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HYDROLOGY OF THE SALT RIVER AND ITS RESERVOIRS, CENTRAL ARIZONA

JOHN N. RINNE[1]
Arizona State University, Tempe

INTRODUCTION. — In 1902 the U.S. Department of Interior, Bureau of Reclamation, was established, having as its primary charge the building of structures for the purpose of water storage in arid lands of western United States. Soon, hydroelectric generation was added to the Bureau's responsibilities. Early facilities, such as Roosevelt Dam in central Arizona, attracted increasing numbers of visitors, inspired by local scenery and enjoyment of recreational activities. Some time passed before Congress recognized the added benefits of fish and wildlife resources of man-made reservoirs, and continued evolution moved rapidly toward today's "multi-purpose or multiple-use concept."

The lower Colorado River and its major tributaries have received a substantial proportion of the reclamation program in western United States (Fig. 1). This river system ranks first in mean annual flow (2.6 x 10^6 hectare meters [ha-m] per annum) of all major rivers within hot, Southwestern deserts. The Gila system comprises the largest drainage area in the lower Colorado River basin and once contributed on the average more than 2.4 x 10 ha-m of water annually to the mainstream Colorado River. Intermittent drought and flooding of two major tributaries of the Gila, the Salt and Verde rivers, precluded development of reliable agriculture, industry, and a large human population in central Arizona until Roosevelt Dam was completed on the Salt River in 1911. Within 20 years, three somewhat smaller structures were constructed below this dam — Mormon Flat (1925), Horse Mesa (1927), and Stewart Mountain (1930); impounding Canyon, Apache, and Saguaro lakes, respectively. Horseshoe and Bartlett reservoirs on the Verde River were completed in 1939 and 1945, respectively. By 1940 the Salt River was contained and an artificial environment supporting human population densities of 154 per square kilometer (km^2) had developed. Since that time, these estimates have soared to $772/km^2$ by 1968 in the Phoenix metropolitan area; and perhaps to $1,000/km^2$ at this writing.

The following paper is written with the intent of briefly introducing some aspects of the quantitative and qualitative hydrology of the Salt River and its reservoirs. Recent structural modifications of the latter and their probable effects on not only the hydrology, but the biology and fisheries of these aquatic environs are purported. Further, it may serve as an introduction to large, man-made impoundments situated in hot, Southwestern deserts, which are essentially unstudied and apparently unique ecologically to those in more mesic areas. It is abstracted from a doctoral thesis completed at Arizona State University (Rinne, 1973).

GENERAL HYDROLOGY. — Major streams of the Sonoran Desert originate in adjacent highlands, and are characterized by seasonal and annual discharge patterns depending upon vagaries of southwestern montane precipitation, and upon cyclonic storms at lower elevations (see below). The Salt River receives water from mountains to the north and east of the desert proper (Fig. 1). Precipitation ranges from 25 to 89 centimeters (cm) annually over the slightly more than 10,000 km^2 of its watershed. Average annual runoff for the entire watershed is 7.11 cm (range, 1.7 to 29.0 cm; Green and Sellers, 1964) and in any given year runoff volume may vary from approximately 2.6 x 10 ha-m to more than 4.0 x 10 ha-m; total storage capacity of the four reservoirs in this chain is near 2.4 x 10 ha-m. Water retained during periods of high flow is subsequently distributed for domestic water supplies, irrigation, and power production.

During a recent study (Rinne, 1973) rates of discharge for Tonto Creek and the Salt River were substantially below average in winter and spring months, 1970-71. Summer rains, however, produced runoff equivalent to previous years, 1960-69 (Fig. 2). Both water courses, based on records since 1960 (Fig. 3) and the occurrence of large runoff in winter 1972-73, display a 3- to 4-year cycle of high annual discharge into these reservoirs.

The Salt River contributes an average of seven (mean flow) to ten (modal flow) times the volume of water to the reservoir system as does Tonto Creek (Figs. 4, 5). System input and downstream release of water vary month to month (Fig. 6-A), but they parallel each other annually (Fig. 6-B). On the average, only 3 per cent more water was released annually than was stored during the period 1960-69. By contrast, the former was almost twice the latter in the 1969-70 and 1970-71 water years (September to September) reflecting drought conditions. Patterns of monthly water inflow and release in the period 1960-61 indicated outflow, on the average, was generally less than 50 per cent of the volume of inflow (Fig. 7-A) until May when the trend reverses and the reservoirs began to be emptied (Fig. 7-B). June-July releases are approximately 6 times inflow resulting in lower reservoir water levels and increasing water movement through the system during summer.

Study commenced and was conducted in a period of decreasing water volume of the entire system (Fig. 8-A). Annual variations of water levels in Canyon and Saguaro lakes are greater than either of the larger, upstream impoundments; however, both have remained more than 80 per cent full since 1960 except in years of drainage — 1969 for the former and 1967 for the latter (Fig. 8-B). Almost all sampling during the 1970-71 study on Roosevelt Lake was performed while volume was less than 50 per cent full-pool (Fig. 8-C). By contrast,

[1]Current Address: EAFFRO, P.O. Box 1881, Kisumu, Kenya.

Apache Lake was over 80 per cent capacity until summer 1971 when drainage occurred to allow for construction activity (see Fig. 11).

Canyon and Saguaro lakes are of similar magnitude in storage ratios, a parameter calculated from reservoir volume and average annual volume of discharge. Calculated mean ratios for these two lowermost lakes in the chain is near 0.1, Apache is 5 times greater, and Roosevelt 3.5 times greater than Apache (Table 1). Consequently the former two would theoretically flush monthly on an average, Apache would require almost 6 months and Roosevelt 1.7 years to flush (Table 2). On an average, all four reservoirs flushed in about 40 per cent less time during the recent study than in the preceding decade. Lower lake levels and extensive draw-down for construction activities, not increased input of water, were obviously responsible.

