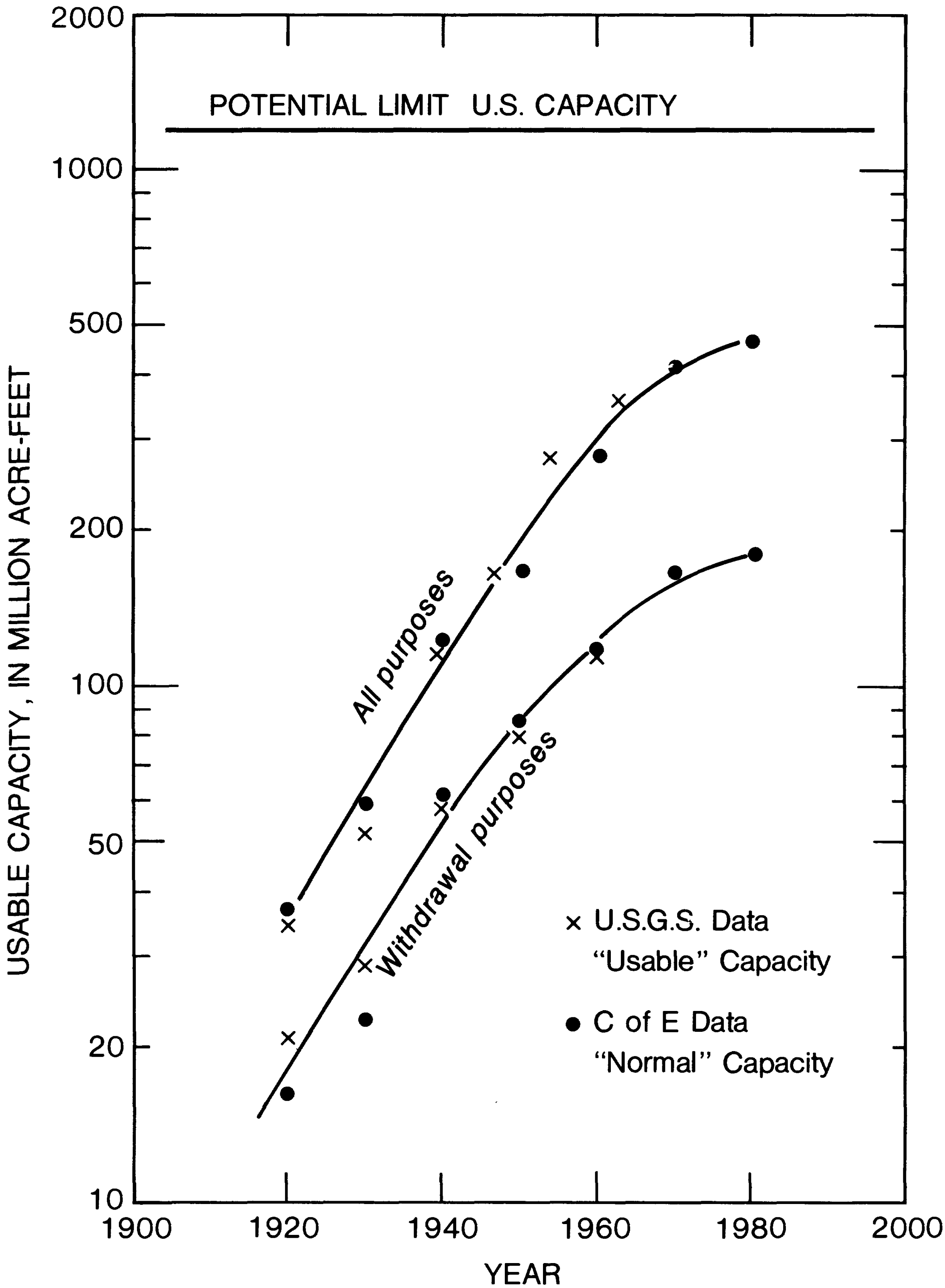

Figure 1.--Trend in reservoir capacity in major reservoirs in the United States since 1920.

Period	Reservoir Capacity per Unit Volume of Dam
1920 and earlier	10.4 acre-feet per cubic yard
1930's	2.1
1940's	.52
1950's	.45
1960's (dams under construction in 1958)	.29

The above data show a steady and marked decline in the storage capacity (acre-ft.) per unit of dam volume (cubic yards). This change in capacity-volume ratio for major reservoirs has been associated with a shift in kinds of dams. The narrow valley sites were suited to masonry dams (gravity, arch, buttress, etc.), whereas the newer sites have been practical only with broad-based earth-fill dams. (The percentage of masonry dams decreased from over 90 percent before 1930 to about 10 percent for those completed after 1960.)

