Summary: Sedimentation of Reservoirs

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Reservoirs for storage or regulation of water are often the key features in man's innovations to use or control the water resources available to him. Reservoirs serve many essential purposes, and many reservoirs serve more than one purpose. Reservoirs range in size from ponds of small capacity and surface area to major lakes of the world.

Though distinctive in their physical features and in their impact on man's innovations, reservoirs have one thing in common: all of them are collecting basins for sediment. Usually, sediment accumulation in a reservoir is unwanted, but sometimes it is beneficial.

As background and substance for our consideration of reservoir sedimentation, several excellent papers have been included in this book. Each paper contains much more information than can be condensed into this introductory presentation, and I recommend for study the papers that follow in this section.

All streams transport some sediment, and there is a natural tendency for this sediment to be deposited when streams enter a dry basin or body of water impounded behind a dam or other obstruction across a stream. Sedimentation of reservoirs, then, is not something new. It has been going on since man's first efforts to impound or divert a flowing stream. Archaeologists and historians tell us that man has always lived near streams, and we suspect that he has been occupied with their management almost from the beginning. As *Biswas* [1970] points out, '. . . evidences of earliest civilizations are found along the banks of rivers: the Tigris and Euphrates in Mesopotamia, the Nile in Egypt, the Indus in India, and the Huang-Ho (Yellow River) in China.' According to the historian Herodotus, a dam was built on the Nile River around 3000 B.C. when King Menes diverted its course 20.1 km (12.5 miles) south of Memphis. This dam, a gravity structure, had a maximum height of about 15.2 meters (50 feet) and a crest length of about 448 meters (1470 feet).

The remains of what is called the oldest dam in the world can still be seen on the Wadi el-Garawi, about 28.9 km (18 miles) south of Cairo, Egypt. This dam (Sadd el-Kafara Dam) was built about 2850 B.C. It was a rubble masonry structure some 106 meters (348 feet) long at the top with a crest height of some 11.2 meters (37 feet) above the stream bed. The drainage area above the dam was 186.4 km^2 (72 mi^2), and the reservoir capacity was about 5.7×10^5 m^3 (460 acre-feet). The absence of sediments upstream from this dam indicates a short life for the structure, or it may have failed during its first flood season. Another dam built by the early Egyptians, around 1319–1304 B.C., on the Nahr el Asi (Orontes) near Homs in Syria is still in use. This rock-fill dam is about 6 meters (20 feet) high and 1999.4 meters (6560 feet) long.

PROBLEM

The amount of sediment deposited in a given reservoir depends on the amount of sediment delivered to it and the reservoir's ability to retain the sediment. Therefore reservoirs differ greatly in the amount of sediment deposited in them because of the tremendous variability, both in time and space, in the amount and characteristics of the sediment carried by streams and the circumstances causing its deposition.

Extent

About 1.235×10^9 m^3 (1 million acre-feet) of sediment are deposited in the reservoirs of the United States each year [*Dendy et al.*, this volume; *Glymph and Storey*, 1967]. Summarizing results from reservoir sediment deposition surveys on 1105 reservoirs made in the United States through 1965, *Dendy et al.* [this volume] point out the great variation among reservoirs in rates of sediment accumulation. The data show, however, a striking inverse relationship between rates of storage loss and reservoir size. The average storage loss was 3.5% annually for reservoirs with a capacity of $<1.235 \times 10^4$ m^3(<10 acre-feet) but decreased to about 0.16% for reservoirs with a capacity of $>1.235 \times 10^9$ m^3 (>1 million acre-feet). For reservoirs with a storage capacity of $\leq 1.235 \times 10^5$ m^3 (≤100 acre-feet) the average annual storage loss was 2.7%, and the median was 1.5%. These statistics suggest that one-half of these smaller reservoirs will be half filled with sediment in 33 years or less. For reservoirs with $>1.235 \times 10^9$ m^3 (>1 million acre-feet) of initial storage capacity, however, the rate of storage loss to sediment averages only 0.16%/yr, whereas the median rate is 0.11%/yr.