MONTANE FLOODING. — Precipitation at higher elevations in the Salt River basin, and in other arid zones may or may not be reflected in runoff, especially if snow melt proceeds slowly, or if rains are relatively gentle and soils are unsaturated. However, high intensity rainfall, rapid snow melt, or combination of both, almost invariably result in some level of flooding. Observations over the past 10 years by personnel of Arizona State University and Arizona Game and Fish

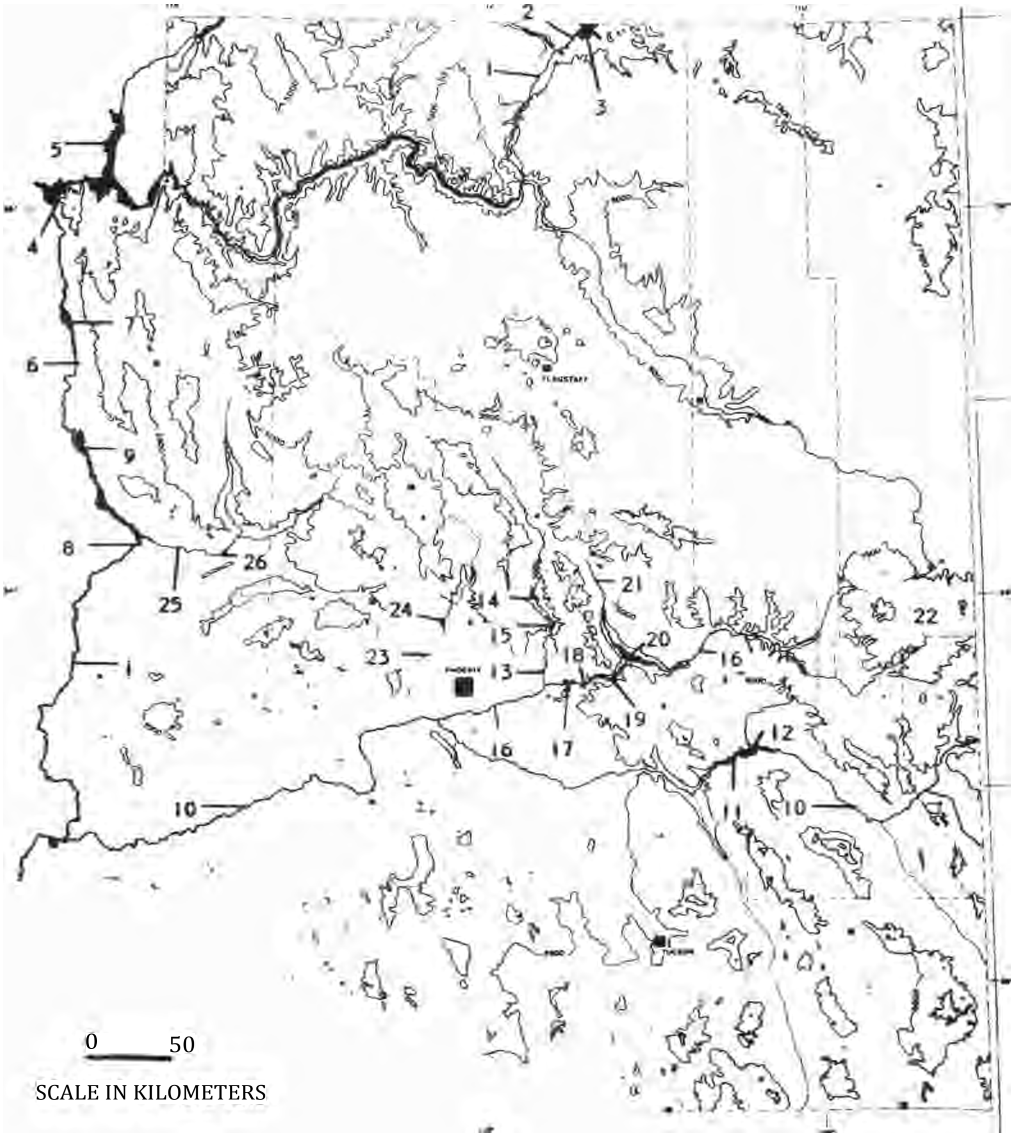

Figure 1. Rivers, dams, and reservoirs in the Lower Colorado River basin: 1. Colorado River; 2. Glen Canyon Dam; 3. Lake Powell; 4. Hoover Dam; 5. Lake Mead; 6. Davis Dam; 7. Lake Mohave; 8. Parker Dam; 9. Lake Havasu; 10. Gila River; 11. Coolidge Dam; 12. San Carlos Reservoir; 13. Verde River; 14. Horseshoe Reservoir; 15. Bartlett Reservoir; 16. Salt River; 17. Saguaro Lake; 18. Canyon Lake; 19. Apache Lake; 20. Roosevelt Lake; 21. Tonto Creek; 22. White Mountains; 23. Agua Fria River; 24. Lake Carl Pleasant; 25. Bill Williams River; 26. Alamo Reservoir.

Department plus U.S. Geological Survey surface water records over the past 20 years provide an example of the magnitude and complexity of this problem.

Mean discharge of the Salt River is about 1,200 cubic meters per minute (m^3/min; Fig. 4). Unfortunately few quantitative data are available on the level or intensity of runoff required to move "x" amount of organic litter into waterways. An arbitrary discharge rate (ADR) of 1.7 x 10 m^3/min was selected as an indicator of adequately heavy flow to result in flood conditions which might move extensive amounts of debris and litter into Roosevelt Lake. Records from the Salt River between 1950 and 1965 show only 9 days in which mean daily discharge exceeded ADR. Only in winter 1951 and 1959 did such volume of discharge persist more than a single day (3 days in the former, 2 in the latter). Between winter 1959 and winter 1965 mean daily discharge for a single day duration exceeded ADR only once (3.3 x 10 m^3/min on 8 January 1965). According to local testimony, none of the floods occurring after 1959 carried great amounts of debris into Roosevelt Lake. Then, in an 11-day period in late December 1965 and early January 1966 mean discharge greater than ADR occurred for 6 days which fell in two 3-day periods, 5 days apart. Discharge on three of these days surpassed 4.9 x 10 m^3/min. Such flooding was equaled only twice (1951 and 1959) in the period 1950 to 1965; however, those two floods were separated by eight years. In 1965-66, the surface of Roosevelt Lake was more than two-thirds covered with debris ranging from finely divided, woody material to huge, heavy logs (W. L. Minckley, pers. comm.). Since that abbreviated period of extremely heavy discharge, records indicated only one brief instance (8 December 1968) in which flow was greater than ADR and little organic debris was moved into the reservoir, in part, due to recent scouring of the watershed. Therefore, studies on these reservoirs have proceeded, since 1965, with minimal particulate organic input from the highland portion of the watershed.

