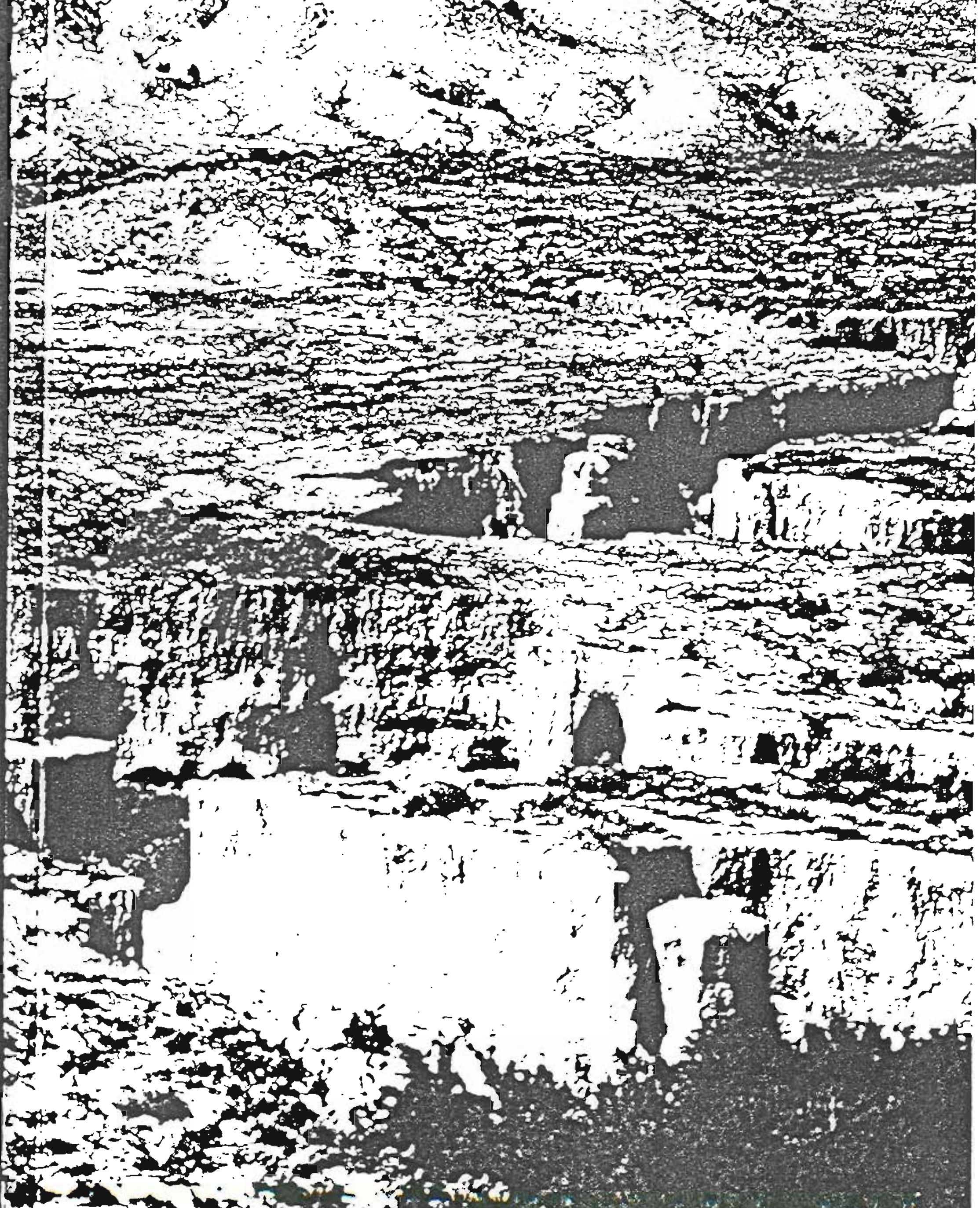
EROSION AND SEDIMENT YIELD:

Some Methods of Measurement and Modelling

EDITED BY R. F. HADLEY D. E. WALLING



EROSION AND SEDIMENT YIELD:
SOME METHODS OF MEASUREMENT AND MODELLING

Edited by

R. F. HADLEY AND D. E. WALLING

Contributors

H. A. Elwell

W. W. Emmett

R. F. Hadley

H. G. Heinemann

C. A. Onstad

D. L. Rausch

D. E. Walling

P. R. B. Ward

published by

Geo Books,
Regency House,
34 Duke Steet,
Norwich NR3 3AP,
England.

ISBN hardback 0 86094 158 2

ISBN paperback 0 86094 141 8

Printed in Great Britain at the
University Press, Cambridge

8.

Reservoir trap efficiency

H. G. Heinemann

Introduction

Even after hundreds of years of designing and constructing dams and reservoirs, man does not completely understand the sedimentation processes in reservoirs. For example, we still need to know more about why or how the sediment is deposited where it is. We also need to improve our accuracy in estimating the long-term sediment trap efficiency for proposed small reservoirs under a variety of environmental conditions. This improved technology is necessary because good reservoir sites are scarce and constitute a valuable natural resource that must be protected and used wisely.