Figure 1 shows a potential or asymptotic limit to usable storage capacity which was inferred from the results of river-basin planning during 1945-60's when diligent search was made for practical or feasible reservoir sites. The data follow:

Region or basin	Date	Total usable capacity (potential plus existing) million acre-feet	Drainage Area (1000 mi^2)	Unit capacity (acre-feet per sq.mi.)
North Atlantic Region	1966	47.9	173	280
Potomac River	1963	3.9	14	275
Colorado River	1946	102	250	400
Missouri River	1969	137	500	270
Southeast Region	1963	26	88	300
Columbia River	1946	52	220	235

In addition, one may examine the usable or normal capacity in place for all purposes in major reservoirs in States where capacity has already been intensively developed as follows:

State	Total usable capacity (million acre-feet)	Area ($1000\ mi^2$)	Unit capacity acre-feet per sq.mi.
Arkansas	13.2	52	250
Kentucky and Tennessee	19.4	82	240
North and South Dakota	44.6	145	300
South Carolina (plus 10,000 mi^2 Savannah River Basin of Georgia)	14.5	41	350
Washington	26.8	67	400

The ratios in the last column of the above two lists indicate a potential limit of about 400 acre-feet of usable reservoir capacity per square mile, or about 1,200 million acre-feet for the country (conterminous) as shown in figure 1. Since about 450 million acre-feet of usable capacity is already developed, this leaves 750 million acre-feet for potential development.

The remaining or potential 750 million acre-feet is apt to be high cost (cheap sites are already in use) or ruled out by environmental considerations. If so, then the reservoir capacity may be approaching an asymptote lower than that suggested above.

Water supply constitutes one of the essential reasons for building reservoirs. The reservoir regulates the naturally varying streamflow so that it matches more nearly the withdrawals of water that are made by municipalities, industry, and for irrigation. These are called the "withdrawal" uses which are unlike flood control, recreation, or hydropower that do not require the off-stream use of the water substance itself. The inventory of dams compiled by the COE lists the several purposes of each reservoir (irrigation, hydroelectric, flood control, navigation, water supply, recreation, debris control, and other).

The order of the listing indicates the relative decreasing importance of each purpose. However, the numerical distribution is not clear, and requires some assumption on allocations among the listed purposes in order to estimate the storage capacity available for withdrawal purposes. Five different formulas were applied, namely:

1. Normal capacity at each reservoir was allocated among listed purposes (including recreation) in descending order of importance using the "sum of digits" method. For example, if three purposes were listed, the first named was allocated 3/(3+2+1) or 0.5 of the capacity, the second named 2/6 or 1/3, and the third named 1/6 of the capacity.

2. The same method was employed except that no allocation was made to recreation unless it was listed as the sole use.

3. Reservoir space can serve more than one use at the same time. For example, recreation may be an incidental use without claim on any capacity; hydropower, as a secondary purpose, may be generated as an incident of falling water released for water supply or irrigation, and so on. Hence, in this third method, capacity was allocated in total to the first named purpose, and thereby assumes that secondary, tertiary, etc., purposes are served as an adjunct to the primary purpose.

4. Same as method 3, except that allowance is made for withdrawal purposes in subsidiary position - thus: all capacity if a withdrawal use is given first, 1/3 of capacity is included if a withdrawal use is in the second position, and 1/6 if in the third position.

5. A final method was to count total capacity for withdrawal purposes if any one of these purposes appears among the uses. This result would define an upper limit.

The results of computing storage capacities for water-supply uses by each of the methods are as follows with respect to 1980:

1. 120 million acre-feet

2. 135 million acre-feet

3. 140 million acre-feet

4. 179 million acre-feet

5. 283 million acre-feet

The results of method 4 agree with data through 1960 provided by Martin and Hanson (1966, figure 1). Figure 1 shows the trend in reservoir capacity for withdrawal purposes as computed by method 4 and based on data from both COE and USGS sources.

Comparison of the two graphs on figure 1, the one showing capacity for all purposes and that showing capacity for withdrawal purposes, shows a relative divergence since the 1940's. Before then, capacity for withdrawal purposes constituted about 50 percent of the total; in 1980 withdrawal purposes made up only 39 percent of the total capacity for all purposes. The first reservoirs were built for withdrawal purposes (Martin and Hanson, 1966, p. 1) and so this downward trend has a long history. Most reservoir capacity now serves purposes such as flood control or power generation, unless increased withdrawal for water supply has induced a reallocation of existing capacity toward withdrawal uses.