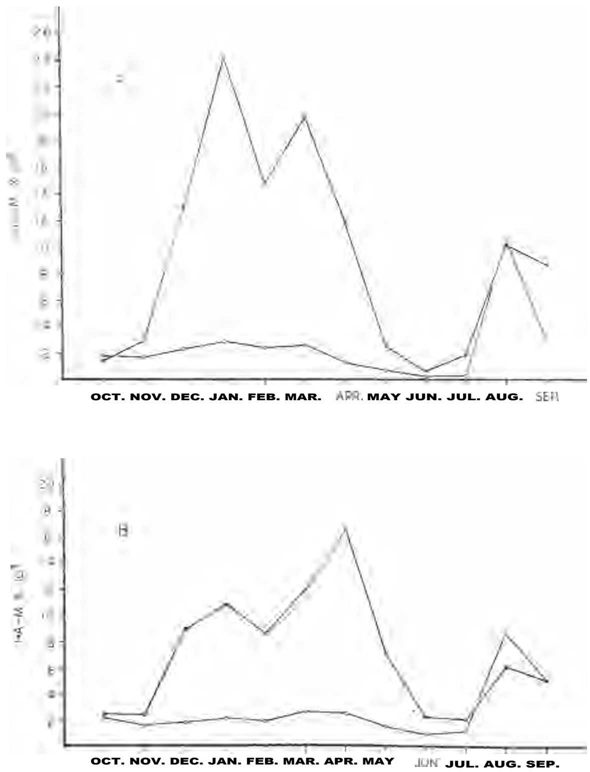

Figure 2. Mean monthly discharge of Tonto Creek (A) and the the Salt River (B) for the periods 1960-70 (solid circles) and 1970-71 (open circles).

Table 1. Calculated storage ratios (following Jenkins, 1970) for the Salt River reservoirs in the period 1960-71.

Water-year	Saguaro	Canyon	Apache	Roosevelt
1960-61	.098	.073	.390	1.64
1961-62	.108	.100	.410	1.35
1962-63	.085	.077	.390	0.58
1963-64	.131	.110	.560	0.82
1964-65	.271	.210	1.570	4.15
1965-66	.052	.049	.290	1.38
1966-67	.080	.080	.450	2.43
1967-68	.064	.059	.290	1.59
1968-69	.066	.032	.380	2.23
1969-70	.059	.009	.180	0.87
1970-71	.116	.089	.220	1.11
Mean	.103	.081	.470	1.65

ORGANIC NUTRIENT ACCUMULATION, TRANSPORT, AND INPUT. - Accumulation of organic matter on ground surfaces in western United States has been documented principally from the standpoint of potential fuel for wildfire (Biswell, *et al.*, 1966; Agee and Biswell, 1970; Dodge, 1972). In Arizona,

Table 2. Theoretical flushing times (days) for the Salt River reservoirs in the period 1960-71.

Water-year	Saguaro	Canyon	Apache	Roosevelt
1960-61	36	27	142	599
1961-62	40	36	150	493
1962-63	31	28	142	212
1963-64	48	40	204	299
1964-65	99	78	573	1515
1965-66	19	18	106	504
1966-67	29	29	164	887
1967-68	23	21	106	580
1968-69	29	12	139	814
1969-70	22	3	66	318
1970-71	42	32	80	405
Mean	38	29	172	602

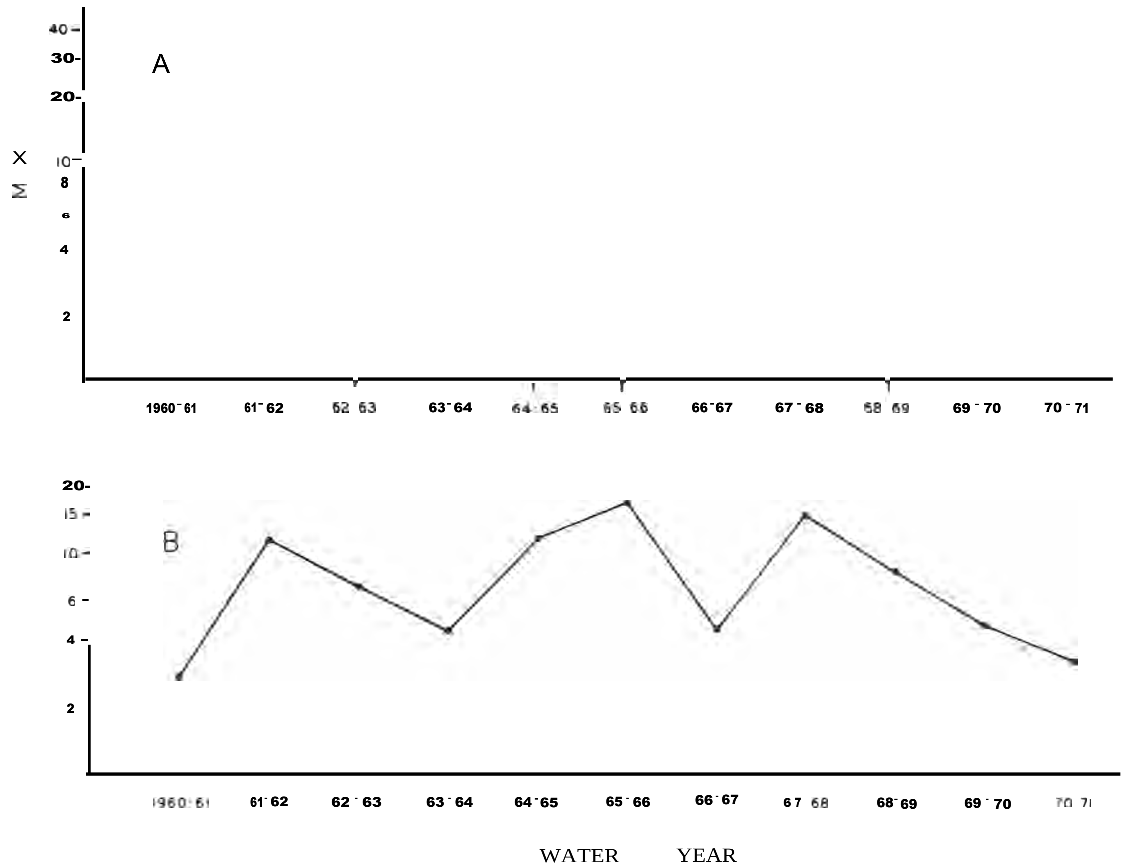

Figure 3. Annual discharge of Tonto Creek (A) and the Salt River (B) for the period 1960-71.

specific studies have been done on litter accumulation in chaparral zones (Pase, 1972; Pase and Glendening, 1965) and ponderosa pine (Aldon, 1968; Ffolliott, *et al.*, 1968). Results of these studies suggest average annual amounts accumulated in chaparral habitat (12.5 metric tons/ha) are 2.5 times that in ponderosa pine forest (5.0 metric tons/ha). Approximately 26 per cent (2,800 km^2) of the Salt River drainage above Roosevelt Dam consists of chaparral and 65 per cent (7,000 km^2) ponderosa pine; the remaining ± 10 per cent is pinyon pine-juniper and desert grassland.