Because of limited sites and increasing construction costs, we must carefully design and build each reservoir to best accomplish its specific objectives - for soil and water conservation, irrigation, domestic or animal watering, fish farming, recreation, or protecting and enhancing our environment. To optimize the effectiveness of each reservoir, we must be able to predict the rate of reservoir sedimentation processes, especially reservoir-sediment trap efficiency. Reservoir-sediment trap efficiency is the fraction of the sediment transported into a reservoir that is deposited in that reservoir, usually expressed as a percentage. Knowledge of this process is needed to control the sediment accumulation and thereby the life of the reservoir, and to assure its proper operation.

This paper contains an explanation of what happens in agricultural reservoirs (most are from 3 to 980 $m^3.10^4$ in capacity) during an inflow event, and using a flow diagram (Figure 8.1), the various parameters that influence sediment trap efficiency are discussed. Included is a

---

Contribution of the Agricultural Research Service, USDA.

Research Hydraulic Engineer, Hydrograph Laboratory, Beltsville, Maryland, USA (deceased).

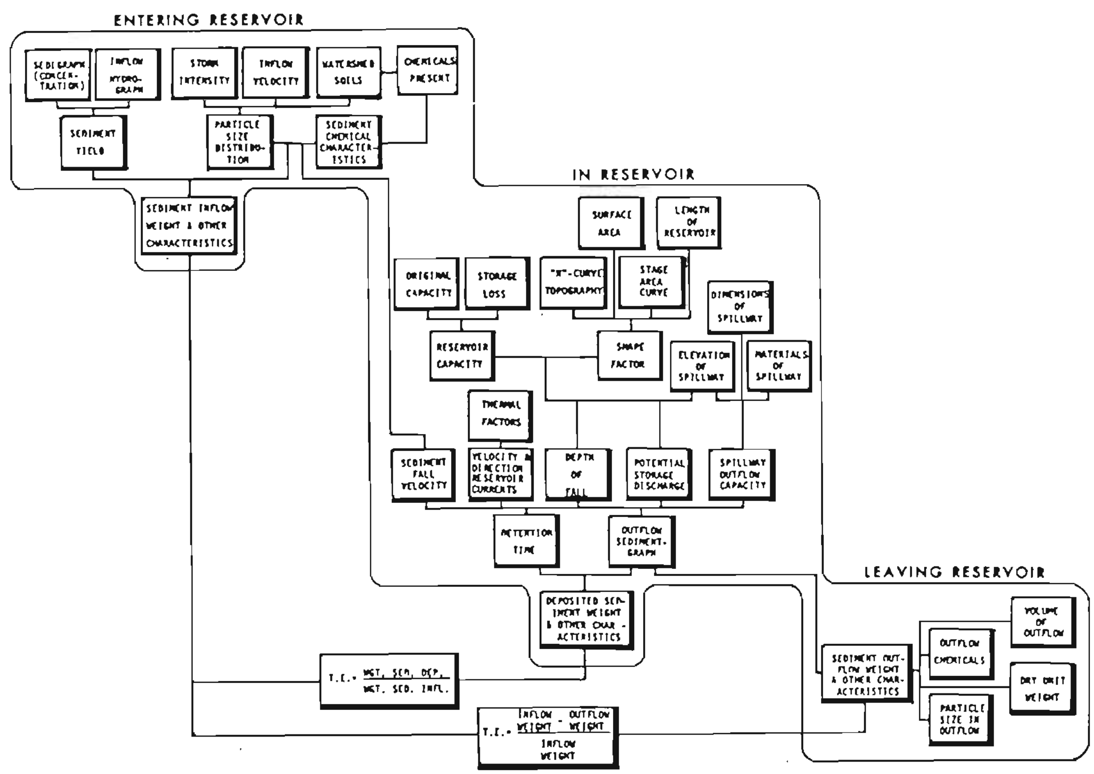


Fig 8.1 Reservoir-sediment trap-efficiency parameter flow chart.

literature review of publications that have helped advance the state of the art to our current level of knowledge. The individual reports can then be compared with the flow diagram to elevate their completeness and adequacy in estimating the sediment trap efficiency in a proposed reservoir.

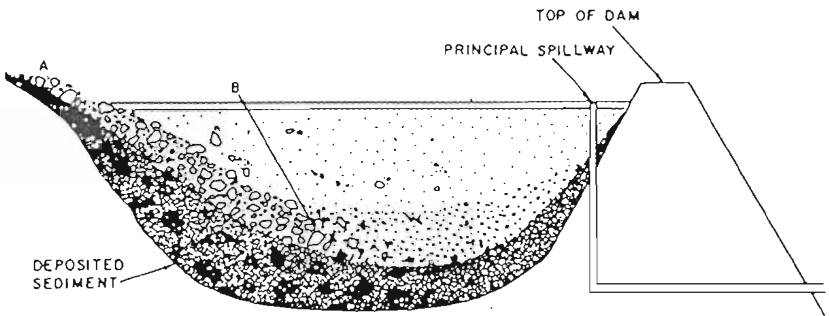


Figure 8.2. Depicting storm runoff moving into and in a reservoir.

