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Reservoir Sedimentation Studies

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It must be recognized that, when a reservoir is constructed on a stream, all or most of the sediment transported into the reservoir by the stream will be deposited there. With few exceptions, there is no practical method for reducing or eliminating the sediment inflow; thus it is necessary to anticipate and to provide for the resulting problems. The major problem is, of course, the accumulative loss of storage capacity. Other items of importance include the distribution of the sediment with respect to various storage increments, the effect on the chemical or physical quality of the water, ecological effects, and the possible degradation of the channel downstream.

The prediction of the quantity of sediment that will be transported into the reservoir is largely a matter of experienced judgment. During the past 20 years, there have been many stations established for the measurement of suspended sediment discharge, but the cost of operating these stations is such that they are restricted in number and location to a relatively few index areas or to specific locations where they may be operated for only a few years. Because of the normal variations in the hydrologic cycle a station must usually have a record of 10–30 years (depending on the physical and hydrologic characteristics of the area) in order to provide a dependable average. Since it is seldom that the need for sediment data at a specific location can be predicted that far in advance, it is also seldom that adequate records are available.

In the Missouri River division of the U.S. Army Corps of Engineers we maintain certain index stations continuously. In regions where the sediment discharge is reasonably consistent we operate stations at one location for 5–10 years; then, providing for an overlap of 1 or 2 years, we move to other locations to establish index values for the region. As soon as the need for data at a specific location is known and if the time available for study is adequate, we establish a station at that location.

Finally, we make an extensive ground reconnaissance of the drainage area above the site. Information from this reconnaissance is correlated with all available data from stations measuring suspended sediment discharge from comparable areas and is integrated to derive an estimate of the average annual sediment inflow to be anticipated. It is necessary to add to this estimate some quantity to account for sediments moving along the stream bed and not measured in suspended load sampling. In streams having a coarse gravel bed, this load can be computed with reasonable adequacy by bed load formulas; however, in sand bed streams it is believed that an estimate based on judgment is equally or perhaps more accurate. In small reservoirs the estimate may be reduced to account for sediment that might be transported through the pool, but, where the drainage area contributing to the project is greater than about 250 km^2, the reservoir will normally be large enough to retain all the inflowing sediment. If the project is constructed under the auspices of the federal government, sufficient storage is provided to retain the anticipated sediment load for a 100-year period without encroaching on the primary project purposes.

In some instances it is possible that the storage required for sediment might be reduced by upstream control measures. It has been demonstrated, for example, that the sediment contribution from very small drainage areas (1–5 km^2) can be reduced by about 85% by intensive soil conservation procedures. In another instance, sediment discharge reductions due to improved land management and conservation on a group of drainages varying in size from several hundred to 5000 km^2 were indicated to be 10–35%. This latter study, however, covered a period of only 3 years under the improved regimen and could well have been in-

fluenced by favorable hydrologic circumstances.

In general, it is usually found that those portions of the drainage area contributing the greatest proportion of the sediment are the areas where conservation measures are the least justified economically for improvement of the land. As an example of this condition, <15% of the structures proposed in a comprehensive conservation plan for one area have proved to be justified economically. In addition, the installation and continued maintenance of conservation measures depend wholly on the cooperation of the landowners. When it is further considered that there will already be a large quantity of sediment available for erosion in the contributing stream system, the sediment discharge reduction available from upstream conservation will probably be less than the errors inherent in the basic evaluation of the sediment storage requirements. Although conservation benefits to the land itself cannot be denied and flood flow reductions due to upstream structures will undoubtedly be beneficial to a reservoir project, it is unwise, except in rare circumstances, to reduce sediment storage requirements in anticipation of benefits from upstream controls.

In a reservoir where the entire operating storage is reserved for one purpose, the location of the sediment deposited in a reservoir might not be important. In multiple-purpose reservoirs, however, where the storage in varying zones of elevations is reserved for individual purposes such as power production, irrigation, recreation, and flood control, it is desirable to know just how much storage will be lost in each zone owing to sedimentation and what the backwater effect on upstream facilities might be. This effect will depend on several factors such as the characteristics of the sediment, the chemical character of the water, the size and shape of the reservoir, the original stream and valley slopes, and the reservoir operation. As soon as the stream enters the backwater reach above the then existing pool, the largest sediments in transport begin to deposit in the channel. The deposition occurs progressively until, some distance within the pool, all the sand-sized materials are deposited. This progression continues with the silt and, finally, the clay-sized sediments.

If the pool is relatively narrow (not more than 3 or 4 times the normal width of the stream channel), the sand materials will be deposited across the entire width of the pool, and, as the process continues, these deposits will form a delta that gradually extends downstream. Deposition of the silt-sized sediments occurs more or less immediately downstream from the sands, and the deposition of clays occurs either a short distance thereafter or perhaps much farther downstream, depending on the chemical characteristics of the sediment and water.

If the stream enters a wide pool, deposition of the sand sediment tends to progress as a finger, and a submerged channel is formed into the pool. A finite flow will continue along this submerged channel and will result in a reverse circulation in which deposition of a large portion of the silt and clay sediments will occur in that part of the pool adjacent to the sand finger. As the process continues, the sand finger extends to the water surface and forms a surface channel extending into the pool. This channel, possibly as a result of Coriolis forces, tends to follow the western or southern boundary of the pool in the northern hemisphere. Vegetation growing on the banks tends to hold this channel in place; however, a high flow will ultimately breach the channel and will start a new finger. The result is a mixture of clay, silt, and sand intrusions forming a swampy, vegetated area that may contain random pools of open water.