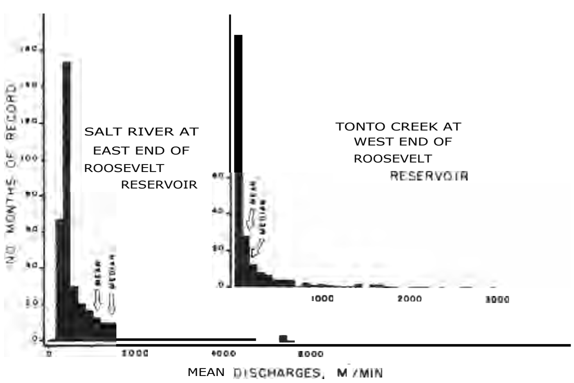

Figure 4. Frequency distributions of mean monthly discharges for major streams flowing into Roosevelt Reservoir, central Arizona.

Calculations provide annual estimates of 3.5 x 10^6 metric tons of litter theoretically accumulating in chaparral and ponderosa pine zones of the Salt River basin. Combined, ± 90 per cent of the watershed could produce as much as 7.0 x 10^6 metric tons of litter each year. Such accumulation is accentuated in this xeric area and especially during drought since the lack of moisture and resulting inhibition of decay may last as long as 5 to 10 years. Large amounts of litter may therefore be available for transport if sufficient precipitation occurs.

Floods may introduce tremendous quantities of organic material into reservoirs. In mesic, temperate zones, this is a regular phenomenon occurring through annual flood runoff, and also as natural input in autumn when deciduous forests provide substantial allochthonous input to streams (Minshall, 1967; Hynes, 1970) and through them into impoundments. Furthermore, watersheds in such zones consist of podozolics, loams, prairie, and forest soils and there is compara-

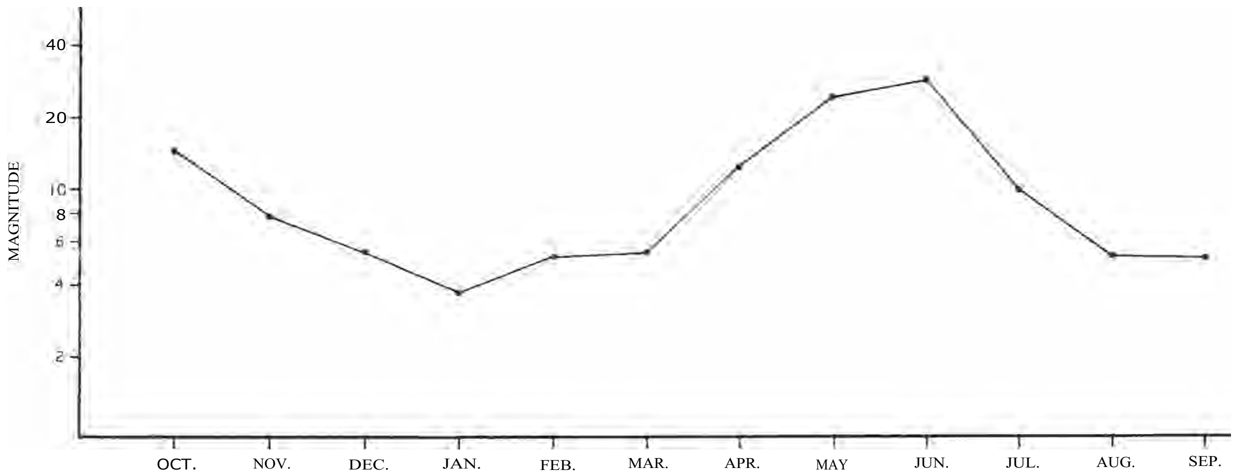

Figure 5. Magnitude of mean monthly discharge of the Salt River relative to Tonto Creek for the period 1960-71. Note how magnitude increases in time of decreased discharge (May to July, see also Fig. 4).

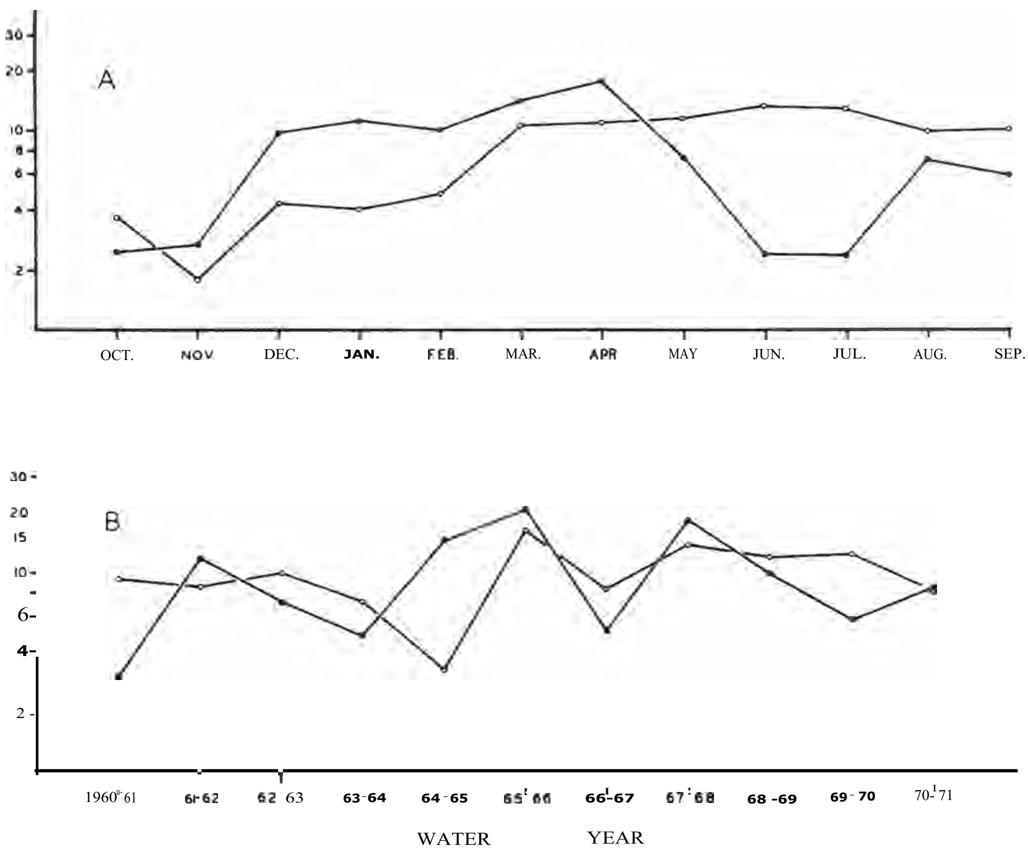

Figure 6.—A. Average monthly discharge in the period 1960-71 of Tonto Creek and the Salt River combined (solid circles) in comparison to release below Stewart Mountain Dam (open circles).