Reservoir Sedimentation

Sediment movement in reservoirs

When storm runoff enters a reservoir (Figure 8.2, point A), the inflow is spread over a larger channel/ reservoir cross-section and its velocity is quickly reduced. This reduces the transport energy and causes the large sediment particles and aggregates to settle to the bottom. The remainder of the inflow moves along the bottom of the reservoir towards the dam until it reaches an elevation in the reservoir where the density of the inflow equals the density of the reservoir water. As the inflow velocity is further reduced, the larger particles left in the remaining flow will settle to the bottom, decreasing the inflow's density. Some of the flow may move horizontally into the reservoir before the bulk of the remaining flow. (This is a very dynamic process that is constantly changing and adjusting). When the flow reaches this point of equal density (point B), it flows horizontally into the reservoir (somewhat like a wedge) between the lighter and denser water, and raises the water in the reservoir above it. In a full reservoir equipped with a surface discharge principal spillway, the upper level of water (the highest quality water in the reservoir) would be discharged.

The density of the storm inflow depends on its temperature and sediment concentration. The sediment concentration is often the more important parameter in reservoirs, because the temperature difference between storm inflow and reservoir water is usually not large. For example, only 1000 ppm of sediment is needed to equal the density difference caused by the reservoir water being 5.5°C cooler than the inflow (in the 10° to 27°C range).

Trap efficiency

Good estimates of sediment trap efficiency of proposed reservoirs are important because the volume of sediment trapped during the design life of the structure must be provided for in the reservoir capacity; this plus water storage for the design storm are the two components that govern the ultimate size of the reservoir. If the trap-efficiency estimate is less than it should be, the reservoir is underdesigned and its capacity will be filled with sediment too soon and its useful life will be shortened. If the estimate is larger than necessary, the reservoir is overdesigned and money will be wasted constructing too large a structure, and the reservoir may not function at an optimal level. Furthermore, we must learn the controlling physical dimensions or characteristics for reservoir-sediment trap efficiency and how to better change these parameters. We can then incorporate the proper controls into the design of each reservoir so that it will trap the percentage of incoming sediment needed to accomplish the primary objectives. If the primary objective of the reservoir is for domestic water supply, irrigation, emergency water for fighting fires, recreation, fish farming of certain species, etc., the reservoir designer would want to limit the amount of sediment trapped.

To determine reservoir-sediment trap efficiency of existing reservoirs requires an accurate measurement of all sediment transported into the reservoir as well as the sediment discharged through the spillways. This requires flow measurements and samples. An as alternative to flow measurements and samples of the inflow and outflow, we can measure only one and determing the sediment retained by making good reservoir sedimentation surveys of the deposited sediment volume and its volume-weight.

Reservoir-sediment trap efficiency is best discussed by considering the parameters in their respective zone of influence. In sequence these are a characterization of: (L) inflowing watershed runoff and sediment, (2) reservoir storage dimensions and properties, and (3) discharge location and capabilities. Using the parameter flowchart (Figure 8.1) as an aid, we can better follow this sequence.

The storm runoff from the contributing watershed will flow into a reservoir at a variable rate for the water component and a different variable rate for the sediment concentration component. The hydrograph will show the water inflow as a function of time, and the sediment graph will show the sediment concentration also as a function of time. When used together, we can compute the sediment yield to the reservoir for the storm or a unit of time. The storm intensity and inflow velocity control the size of sediment particles eroded on the watershed uplands and channels and transported to the reservoir. Of course, certain chemicals in the soil or water may cause flocculation or aggregation and affect the particle or aggregate size, density and fall velocity. All of these characterize the inflow and determines the amount of sediment moving into the reservoir.

In the reservoir, the capacity and its configuration are very important parameters. We do not know which reservoir configuration parameter will be most important. These might take on different degrees of importance depending on the size of the reservoir. For example, in a very small reservoir, the sediment inflow will be close to the dam and there will be little opportunity for even the larger particles to be deposited far from the dam. The situation will be quite different in a large reservoir. Another important factor governing reservoir dynamics is thermal stratification. The spillway characteristics of elevation, size, design and roughness will control the spillway outflow capacity. This, with sediment fall velocity, depth of fall, storage to be discharged, temperature, and current velocity will govern detention time and the outflow sediment graph. They, in turn, will control the amount of sediment that will be deposited and the residual - the amount that will be released from the reservoir.

The spillway location, elevation, and capacity will greatly influence the sediment outflow. Usually, the sediment passing through a reservoir will be clays and highly dispersed particles. The sediment discharge or outflow can be characterized as to volume, particle-size distribution, adsorbed chemicals, and dry volume-weight.

Trap/efficiency can be determined in several ways. Reservoir-sediment trap efficiency (E) (usually expressed in percent) is the ratio of the weight of sediment (S) coming into a reservoir to the weight that is trapped therein

$$E = \frac{\text{S retained}}{\text{S Yield}} \text{ or } E = \frac{\text{S inflow - S outflow}}{\text{S inflow}}$$

Sediment yield and sediment inflow are the same parameter.