The paper by *Cyberski* [this volume] presents information about sediment deposition in 19 reservoirs in Central Europe having initial storage capacities ranging from 1.49×10^5 m^3 to 23.15×10^6 m^3 (120 to 183,000 acre-feet). The rate of storage depletion has averaged 0.51%/yr for these 19 reservoirs. This average is 2½ times greater than the weighted average of 0.20%/yr reported by *Dendy et al.* [this volume] but is based on a much smaller sample of reservoirs. Cyberski gives rational reasons for the difference in silting rates of the European reservoirs, but we have no basis at present for rationalizing the differences between the United States and European experiences except, perhaps, the great disparity in the number of reservoirs in the two cases.

An annotated bibliography prepared by the *Israel Program for Scientific Translations* [1965–1969] contains many entries about reservoir sedimentation from the literature of non-English-speaking countries, notably, Russia, Germany, France, Bulgaria, Poland, Japan, Italy, Hungary, Rumania, and Czechoslovakia. Information on the subject from literature of the United States and Canada is contained in a series of publications published by the *Water Resources Council* [1970]. A new publication series from the *U.S. Department of the Interior* [1968–1971] contains information from United States literature since 1968.

Data on the silting of 44 reservoirs in the central Chernozem provinces of Russia have been summarized by *Yakovleva* [1965]. Thirty-three of these reservoirs had initial storage capacities of $<1.235 \times 10^4$ m^3 (<10 acre-feet), and their average rate of storage loss was 0.71%/yr. This average rate is substantially less than that reported for reservoirs of similar size by *Dendy et al.* [this volume]. Such comparisons, of course, have little meaning without full consideration and evaluation of the causes of the differences, but they do point up the universality of the problem and widespread concern about reservoir sedimentation.

Consequences

Functions. The effects of sediment deposition in reservoirs are evidenced in many ways but perhaps most significantly in terms of the reservoir's ability to perform its intended functions. Water resource functions most commonly served by reservoirs include water supply (domestic, municipal, and industrial), irrigation, flood control, hydroelectric power, navigation, water quality management, recreation (swimming, skiing, boating, and fishing), wildlife habitat, beautification (aesthetics), and sediment storage.

To the extent that sediment distracts from the services provided or expected from a reservoir, it is a liability expressible as the lesser of either (1) the cost of services foregone because of the sediment or (2) the cost required to remove the sediment from the reservoir or to keep it out in the first place.

When the presence of sediment in a reservoir is beneficial, the values added should be recognized and included among the assets of the development. Should circumstances arise requiring an increase in the amount of sediment available to a reservoir, the cost of providing the additional sediment would be an item of cost for maintaining the reservoir.

Upstream effects. Depletion of storage capacity is but one of the effects of reservoir sedimentation. The stream channel is likely to aggrade for some distance above the reservoir because of backwater effects on sediment transport. The formation and growth of deltas tend to accelerate and extend the process still farther upstream. Thus channel gradients become flatter, channel cross sections are reduced, flooding occurs more frequently, and drainage of floodplain lands is impeded because of reservoir sedimentation. Such detrimental effects are severe in some instances and may require compensation. *Busby* [1961] has discussed some of the legal and engineering considerations involved in adjudicating disputes in the United States arising from sediment deposition, including that upstream from reservoirs.

Downstream effects. *Bondurant and Livesey* [this volume] point out that the total capacity for sediment transport below a dam will be reduced from 25 to 75%, depending on the comparative sediment transport characteristics of the controlled releases and the normal flows.

It is not uncommon, however, for reservoir sedimentation to cause channel degradation and stream bank erosion downstream. The sediment-free water passing through the reservoir can entrain another sediment load and proceeds to do so where the material is available. The phenomenon applies downstream from both large and small reservoirs. It is most likely to occur when a dam is built on an alluvial channel that previously had a generally stable relationship between such factors as stream discharge, sediment load, channel gradient, and widths and depths of stream channel.

When channels degrade downstream from dams, a new base level for erosion is established that may have more far-reaching effects than the loss of land immediately adjacent to the main stem channel. The deepening tends to extend throughout the watershed or river basin and may induce a new erosion cycle and thus generate more sediment for the next reservoir downstream.

There are circumstances, however, when channel degradation below dams is beneficial rather than detrimental. Such is the case when penstocks in power plants can be placed at lower elevations and thus result in greater heads for power generation than would be possible without the deepened channel.

Water quality. Sediment in reservoirs also greatly influences the chemical and biological processes in reservoirs and the suitability of their water for various uses. But the impacts of sediment on water quality and aquatic environments are still largely speculative.