B. Annual discharge below Stewart Mountain Dam (open circles) compared to system input (Salt River plus Tonto Creek; solid circles), 1960-71.

tively little pronounced relief. Less movement of litter occurs with runoff from such topography, and in combination with more mesic climate, greater time is provided for decomposition and leaching. Greater amounts of nutrients in dissolved form, ready for more immediate utilization by biotic components of aquatic habitats, may inflow under such circumstances.

Desert impoundments, by contrast, may be forced to function over a period of years on nutrients resulting from brief, yet massive floods carrying organic particulate matter and relatively few dissolved substances (Fig. 9). To a large extent, this type of input in an undissolved state results from slowed decomposition and leaching in the more xeric climatic regime (McConnell, 1%8). It is also due to the nature of soils and the more precipitous terrain, both of which allow much greater transport of litter. Relatively unpredictable timing of heavy precipitation and flooding also greatly influence input of debris and this seems a major factor in the ecology of desert impoundments.

For example, although difficult to quantify, organic input of 3.5 x 10 kilograms (kg) annually or 1.5 x 10 kg/ha of lake surface was estimated for Pena Blanca Reservoir in southern Arizona (McConnell, in Cole, 1963: 422). Pena Blanca's watershed lies almost exclusively in chaparral and oak-woodland vegetation zones. McConnell's estimates expressed in relation to approximate drainage area of that reservoir (40 km^2) suggest organic input of 9 metric tons/km^2 per year. If one employs similar weight-area relationships, somewhat more than 2.5 x 10 metric tons could theoretically be contributed annually to Roosevelt Lake by the Salt River basin chaparral zone alone.

Estimates of input of organic matter from ponderosa forest were not available to me. Considering relative litter collection in the vegetation types discussed above, however, and assuming similar runoff characteristics, about half that from chaparral or 4.5 metric tons/km^2 per year might be reasonable. If accepted, organic input could reach 3.2 x 10 metric tons annually from this zone. In an average year a total of about 5.7 x 10 metric tons of organic matter (less than 1 per cent theoretical annual accumulation) might be introduced, or 8,150 kg/ha of lake surface. I calculate an approximate ratio of one hectare surface area to 200 ha drainage for Pena Blanca compared to a ratio of 1 to 140 for Roosevelt Lake. Proportionally adjusted, it seems feasible that an annual average of 1.2 x 10

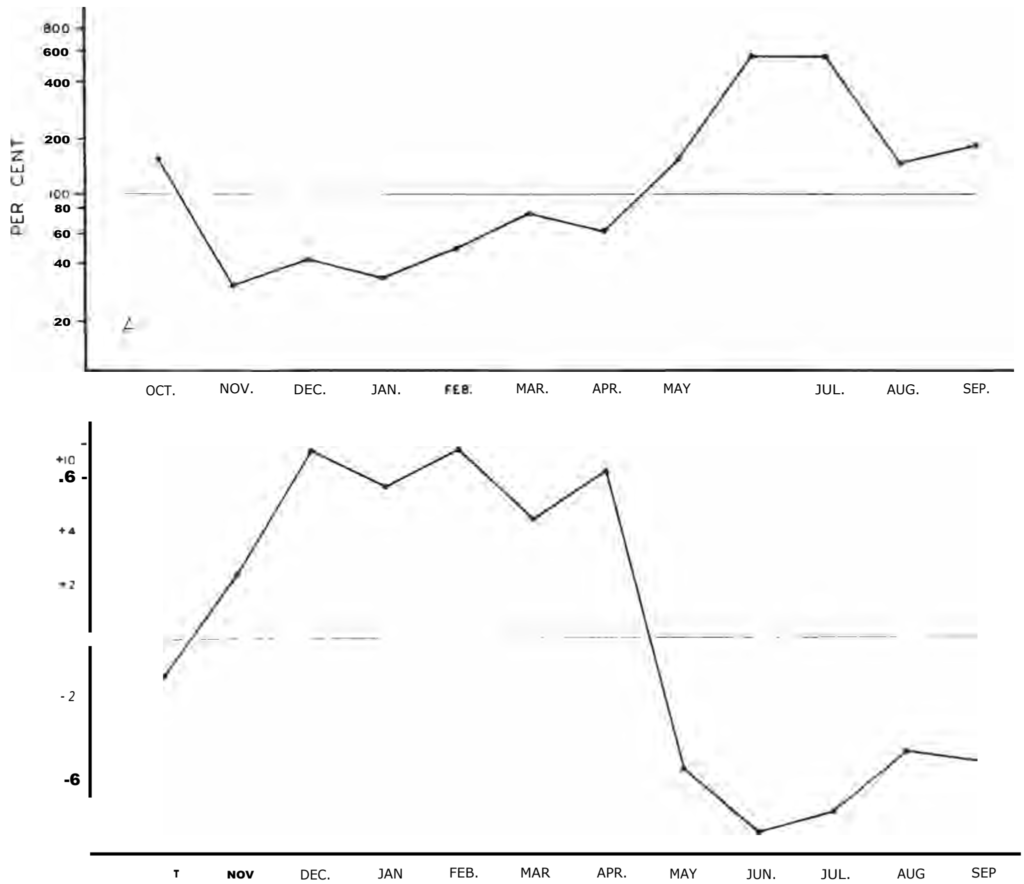

Figure 7.—A. Percentage of water flowing out of the Salt River reservoir system for the period 1960-71 relative to that entering.
B. Mean monthly change in volume of the Salt River reservoir system in the period 1960-70.

kg/ha organic material might enter the latter body of water. Again, these are annual estimates only and may be 3 to 4 times greater or less due to above-discussed non-annual flow regimes.