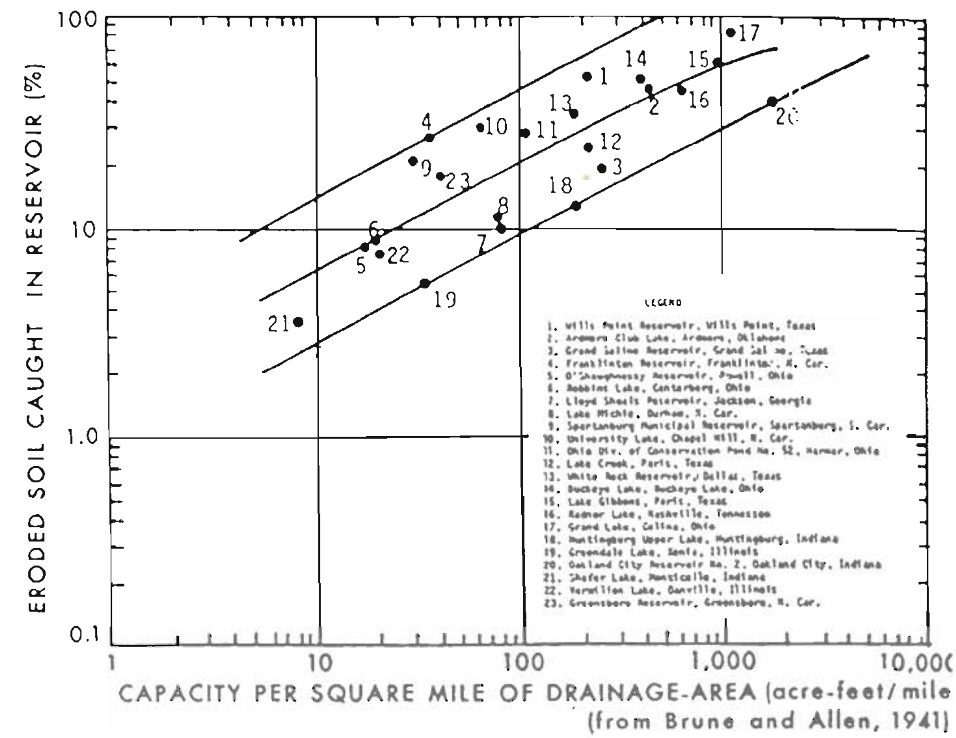
Evolution of current state of the art

Through the early years, the methods for estimating reservoir-sediment trap efficiency remained relatively unchanged. They were based primarily on empirical relationships.

Hazen (1904) has been credited for developing the first real theory on the operation of sedimentation basins. This was a further development of some ideas proposed by Seddon in 1889. Hazen developed his concepts by considering a series of increasingly complex hydraulic situations and assumptions. His fundamental proposition was that a particle of sediment settles at a velocity that depends upon its size and weight, and upon the viscosity of the water. Second in importance was the density of sediment in the water immediately above the bottom.

Hazen (1914) first introduced reservoir storage, or capacity, in terms of runoff per square mile of tributary area - the C/I ratio. However, he used this term in connection with reservoir storage requirements, instead of reservoir-sediment trap efficiency.

Brune and Allen (1941) reported a good relationship (Figure 8.3) between the percentage of eroded soil (gross erosion) caught in the reservoir and a capacity-watershed ratio, expressed as storage capacity per square mile of drainage area. They used 23 reservoirs from Texas to



1 acre-foot/mi^2 = 0.0476 ha-m/km^2

Fig 8.3. Percentage of eroded soil caught in reservoir as a function of reservoir capacity-drainage-area ratios. (from Brune and Allen, 1941).

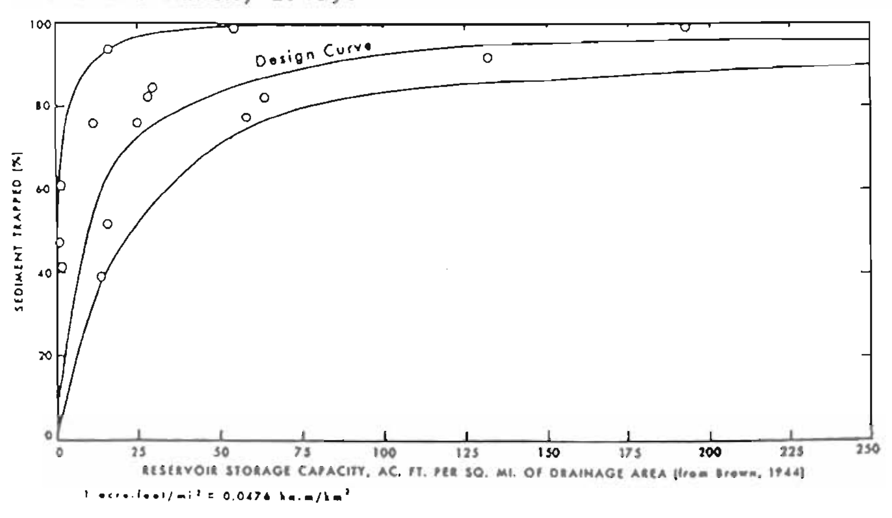


Fig 8.4. Relation of reservoir trap efficiency to reservoir storage capacity per sq. mi. of drainage area. (from Brown 1944).

Ohio as a basis for their work, one of the first reservoir-sediment trap efficiency studies.