Table 1 and figure 2 compares the development of reservoir capacity for withdrawal purposes with the actual withdrawals from surface supplies (streams, lakes) as reported by Picton (1960) through 1950, and by the U.S. Geological Survey since 1950 (Murray and Reeves, 1970). A provisional figure is available for 1980, based on the inventory now in preparation. Withdrawals and capacity are clearly related through 1970. But, in the 1970-1980 decade, capacity did not keep up with the continued increase in withdrawals. The historic relation on figure 2 appears to be shifting to one with a greater rate of withdrawal per unit of capacity. This suggests a decrease in reliability from less than 2 percent chance of deficiency to greater than 2 percent (Hardison, 1972).

Table 1.--Reservoir capacity for withdrawal purposes and surface-water withdrawals, by decades, 1920 - 1980.

Year	Reservoir capacity for withdrawal purposes a/ (million acre-feet)	Surface-water withdrawals (bgd)
1920	17	75.7 b/
1930	23	92.3 b/
1940	62	113.2 b/
1950	86	160 c/
1960	119	190 c/
1970	166	250 c/
1980	179	310 d/

a/ COE data, allocation method 4

b/ Picton, 1960, table 1

c/ Murray and Reeves, 1972, table 3

d/ Provisional

DISCUSSION

For decades the United States has relied upon storage reservoirs to regulate the variable flow of rivers for diverse useful purposes. In 1957 Carl Paulsen, then Chief Hydraulic Engineer of the USGS, observed, "Reservoirs are becoming an increasingly prominent feature of the American landscape" (Paulsen, 1960). There are today about 2600 major reservoirs and tens of thousands of smaller ones if structures down to farm pond size are included. But the long trend

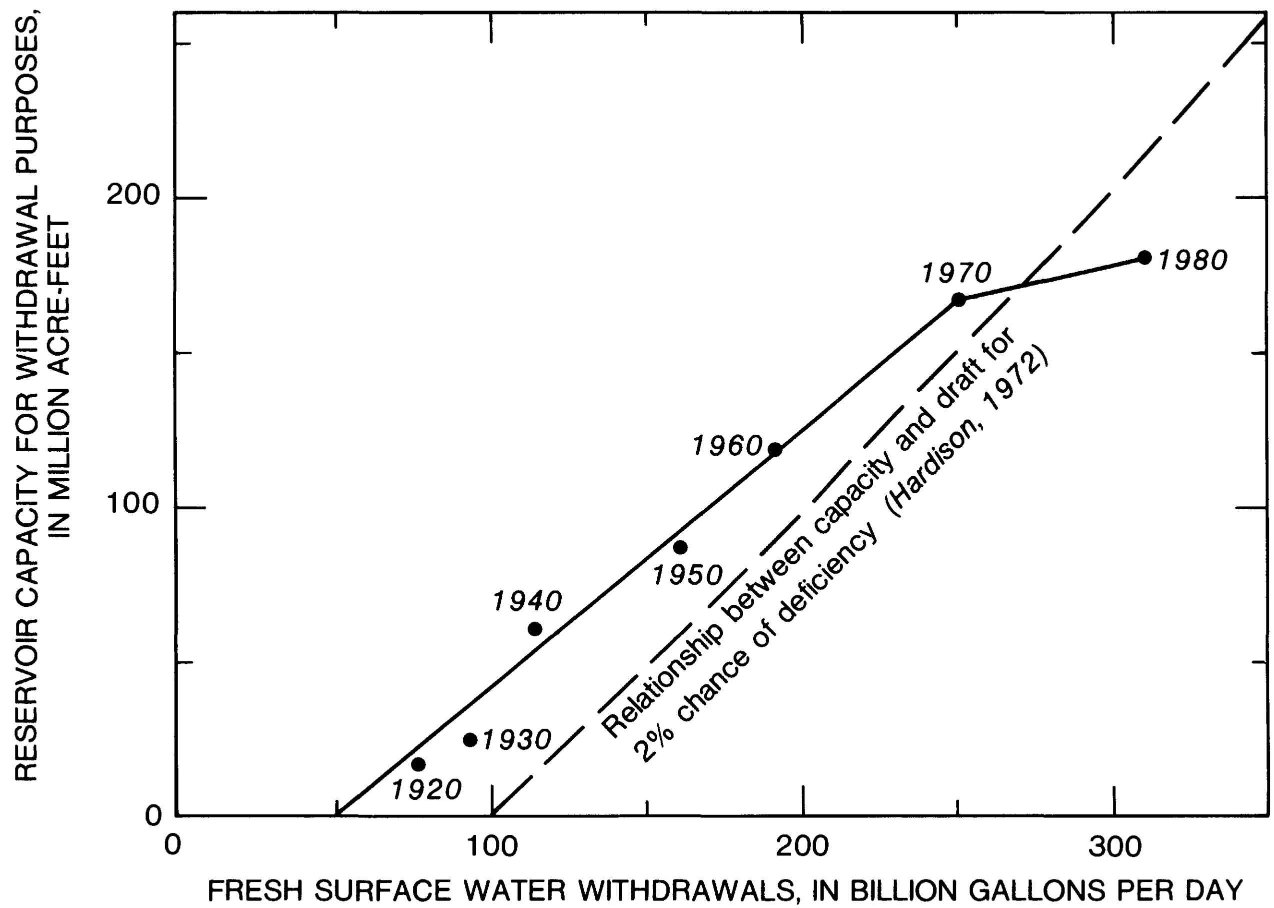

Figure 2.--Relations between reservoir capacity and withdrawals of surface water, 1920-80.