ISOLATED, LOW-ELEVATION STORMS.— Local, isolated cyclonic storms of great intensity are not uncommon at lower elevations and also introduce debris from desert habitat immediately surrounding these reservoirs. Estimates of amounts again are unavailable; however, drought conditions and the exceedingly local movements of storms allow substantial build-up of organic materials. These are primarily in the form of dried excrement of native animals and livestock, plus vegetative material. Isolated, heavy thunderstorms sometimes only a few kilometers in diameter produce rainfall amounts exceeding 15 cm in a few hours, and due to the sparse ground cover flush areas almost completely, collecting and pouring water and organic materials into a single drainage basin or desert wash

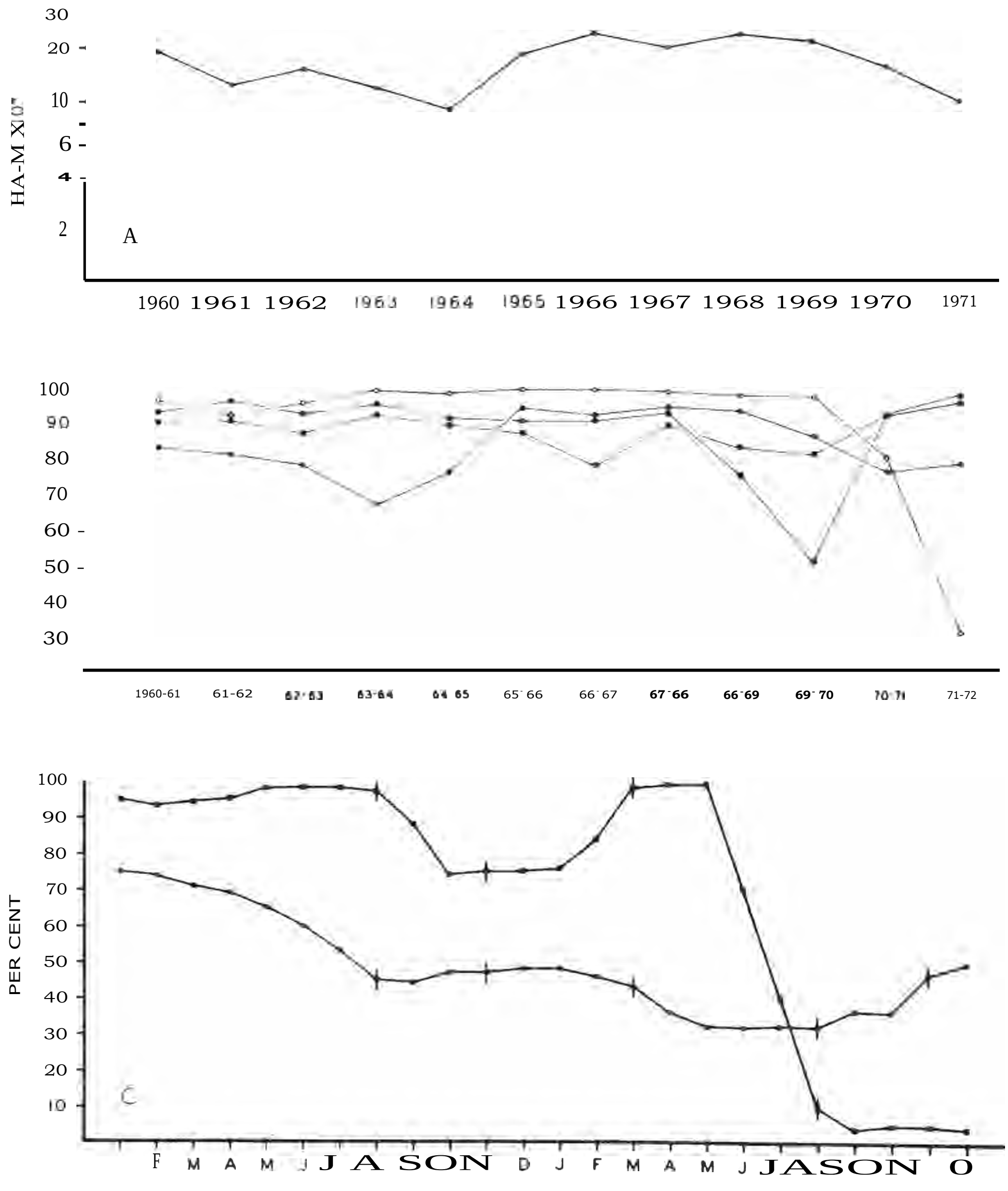

Figure 8.—A. Volume of the Salt River reservoir system at the beginning of water years (September to September) since 1960.
B. Percentage fullness of the Salt River reservoirs in the period 1960-71. Values are based on mean gauge height for the year. Roosevelt is represented by solid circles, Apache by open circles, Canyon by hexagons, and Saguaro by squares.
C. Percentage of maximum capacity of Roosevelt and Apache lakes for 1970-71. Sampling periods are indicated by vertical bars. Note Apache was not sampled in November 1971 due to extremely low water conditions.

(Fig. 10), which then empties into a reservoir. This occurred in October 1972 on the downstream end of Canyon Lake. Water was brown with humic matter and contained debris ranging from small leaves and twigs to large logs and saguaro cactus (N. F. Hadley, pers. comm.).

SYSTEM MODIFICATIONS, PUMPED-STORAGE INSTALLATION. — Recent construction activities surrounding modifications of dams on the Salt River system of reservoirs to facilitate pumped-storage units drastically altered operation procedures and reservoir conditions temporarily (Fig. 11) and permanently (Fig 12). Penstock release capabilities of the upper three dams were not only increased two to five times, but the middle two structures can reverse flow of water two to three times more than their previous downstream (generation) capability.

Effects of withdrawal of reservoir waters through generator penstocks have been studied and are relatively well understood (Wunderlich, 1971; Wunderlich and Elder, 1967; Elder and Wunderlich, 1969). Much less is known, excluding theoretical predictions, of injection in reverse fashion of turbulent or possibly buoyant "jets" of water (Reynolds, 1967). Injection of water at depths in reservoirs may cause destruction of thermal and chemical stratification (Irwin, *et al.*, 1966). This has been observed during preliminary testing of units on the Salt River reservoirs.

DISCUSSION AND CONCLUSIONS. — The Salt River system of reservoirs is situated under hot-desert climatic regime and merits constant and continued monitoring of environmental conditions. Ever-increasing population densities in the metropolitan Phoenix area and its requirements for water in a climate and area not characterized by such continually amplify the activities imposed upon these multiple-use impoundments. Highly variable, non-annual, cyclic input of the Salt River and Tonto Creek combined with irrigational, power and domestic use of water render these storage reservoirs complex and unique hydrologically to those of temperate, more mesic, regions.