Brown (1943) reported that "Study of reservoir silting, both in this country and abroad, has shown that one of the most important factors governing the annual rate of storage loss is the ratio between the original storage capacity of the reservoir and the inflow of water from the drainage basin". Brown then separated his data into groups depending upon the original storage of the reservoir per square mile of drainage area. Those with the lowest capacity per unit drainage area had the highest rate of storage loss due to sediment deposition.

Brown (1944) developed a curve (Figure 8.4.) showing the relationship between reservoir-sediment trap efficiency, and the ratio of capacity (original) to watershed drainage area. His curve was based on data from 15 reservoirs. Brown enclosed his data spread in an envelope of curves and attributed the higher percentage trap efficiency curve to smaller and more variable runoff, coarse, or highly coagulated sediments, and structures with greater storage capacity.

Campe (1945) developed several theories regarding the settling velocities of particles (based on Stokes' law) in an idealized, rectangular, continuous flow basin. His studies included work on the particle drag coefficients; hinderance of settling due to close proximity of other particles; factors influencing settling velocity; effect of flocculation on settling velocity; settling path; resuspension; and effects of turbulence, water depth, and detention period on deposition. Camp also developed a family of trap efficiency curves based on settling velocity, rate of outflow from the basin, and surface area of the basin.

Churchill (1948) outlined the method used by the Tennessee Valley Authority in estimating reservoir-sediment trap efficiency. He used a ratio of period of retention to transmission velocity as the Sedimentation Index and related it to trap efficiency. Churchill used two sizeable reservoirs, Hales Bar and Wilson, as the principal basis for his curves (Figure 8.5.). These curves fitted the relatively fine-grained sediment found in the Tennessee Valley; however, different particle sizes will result in different relationships. The components of the sedimentation index, period of retention, and mean velocity of flow through the reservoir, are not generally available for most reservoirs.

Brune (1953) used data from 40 reservoirs (44 periods of time) to develop trap efficiency curves (Figure 8.6.) based on the capacity-inflow ratio. Brune originally constructed envelope curves for normally ponded reservoirs, but these were named to reflect the expected character of the sediment, such as highly flocculated and coarse sediment versus very fine sediment. Brune's curves have been used more widely than other methods, especially for estimating the trap efficiency of small reservoirs. Brune concluded that the capacity-inflow (C/I) ratio is much better than the capacity-watershed (C/W) ratio formerly used.

Guy et. al. (1958) described the plan of operations and

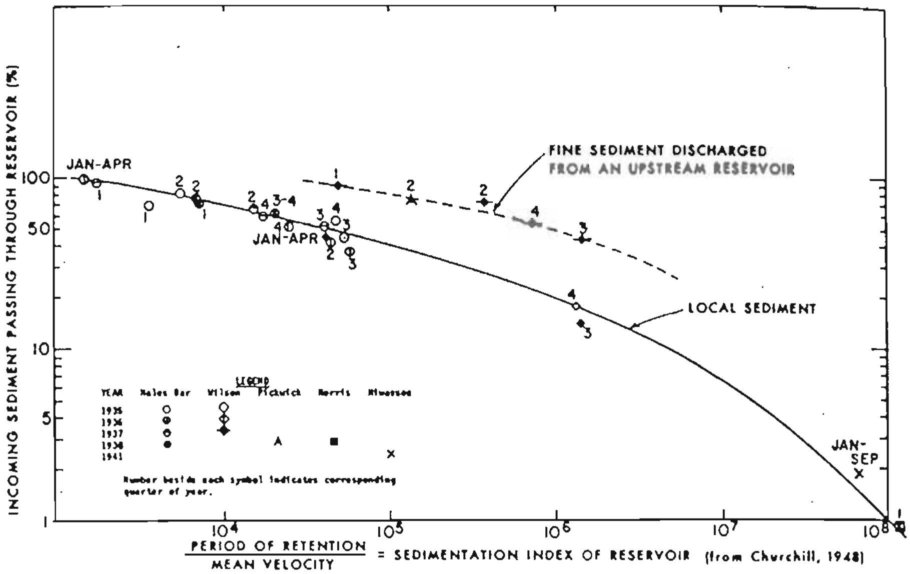


Fig 8.5. Relation of reservoir sedimentation index to percent of incoming sediment passing through reservoir. (from Churchill, 1948).