We are just beginning to find some answers, for instance, to questions about the complicity of sediment as a source of nutrients for eutrophication. We probably know even less about how sediment in water affects light penetration for photosynthesis. Neither are we prepared to make very definitive statements about the potential of sediment in reservoirs as a sink for trapping harmful chemicals in the environment. *Ritchie et al.* [1970] have recently reported on the initiation of studies to determine the accumulation of fallout cesium 137 in sediments of widely separated reservoirs of the conterminous United States.

DEPOSITIONAL PROCESSES

Sediment in a reservoir tends to be sorted and deposited in a gradation of particle sizes along the longitudinal axis of the reservoir basin. Generally, the coarser and heavier particles are dropped in the headwaters of the reservoir, and the finer sediments are deposited toward the dam. Numerous factors, however, affect the actual patterns and processes of deposition, among which are the following: water level in the reservoir; temperature and dissolved minerals of the reservoir and influent waters; mineral composition of the sediments, especially the clay-sized fractions; volume relationships of reservoir storage capacity and influent water; configuration of the reservoir basin; and amount of sediment previously deposited within the basin.

Worsley and Dennison [this volume] effectively illustrate the complexity of depositional patterns in a delta system with data and maps from their study of Whites Creek delta in Watts Bar Lake, Tennessee. They found the coarser sediment in the upper reaches of the delta and the finest sediment in the deeper water below the effects of wave action.

The influence of the mineralogy of sediments on depositional processes is referred to by *Bondurant and Livesey* [this volume]. They comment that montmorillonitic clays may react with dissolved salts in the water and form floccules that settle out faster than kaolinitic clays. It is suggested that the dissolved minerals in water and perhaps temperature may have greater influence on depositional processes and maintenance of turbidity in reservoirs than is commonly realized.

Density currents. Deposition in reservoirs is also greatly influenced by sediment-laden density currents that may occur as underflows, interflows, or overflows, depending on the relative densities of the fluid masses involved [*Bell,* 1942]. Underflows are more commonplace. They occur when a relatively muddy stream enters a clear reservoir, plunges beneath the surface, and continues to flow downstream. The current may be dissipated enroute, or it may reach the dam.

Undoubtedly, the enabling combinations of sediment concentrations, velocity of inflowing currents, and temperature differentials are sufficiently prevalent that density flows occur frequently on all man-made lakes. Such flows explain the presence of sediment at the face of many dams where the surface waters of the impounded reservoir have never been turbid.

Trap efficiency. Some of the sediment entering a reservoir is discharged through its outlet works and thus is not deposited within the basin. The relationship between the amount of sediment remaining in a reservoir and the amount delivered to it, on a percentage basis, is termed reservoir trap efficiency. Trap efficiency is always a variable statistic affected by properties of the influent sediment, detention storage time of the reservoir, type and locations of spillways, dissolved solids in the water, and undoubtedly many other factors.

Studies have shown a workable relationship between trap efficiency and the reservoir capacity–inflow ratio (ratio of the storage capacity of the reservoir to the average annual inflow of water to it) [*Brune*, 1953]. Trap efficiency would be expected to decrease in relation to the displacement of reservoir water storage capacity by sediment. This hypothesis is confirmed by data in the paper by *Cyberski* [this volume]; those data show a decrease in the rate of sediment accumulation in three reservoirs in Bavaria when progressively larger quantities of sediment were deposited in them. Even after reservoirs become filled with sediment, they cause some deposition and thus continue to reduce the amount of sediment passing beyond the reservoir site.

Roehl and Holeman [this volume] show short-term trap efficiency ranging from 58 to 94% for 15 small upstream floodwater detention reservoirs. For the five dry reservoirs in the group the average trap efficiency of 84% (ranging from 65 to 94%) was higher than had been expected.

Heinemann et al. [this volume] found trap efficiencies associated with 28 storms on two reservoirs in Missouri to range from 33 to 99%. The 33% trap efficiency value resulted from the discharge of suspended sediment already in the reservoir; this sediment had been brought in by a storm on the preceding day.

Distribution. When a reservoir basin is completely filled with sediment, the pattern of its deposition conforms essentially to the volume distribution of the initial storage capacity. Until the basin is filled, the possible patterns for distribution of the sediment are practically unlimited. Nevertheless, information on both the location and amount of accumulated sediment is required for assessing the consequences of sediment accumulation at selected points in time. The distribution of sediment expected in multipurpose reservoirs is a critical consideration in the allocation of storage for various functions.