The majority of water is input from the Salt River

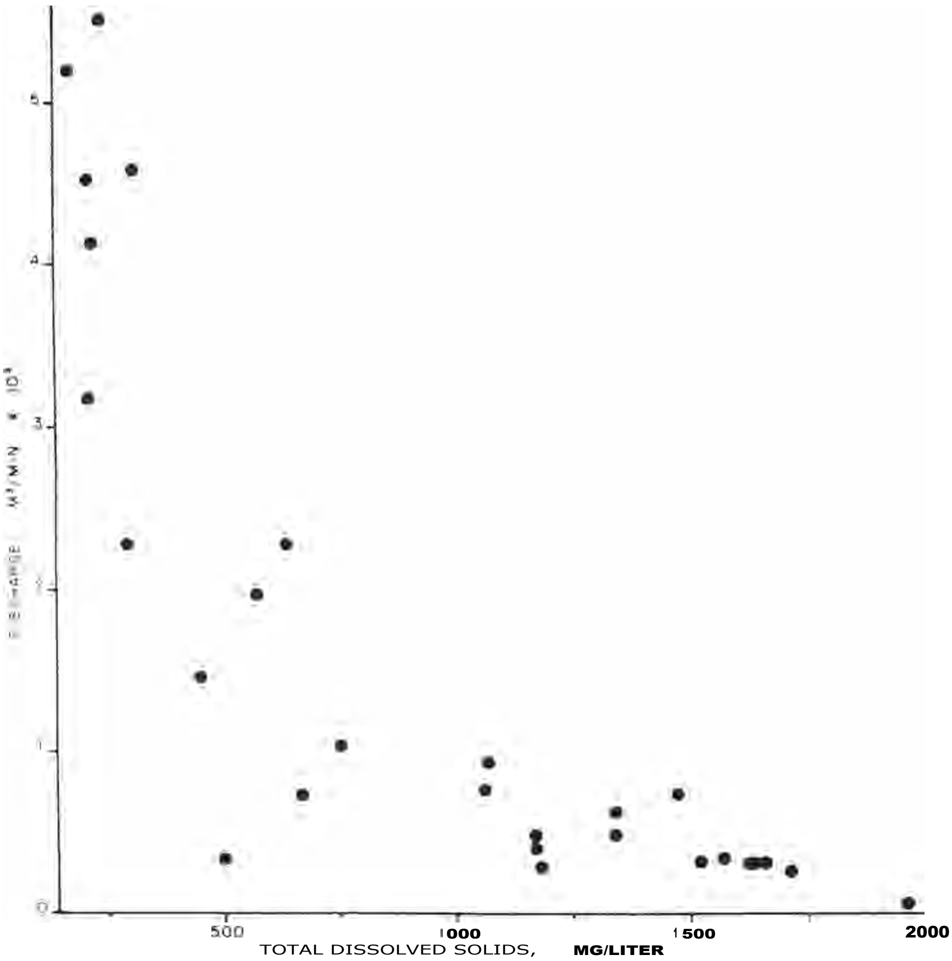

Figure 9. Relationship of total dissolved solids and discharge, Salt River, central Arizona, upstream from Roosevelt Lake. The correlation coefficient between total dissolved solids and specific conductance is -0.99.

(Fig. 5) which originates in the White Mountains of Arizona. In addition, most of the volume inflows under flood conditions which introduces enormous amounts of organic matter in very brief time periods (McConnell, 1968, 1973). Climatic conditions and periodicity of flooding allow for accumulation of organics upon the watershed over a period of years. Water is then dilute (Fig. 9) and if conditions are right, literally thousands of tons of organic matter may be introduced into the aquatic environment of Roosevelt Lake. This generally can be considered as a positive influence to the basic links of the food chains. Yet, extreme concentrations of certain dissolved organics may on the other hand have short-term, immediate, and harmful effects on living organisms (McConnell, 1973).

Following massive input of organics the biotic components of these desert lakes must then function over a period of years on these basic nutrients input by a single flood of one to a few days duration. Organic material settles and breaks down and is distributed from the uppermost reservoir through the system. Accordingly, one would expect Roosevelt to be most productive (primary) and this appears to be the case when considering relative mean chlorophyll-a concentrations of the respective reservoirs (Rinne, 1973). In addition, primary production and fish concentrations in isolated bays of these reservoirs (Portz, 1973; Bersell, 1973), reflect the reality and importance of localized "point input" of nutrients by low elevation storms. Meager data on the Salt River reservoirs of runoff from forest or range fires suggest stimulation of plankton blooms, presumably because of intensive, local, nutrient loading. Unpredictable periodicity in organic nutrient input, both distant and local, increase the complexity of desert reservoir ecosystems and make them unique from classical, better-documented reservoirs in temperate more mesic areas.

Finally, structural modernization of the system and pumped-storage installation emphasize the importance of research on these bodies of water. Great energies have been expended in site selection, development, and installation of pumped-storage units in the past several decades (Karadi, *et al.*, 1971). Parallel studies to assess overall influences of pumped storage units on water quality, and in general on aquatic environments, are lacking. Effects of pumping on spawning and migration