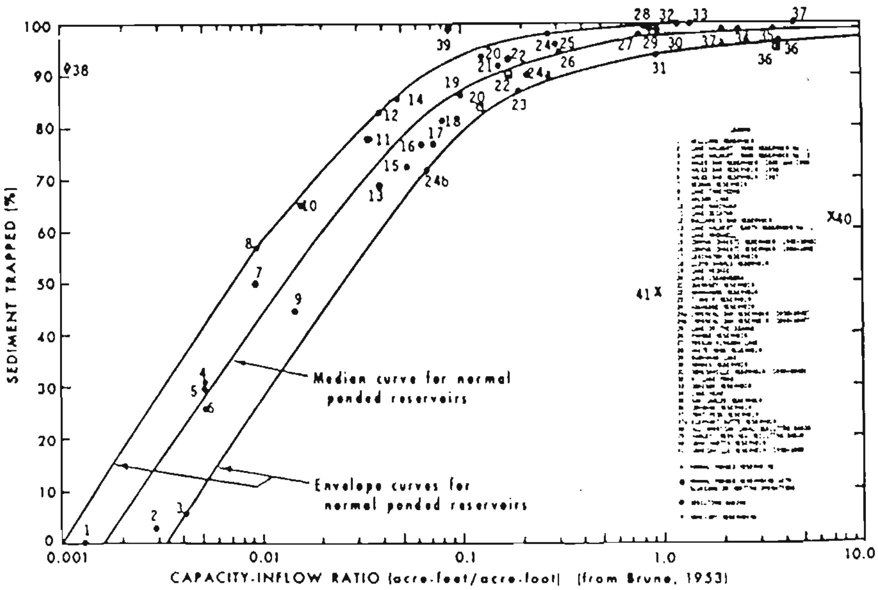


Fig 8.6. Trap efficiency as a function of capacity-inflow ratio, type of reservoir, and method of operation. (from Brune, 1953).

some of the details of a cooperative reservoir-sediment trap efficiency study financed primarily by the Soil Conservation Service, with participation also by the US Geological Survey and the Agricultural Research Service. The authors discussed how the sediment trap efficiency depends on settling velocity of sediment and retention time in the reservoir. They included information on 12 reservoirs in 11 states and trap efficiency estimates of 10 of these reservoirs (to June 30, 1957).

Heinemann and Reynolds (1962) reported on the same cooperative reservoir-sediment trap efficiency study and listed 26 basic measurements or parameters that might influence trap efficiency, including a characterization of the inflow, the reservoir itself, and the outflow structure. They used a form of sedimentation information curve to study reservoir sedimentation and the effect of the size of principal spillways on the trap efficiency and sediment deposition of several small reservoirs.

Gottschalk (1965) more fully explained the above mentioned cooperative study and the use of such data in designing small floodwater retarding structures. He also showed the measured trap efficiencies for 18 small reservoirs - these data points fell between or below Brune's envelope curves, indicating a possible overestimation of trap efficiency.

Beer, Farnham, and Heinemann (1966) evaluated sedimentation prediction techniques in western Ohio using data from a detailed study of 24 small reservoirs and their watersheds. Their results suggested that capacity-inflow may not be the best estimator of trap efficiency for reservoirs in the loess area. A regression correlation showed that a reservoir capacity-watershed area term was about twice as good as an indicator of trap efficiency as capacity-inflow in the loess area.

Borland (1971) used the basic Churchill (1948) curve and added 15 data points representing desilting basins and semidry reservoirs. He concluded that this relationship was more applicable than Brune's curves for estimating trap efficiencies for desilting and semidry reservoirs.

Dendy (1974) summarized the results from the cooperative study by the Soil Conservation Service, US Geological Survey, and the Agricultural Research Service referenced earlier. These studies were conducted on 11 normally ponded and six dry reservoirs in the southern United States. Dendy makes the point that trap efficiency usually depends on the reservoir's ability to trap the silt-size and smaller sediments. He also emphasized that all but one data point for these reservoirs plotted below Brune's (1953) curve (Figure 8.6.).

Chen (1975), in addition to providing a good general review of the state of the art of trap efficiency, developed a series of curves (Figure 8.7.) for various particle sizes (d) showing trap efficiency related to the ratio of basin area to outflow rate (A/Qo). These showed that clay-size particles require excessively large basin dimensions to be trapped, unless chemical flocculants are added to increase settling velocity. He also compared Brune's curves (1953) and Churchill's curve (1948) with the trap efficiency