The paper by *Lara* [this volume] shows the effects of reservoir drawdown on the longitudinal and lateral distribution of sediment in the Guernsey Reservoir on the North Platte River. *Heinemann* [1961] has presented information on the distribution of sediment in small floodwater-retarding reservoirs in the Missouri basin loess hills land resource area, including graphic and statistical methods for predicting sediment distribution and the minimum elevation of the principal spillway with respect to sediment accumulation. *Borland and Miller* [1958] have developed and presented methods for predicting the manner in which sediment will be distributed in large reservoirs.

Volume-weight. The space occupied by sediment delivered to and remaining in a reservoir is determined by the volume-weight of the sediment on deposition and consolidation. The volume occupied by the deposited sediment will depend essentially on its texture and whether it is permanently submerged or subject to alternate submergence and aeration. Since the use and operation of a reservoir greatly affect submergence of the sediment, they also exert a major impact on the volume-weight of the sediment. The volume-weight of sediment in reservoirs ranges from 0.32 to 1.84 g/cm^3 ($<$20 to about 115 lbs/ft^3).

Lara and Pemberton [1965] have published equations for predicting the unit weight of reservoir sediment for four types of reservoir operations; these equations were based on 1316 measurements of unit weights in 117 reservoirs and stream reaches. Using data from Sabetha Lake in Kansas, *Heinemann* [1962] has illustrated and discussed the great variability of sediment volume-weight both in the vertical and in the longitudinal profiles of a reservoir.

Reservoir sediment deposition surveys [*Task Committee on Preparation of a Sedimentation Manual*, 1970*a*, *b*] are one source of data for estimating sediment yield from watersheds. Because of the variation in the volume-weight of reservoir sediment, it is necessary, however, to express the measured volumes on a weight basis before they are used as indices of sediment yield. Many reservoir sediment surveys include measurement of sediment volume-weight; it would be a great contribution if all surveys included such information and the results were reported. *McHenry* [1963] has developed a two-pronged gamma gage that greatly improves the accuracy of in situ measurements of the volume-weight of reservoir sediment.

Chemical transformations. *Heinemann et al.* [this volume] have presented data on the influence of sediment on the nutrient status of water in lakes. Bottom sediments from two eutrophic natural lakes in Minnesota were highly capable of removing orthophosphate from solution. In laboratory tests the lake sediments, by adsorption, reduced orthophosphate concentrations; in one case the reduction was from 8.2 to 0.02 ppm, and in another it was from 42.0 to 0.05 ppm.

Heinemann et al. further found that the nitrate and ammonium discharges from a reservoir in Missouri were about equal to their inflows. Total nitrogen discharge from the reservoir, however, was approximately 80% of its inflow; thus it is probable that some of the nitrogen in the organic matter was deposited in the reservoir. On the other hand, 56% of the influent phosphorus was deposited in the reservoir with the sediment. Only 16% of the influent sediment, but 44% of the phosphorus, passed through the reservoir. The sediment passing through the reservoir was of a finer texture and could adsorb more phosphorus per unit weight than the average incoming sediment. In view of the increasing concern about eutrophication and the quality of water in lakes, the term reservoir trap efficiency might well be used in reference to plant nutrients and other chemicals brought into and deposited in reservoirs, as well as to quantities of sediment.

METHODS OF SEDIMENT CONTROL

In a decision on whether the services to be derived from a reservoir are sufficient to justify the costs, it is usually assumed that the reservoir will provide uninterrupted services during a specified period of time. If it is expected that the services will be interrupted, information is required on the frequency and duration of the interruption as part of the criteria needed before the decision is made to invest in the reservoir. It is essential therefore that the amount and character of sediment be anticipated and provided for in the planning stages.

When the purpose of the reservoir is to provide flood control or water storage, the reservoir sites expected to receive the least amount of sediment should be chosen if alternatives are available. If the purpose of the reservoir is to impound sediment, then, of course, the site should be chosen with respect to the sediment source areas, and the reservoir or debris basin should be planned to attain the maximum feasible trap efficiency. In either case the amount and character of sediment involved should be one of the first considerations. A pioneering bulletin on the control of reservoir silting [*Brown*, 1944], though written nearly 3 decades ago, contains much pertinent information about reservoir site selection and other methods for sediment control.