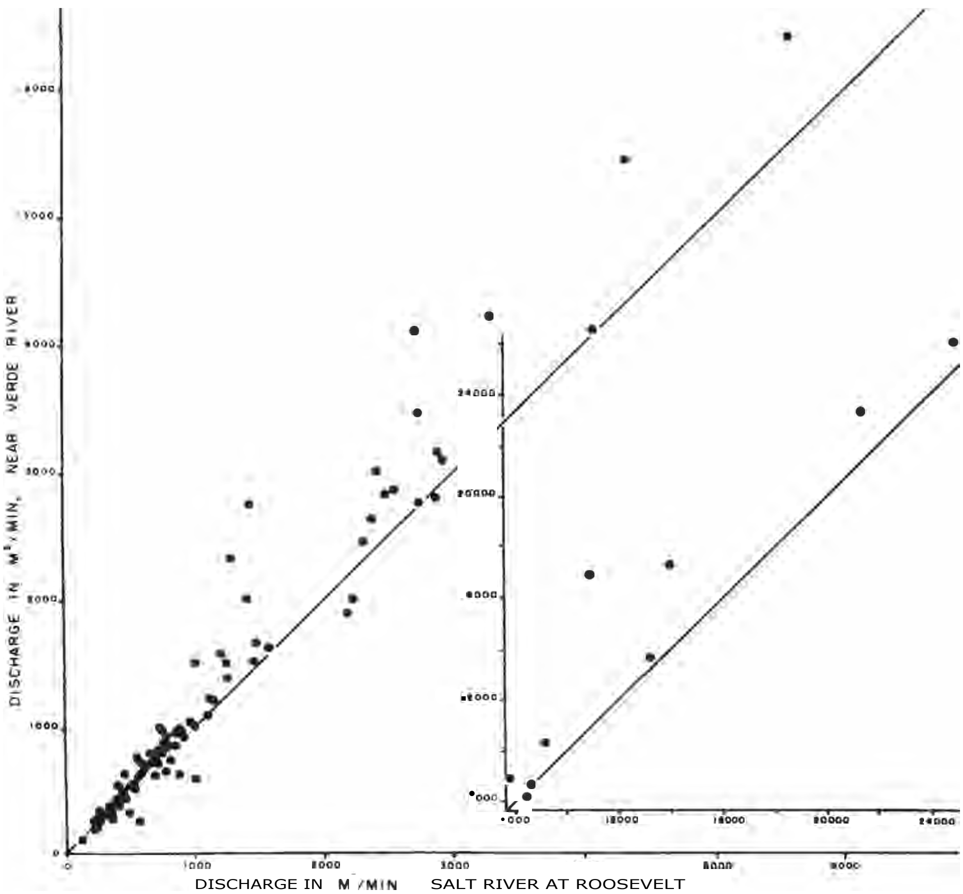

Figure 10. Relationship of discharge of the Salt River at Roosevelt Dam, with those near the mouth of the Verde River about 100 km downstream. Note greater variation in flow relationships between these two points at high (1,700 to 5,000 m^3/min) in comparison to low discharge (less than 1.700 m^3/min), reflecting locally severe, convectional storms on minor watersheds in summer. The line represents an arbitrary one-to-one relationship at the two gauging stations.

of fishes have been measured in the eastern United States (Jensen, 1969), and model field and laboratory studies examining some effects of such units on fish populations and aquatic systems in general have been performed (Barens and Howlett, 1971; Chen and Orlob, 1971). For the most part, however, when compared to technological data involved in development and utilization of such units, limno-biological studies are few and information is far too scanty to adequately predict the effects of pumping on lakes and/or reservoirs.

"Back-pumping" obviously has very direct hydrodynamic influences on both the fore- (upstream) and afterbay (downstream) of a structure. Considering the former, perhaps the only data for comparative purposes may lie in impoundment destratification studies by mechanical pumping of water or air into hypolimnia of reservoirs and lakes. These studies have generally suggested beneficial results — increase in water quality, heat budgets, production, and augmentation of fisheries (Hooper, *et al.*, 1952; Korberg and Ford, 1965; Fast, 1968, 1973; Fast, *et al.*, 1973). Nevertheless, such devices or techniques are small in size in comparison to pumped-storage units and are generally designed

Figure 11.—A. View of Apache Lake immediately above Horse Mesa Darn during drawdown in summer and autumn of 1971. Water is approximately 24 m deep in comparison to 76 m at maximum capacity (Bureau of Reclamation photo by E. E. Hertzog).
B. View of upstream face of Horse Mesa Darn in October 1971. The hole to facilitate installation of the new penstock is in the lower left below the evident construction equipment on top of darn (Bureau of Reclamation photo by E. E. Hertzog).

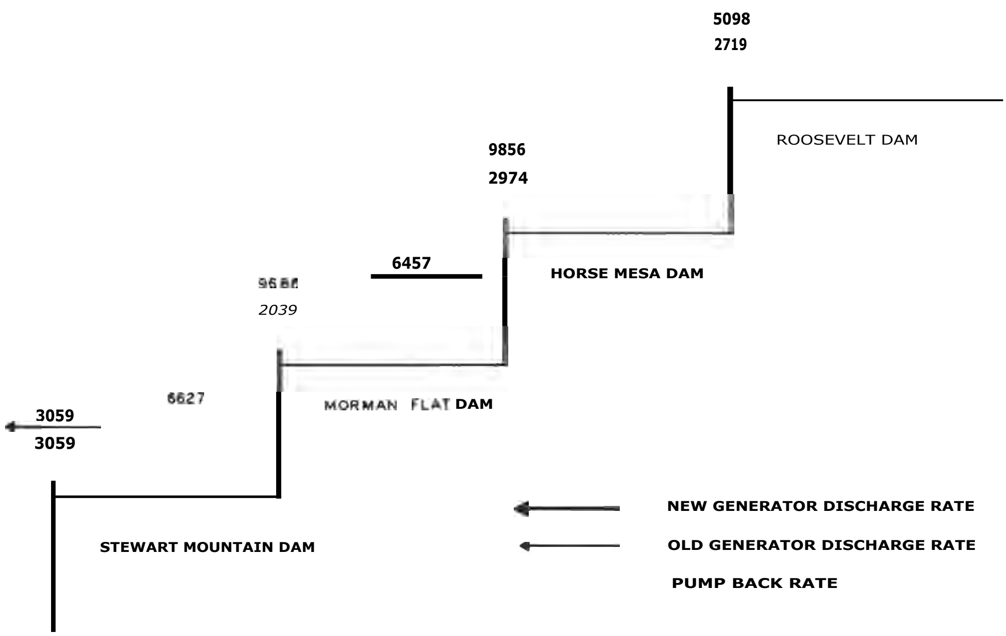

Figure 12. Generation and pumping capacities of units in dams on the Salt River system of reservoirs before and after modifications and installation of pumped storage. Volumes are expressed in m3/min.

specifically for fisheries management in temperate lakes. Under hot-desert conditions, and in light of current fisheries management of the Salt River reservoirs, it seems unlikely that any of the four, above-mentioned results of destratification perhaps caused by pumped storage units would occur, or if they did, would be desirable.

The possible influences of pumping on the aquatic environments of the Salt River reservoirs are not as yet adequately documented. Their effects on the hydrological scheme, biology, fisheries, and recreational activities are unstudied and should be the primary objective of future research effort on these artificial, desert impoundments. No other such units known to me and/or similar to those installed on this system are currently in operation under hot-desert climatic regime. Until more data on these reservoirs are accumulated, conjecture as to the possible influences of these units on this system of impoundments can only be based upon studies in temperate, more mesic, regions. Even here, data are few.

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SUMMARY. — Hydrology, organic nutrient input and ecology of hot-desert reservoirs such as those on the Salt River, central Arizona, are largely dependent upon periodic flooding caused by precipitation of distant montane weather patterns and local, intense cyclonic storms. As a result, these aquatic systems may be unique ecologically when compared to better documented reservoirs and lakes of temperate, more mesic regions. Extended drought periods occur and combined with seasonal patterns of operation of dams to supply domestic and irrigation water and hydro-electric power induce extreme changes in reservoir water levels and ecology. Recent structural modifications resulting in two pumped-storage units and increased penstock (generating) capacities will not only impose further complexity upon the presently reported hydrological scheme, but also upon future study of these aquatic environs.

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