toward development of reservoir capacity in the interest of greater river regulation has been slowed if not arrested. About 1960 the upward rate began to flatten, reflecting, it is believed, social, environmental, and economic conditions. Reservoir functions--flood protection, hydropower, water supply, etc.--are still acceptable and, indeed, sought-after uses; but, at present, non-structural means are favored as avoiding environmental disruption, risk of dam failure, evaporation losses, sediment problems, and so forth, through a long list of chemical, physical, and biological impacts commonly attributed to 'man-made lakes.' In recent years one function of storage reservoirs has been judged unacceptable--that of augmentation of low flows to improve water quality, and no new uses for reservoirs have been adopted in recent decades. (Recreation is increasingly popular, and reservoirs have potentials as heat sources and sinks.) Although the several purposes continue to be useful, their role in water supply seems most essential.

The construction of surface reservoirs for the purpose of assuring water supplies (municipalities, irrigation) has also lessened, even though withdrawals of fresh surface water continued to increase at a steady rate during the past decade. By 1970 the capacity (166 million acre-feet) had grown to 216 days (7 months) of withdrawals at 250 bgd; in 1980 the storage period had decreased to 188 days (6 months). This decrease does not conform to the principle that storage period must increase with increase in draft if risk of deficiency is not to be impaired. The decreasing period of storage suggests a less assured supply of water during critical periods, when intensive conservation of use must be practiced. There are, however, other means for making do with less storage. There are a large number of multi-purpose reservoirs where withdrawal is not now the primary purpose, and where a shift in the allocation could, of course, make additional capacity available to meet water-supply shortages in time of drought. Pipeline interconnections would do the same. Better management of existing capacity through probabilistic forecasts of future flows (Hirsch, 1981), makes possible the scheduling of reservoir releases so as to minimize or control the risk of deficiency during critical periods. Further, an increased use of ground-water reservoirs can lessen the demand upon surface-water storage. Such methods could, indeed, permit storage capacity to increase at a lesser rate than in the past.

In sum, the graphs on figure 1 indicate a lessening role of reservoirs in the future development of water resources, far short of potentials. The trend toward non-structural measures places greater dependence on management skill and on understanding the nature of river behavior, (better forecasts). At some point, as yet unknown, the potentials of conservation and better management will become less effective than reservoirs. If so, the flattening of the graphs on figure 1 would be seen as merely an inflection along a generally upward trend in capacity, albeit at a rate slower than formerly.

NOTES ON DATA

In reporting these results, one must be aware that U.S. practice has not, in the past, given the same attention to gathering information about water uses and water development as to information about river flow, although the two are equally important in decisions about water policy. The data on water use, as explained in the pertinent USGS reports, are compiled from diverse sources and are only approximations of the quantity used. Plans are in progress toward improving these data.

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REFERENCES

Hardison, C. H., 1972, Potential United States water-supply development: Jour. Irrig. and Drainage Div., Proc. Am. Soc. Civil Engrs., p. 479-492, paper 9214.

Hirsch, R. M., 1981, Stochastic hydrologic model for drought management, Proc. Am. Soc. Civil Engrs., Vol. 107, No. WR2.

Holmes, B. H., 1979, History of Federal water resources programs and policies, 1961-70: U.S. Dept. of Agric. Misc. Publ. 1379, 330 p.

Martin, R. O. R., and Hanson, R. L., 1966, Reservoirs in the United States: U.S. Geological Survey Water-Supply paper 1838, 115 p.

Mermel, T. W., 1958, Register of dams in the United States. McGraw-Hill Book Co., N.Y.C., 429 p.

Murray, C. R., and Reeves, E. B., 1972, Estimated use of water in the United States, 1970: U.S. Geological Survey Circular 676, 37 p.

Paulsen, C. G., 1960, in Comprehensive survey of sedimentation in Lake Mead, 1948-49, U.S. Geological Survey Professional Paper 295, Foreword, p. III.

Picton, W.L., 1960, Water use in the United States 1900-1980: U.S. Dept. of Commerce, Business and Defense Services Admin., 6 p.

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