Sediment yield estimates. Reservoir sediment deposition surveys [*Task Committee on Preparation of a Sedimentation Manual*, 1970*a*, *b*] are a significant source of data on sediment yields if adequate data on sediment volume-weight are obtained. The measured volumes must also be adjusted for trap efficiency. In their paper, *Roehl and Holeman* [this volume] refer to a long-term study initiated by the U.S. Department of Agriculture's Soil Conservation Service to obtain sediment yield and other information for improving the design of small reservoirs. *Cyberski* [this volume] strongly recommends continued investigation of reservoir sedimentation phenomena. *Priest* [this volume] presents a method that he derived for estimating sediment accumulation in reservoirs of moderate size.

Records of suspended load measurements integrated with streamflow data provide another source of information on sediment yield. *Bondurant and Livesey* [this volume] describe the concept of index suspended load measurement stations operated by the U.S. Army Corps of Engineers in the Missouri River division. A procedure for deriving sediment yield estimates from suspended load records was suggested by *Straub* [1935], was further developed by *Campbell and Bauder* [1940], was extended by *Miller* [1951], and more recently was reported on by *Piest* [1965]. Equations for estimating bedload transport have been described and compared by *Shulits and Hill* [1968]. The subject of sediment sources and yields is treated in considerable detail in a recent report by the *Task Committee on*

Preparation of a Sedimentation Manual [1970*a*, *b*].

Reduction of sediment yield. Most of the sediment delivered to reservoirs is the product of soil erosion in the watershed (catchment) area draining into the reservoirs. It comes from a multiplicity of sources, including farmlands, rangelands, forest and woodlands, gullies, stream channels, roads and highways, urban developments, and construction sites. *Cyberski* [this volume] mentions erosion of shorelines of lakes as another important source of sediment.

Stabilization of sediment sources is usually the most direct and effective means of controlling reservoir sedimentation. It is usually much more feasible and less costly to keep sediment out of a reservoir than to cope with it after it gets into the reservoir. Land use and treatment practices that reduce sediment yields also preserve the land resource and thus result in benefits both on site and off site.

The potential for reducing sediment yields by erosion control and watershed protection measures has been shown by *Gottschalk* [1962] in a summary of 157 work plans authorized for installation under the small watershed program carried out by the U.S. Department of Agriculture. The combination of land treatment and structural measures recommended for these watersheds, having a combined drainage area of 3.9×10^6 ha (9.7×10^6 acres), would reduce sediment outflow from these watersheds by 55%. *Bondurant and Livesey* [this volume] recognize the potential of soil conservation practices for reducing sediment yields from small watersheds but seem skeptical that such measures can be applied over a broad enough area to have much effect on the sediment reaching large reservoirs.

Sediment storage. *Cyberski* [this volume] cites data showing a reduction of reservoir silting following the construction of additional reservoirs upstream. Debris basins are sometimes called for on steep mountain channels to trap and impound sediment as an alternate to channel stabilization works. These basins are also being used increasingly in the United States to trap and contain sediment arising from construction sites, such as housing and industrial developments.

Venting of sediment. Discharge of sediment-laden waters through the outlet works of dams, especially when density currents are operative, may have more potential for controlling sedimentation of reservoirs than has been realized. *Lara* [this volume] shows that the capacity of Guernsey Reservoir increased 5.38×10^5 m^3, or 428 acre-feet (about 1%), between 1957 and 1966 as a result of discharging sediment by controlled release of water from the reservoir. *Bondurant and Livesey* [this volume] cite successful operation of reservoir outlets works to evacuate sediment from reservoirs in Algeria.

Dredging. Dredging is another method for controlling reservoir sedimentation, but it is usually too costly just to preserve or restore storage capacity. There are occasions, however, when dredging may be practical for site beautification, creation of recreation areas, maintenance of marinas, or shoreline development.

CONCLUSION

The processes of reservoir sedimentation are complex. There are many alternatives and options to be identified and evaluated in meeting the problem. In the final analysis, our concern about reservoir sedimentation cannot be separated from our concerns about water supply, irrigation, flood control, water quality management, eutrophication, navigation, recreation, fish and wildlife, and erosion. Control of reservoir sedimentation, then, becomes an integral part of man's endless endeavor to wisely develop and use the water and related land resources available to him.

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