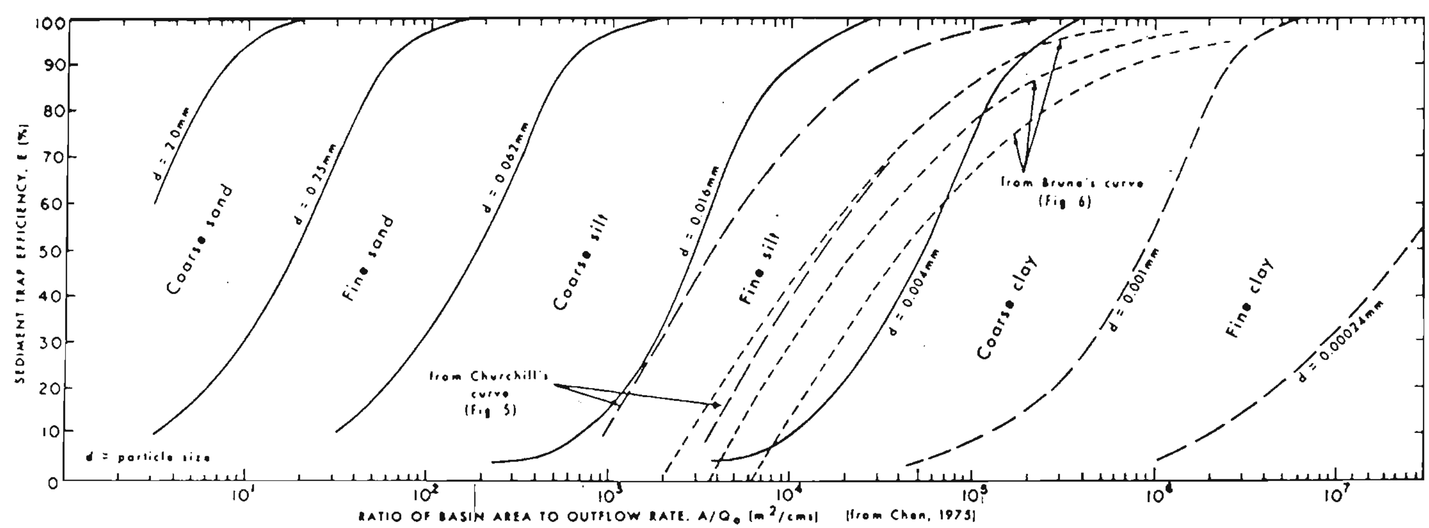


Fig 8.7. Trap efficiency as a function of ratio of basin area to outflow rate. (from Chen, 1975).

curves developed by Camp (1945) and found that they were compatible in the silt range. He concluded that for a given basin dimension, both Brune's and Churchill's curves tend to underestimate trap efficiency for coarser material, but overestimate it for finer sediments. He also concluded that trap efficiency increases as the basin outflow rate decreases and that outflow rate is governed by basin storage capacity and the configuration and capacity of spillways and release outlets.

Bondurant, Brockway and Brown (1975) reported trap efficiency information on two irrigation return flow ponds. They found that sediment removal efficiency correlated well with flow rate and sediment concentration. They also showed the sediment particle size distribution of one pond.

Rausch and Heinemann (1975) reported on their trap-efficiency studies of three reservoirs in central Missouri, the first study of its kind on a storm basis. Their study yielded 48 data points for a regression analysis which showed that the most important parameters were reservoir detention time and particle size of the inflowing sediment. Peak inflow rate was substituted for sediment particle size since they found a high direct correlation between these two parameters. Storm runoff volume, sediment yield, reservoir capacity and drainage area also improved the prediction of trap efficiency.

Pennell and Larson (1976) developed a mathematical model to evaluate reservoir design factors and their significance and effects on trap efficiency. They showed that the most significant design factors are capacity, basin depth, and length of detention time.

Curtis and McCuen (1977) developed a model, based on Camp's (1945) approach, which shows the effect of four parameters on reservoir-sediment trap efficiency:

(1) particle size distribution: trap efficiencies are higher in reservoirs below watersheds with eroded soil composed of a high portion of large, heavy particles.

(2) initial basin storage: the more runoff already stored, the less available for additional runoff and, therefore, the lower the trap efficiency.

(3) outflow: the larger the outflow, the lower the trap efficiency.

(4) basin depth: when the volume of water stored is held constant, the shallower depths gave higher trap efficiency.

Their model was developed on the basis of small idealized settling tanks and they found no data that could be used for verification or calibration.

Ward, Haan, and Barfield (1977a) conducted an extensive literature review on the sedimentation processes in detention basins and developed a mathematical model describing the sedimentation characteristics of such small basins. This model is very comprehensive and uses as basic input the inflow hydrograph, inflow sediment graph, sediment particle size distribution, detention basin stage-area relationship, and detention basin stage-discharge relationship. The model is used to route the water-sediment mixture through the basin, and in the process, estimates the outflow sediment concentration, sediment distribution, and the sediment trap efficiency.

With respect to sediment particle size, the percent finer than 0.02 mm was the most critical in determining the performance of a sediment basin.

Ward, Haan, and Barfield (1977b) evaluated the most commonly used trap efficiency methods, emphasizing that most are empirical. The authors further explained their DEPOSITS model - a mathematical simulation model for predicting the sediment processes occurring in small reservoirs. They also stressed the importance of aggregation and flocculation in settling of particles, and the need for suitable field data for testing theory and models.

Ward, Haan, and Barfield (1977c) reported additional studies with their DEPOSITS model and limiting conditions for its use. They used their model to develop regression equations for estimating reservoir-sediment trap efficiency for different kinds of small basins, especially those used to control sediment from strip mines and urban areas.

Schiebe and Dendy (1978) used a small laboratory reservoir to study residence or detention time under several different inflow and reservoir stratification conditions in an effort to learn how better to control detention time in different kinds of reservoirs. They also verified that the time available for sediment settling can be changed by manipulating the location and operation of the reservoir outlet.

Of the above studies on reservoir-sediment trap efficiency only five authors; Chen (1975), Rausch and Heinemann (1975), Curtis and McCuen (1977), Ward, Haan, and Barfield (1977a, b, and c), and Schiebe and Dendy (1978), considered trap efficiency in its entire context - that is, considered and characterized the inflow, the reservoir storage dimensions and its effect, and the outflow. Some of these are field studies and others are primarily theoretical studies, and the mix is a healthy one which should lead to more progress. Actual verification is still needed for the theoretical models

Application of trap efficiency in design B

As discussed earlier, the estimated volume of sediment that will be trapped in a reservoir is one of the two components determining the design capacity of the reservoir. This estimate of trapped sediment is made by multiplying estimated reservoir-sediment trap efficiency values times the C sediment yield to the reservoir site for the design life of the structure.