The character of the clay sediments in conjunction with the chemistry of the water plays an important role in the deposition of the clay materials. The active clays, the montmorillonite group, may react with the dissolved salts in the water in a manner such that the particles have a mutual attraction and tend to form clumps of floccules that settle out of the water with relative rapidity. On the other hand, these clays may form a low-density, semifluid mass that may accumulate downstream from the sand delta, may travel through the reservoir as a density flow, or may accumulate immediately at the head of the reservoir. Which of these phenomena will occur is governed by the activity and concentration of the clays, the character and concentration of the dissolved salts in the water, and the slope of the original stream channel and valley. Sediment density flows of any magnitude apparently do not occur with slopes of <0.2 m/km.

The inactive clays, the kaolinite group, do not react as readily as the active clays with the salts in the water, and the particles tend to be mutually repulsive unless they are present in sufficient concentration for mass attraction forces to be dominant. The finer particles may remain in suspen-

sion in the reservoir for days or even weeks and thus may maintain turbidity throughout the entire reservoir.

It is only in rare cases that sediment can be evacuated from a reservoir except by mechanical methods, and the use of these methods is seldom within economic reason. It is true that the debris basins used primarily in the western coastal regions of the United States to protect high-value urban areas from sediment and debris are developed to be cleaned by physical removal of the material, but these basins are a separate consideration and normally have no connection with storage reservoirs. In a few instances where openings have been made in existing dams in an attempt to flush out sediment deposits, the only result was the erosion of a deep, narrow channel to the outlet. A few small detention-type reservoirs are known to be self-cleaning, but in these instances the width of the pool is not much greater than that of the original stream channel.

There are instances where the character of the sediment and the water complex is such that density flows can be used to evacuate the reservoirs and maintain storage capacity. Insofar as is known to the authors, these instances are all in Africa, primarily in Algeria. Here, the sediment is permitted to accumulate until it reaches a predetermined density; then outlets specifically provided for the purpose are opened, and the sediment is evacuated with a minimum waste of water. In another instance a subdam at the head of the pool is designed to accumulate water and coarser sediments and then to release the entire mass through the pool. A detailed description of these operations is given in papers presented by H. Duquennois and J. Thevenin and reproduced in the minutes of an international colloquium on dams and reservoirs held at the University of Liege, Liege, Belgium, in May 1959.

In recent years, problems of ecology, water quality, and recreation have assumed major importance in the planning and operation of reservoirs. In many instances the influence of sedimentation on these functions is not completely known; however, there are many ramifications that need to be analyzed. Sediments deposited in relatively shallow areas tend to prevent the reproduction of many of the media on which fish feed or tend to result in a variation of the food pattern such that the growth of one fish species is inhibited and that of another is enhanced. The formation of a delta may block the passage of fish that must travel to the open river upstream for spawning, and at the same time the delta may form a swampy area that provides a desirable habitat for entirely different species of wildlife. Inactive or dispersive-type clays tend to remain in suspension for relatively long periods and spread throughout the reservoir to create a turbid condition. These clays will adhere to the microorganisms forming a part of the fish food cycle and will carry these microorganisms to the bottom as the particles settle; thus the food required for fish life is destroyed.

Sedimentation also plays an important role in the eutrophication processes of lakes and reservoirs. Organic material transported into the pool decomposes; during this process, available oxygen is used, and, at the same time, nutrients are released. These and other nutrients transported by the sediments result in accelerated biological activity and overproduction by both plants and animals within the photosynthetic region. These plants and animals, in turn, die off and accumulate at the bottom where they decompose and start the cycle again. In shallow waters the excessive growth of aquatic plants so generated may completely fill the reservoir; however, within reasonable limits it is beneficial to fish life. Dispersive clays that create a turbid condition in the waters restrict the photosynthesis and thus restrict the biological activity. Such a condition may be desirable for swimming, boating, and other water contact sports for which an accumulation of aquatic growth would be detrimental.

Since sediments provide large surface areas for chemical action, they may contribute significantly to the rapid degradation or detoxification of pollutants. Pollutants attached to sediment particles are not dispersed or transported as readily as dissolved pollutants. Large concentrations may build up in the stream bed or reservoir deposits. These pollutants might be removed from the water environment by burial in the deposits, or they might accumulate and be released into solution by a later significant change in the water chemistry. One of the more beneficial aspects is the removal of pesticides from solution by chemical reaction with clay materials.

The physical effect of a reservoir on the downstream channel is also an important consideration. After deposition of sediment in the reservoir the clear water released through the dam will have an unsatisfied transport capacity that it will attempt to satisfy by eroding the bed

and banks of the stream. The total capacity for transport will be substantially reduced, however. because of the elimination of flood flows by reservoir operation. The degree of reduction will vary from 25% to as much as 75%, depending on the relative character of the controlled releases versus the normal flows. It should be noted, however, that in some instances the magnitude of bank caving may be severely increased if the reservoir operation results in sustained periods of near bank-full flow. These sustained periods permit the banks to become saturated, and thus they are more susceptible to caving during sustained periods than during short periods of high flows. The effects of the downstream erosion may include degradation of the channel, possible head cutting in tributaries, damage to downstream bridges or other facilities, and possibly damage to outlet works or hydroelectric power units.