The estimated reservoir-sediment trap efficiency value can be determined by any of the methods just described. The method selected will probably depend on the users experience with these methods and the availability of data. The method that has been used more than any other is Brune's (1953) curves. In this method, trap efficiency is estimated on the basis of the ratio of reservoir average capacity to the average annual inflow using the following procedure.

A Estimate the total required capacity of the reservoir for water and sediment storage (Roehl, 1975). Since an actual value for the total capacity cannot be obtained until final design is completed, and approximation of the total capacity is made as follows.

1. Estimate the sediment yield to the reservoir site, using procedures outlined elsewhere in this manual, the ASCE Sedimentation Manual (ASCE, 1975), or the USDA publication, "Present and Prospective Technology for Predicting Sediment Yields and Sources" (UDSA, 1975). If the reservoir objectives and design are to trap most of the sediment, multiply the sediment yield value times a large trap efficiency, but if the objectives and design are to trap a small percentage of the sediment inflow, multiply the sediment yield times a low trap efficiency value. This gives the required sediment storage for a short period or the design life, depending on the time span considered. Another alternative is to assume a reasonable and realistic volume of sediment storage that might be required for the design life of the structure. For example, 4 cm (from the entire watershed).

2. Obtain an estimate of the required water detention storage of the design storm. For example, 12 cm.

3. The sum of 1 and 2 is the estimated total original capacity of the reservoir. That is, 4 + 12 = 16 cm.

4. Repeat step 1 (above) progressively by time increments, or for the entire design life in one calculation, to obtain a final capacity of the reservoir. This decrease in reservoir capacity must depend on the trapping of sediment in the reservoir during the time period (or periods) being considered. For simplicity here assume that all of the sediment storage allocation has been filled. The capacity of the reservoir at the end of the reservoir design life would then be, 0 + 12 = 12 cm.

B Determing the average annual runoff into the reservoir, in the same units as above. This value may be obtained from the hydrologic analysis of the watershed or other available information. For purposes of this illustration, it is determined to be 40 cm (from the entire watershed).

C Divide the approximate average total capacity, item A-3 plus A-4 divided by 2, by the average annual runoff, item B above, to obtain the capacity-inflow (C/I) ratio. That is $\frac{16 + 12}{2} \div 40 = 0.350$ = C/I ratio.

D The trap efficiency for a given C/I ratio is determined on the vertical axis of Brune's curves (Figure 8.6.). The texture of the sediment should be estimated on the basis of the character of the watershed soils and the principal sources of sediment. Where incoming sediment is assumed to have a predominance of bed load or coarse material or is highly flocculated, the upper of Brune's curves should be used to determine the trap efficiency. If the incoming sediment is composed primarily of colloids, dispersed clays and fine silts, the lower curve should be used. The median curve is representative of incoming sediment consisting of a wide distribution of various grain sizes. This trap efficiency value then is the first approximation used in the preliminary designs. As the basic design values become established the above procedure is repeated and a refined estimated trap efficiency value is developed and used.

Research needs

As indicated, there have been a number of theoretical studies and data analyses pertaining to reservoir-sediment trap efficiency. In general terms we know about the reservoir sedimentation processes and trap efficiency, but we lack specific quantitative data. We would be hard pressed to design a reservoir that was to trap only 50% of the incoming sediment, or to trap only the sediment larger than a specific particle size on a given watershed. We need to improve our understanding of the depositional process and to improve prediction and control of sediment deposition in reservoirs. We also need to learn how to better control and predict reservoir-sediment trap efficiency.

I know of only 20 small reservoirs in the USA that have been studied and measured in sufficient detail to provide usable trap efficiency data. These are:

7 reservoirs from Brune's (1953) report. These have drainage areas less than 38.85 km^2 (15 mi^2), which is the limit of the ponded reservoirs in Dendy's (1974) report.

10 reservoirs (ponded) from Dendy's (1974) report. This does not include Brownell No. 1-A, which is almost filled and functions more like a dry reservoir.

3 reservoirs from Rausch and Heinemann's (1975) report.

Some other data exist, but these reservoirs were sampled and runoff measured during only a part of some storms. Questions have been raised regarding the adequacy of those measurements.

Obviously, this lack of good usable data is a very serious research deficiency in the USA, and this problem is being addressed by conducting additional studies at Oxford, Mississippi, and at Columbia, Missouri. Other studies have been started by Dr. Haan at the University of Kentucky.

More information is also needed on sedimentation processes in small reservoirs between runoff events. There are many unanswered questions about sediment movement, resuspension, temperature effects, and changes with time. These items, too, are included in the studies at Oxford and Columbia. The effects of temperature on small reservoir sediment deposition is not understood. How important is it? What is the effect of temperature on density currents and can they be utilized to control reservoir-sediment trap efficiency?

The entire area of flocculation and aggregation needs to be studied with regard to trap efficiency and predicting its effect in proposed reservoirs. Can chemical flocculants and flow velocity controls be used efficiently and practically to induce deposition where it is desired? Changes in trap efficiency and compaction of sediment with time must be investigated further. Further studies should be based on sediment weight. Sediment volumes alone are not very helpful because they change, depending on the degree of compaction experienced. For this reason, volume units are sometimes misleading.

Our future studies should also be on a storm basis so that the information can be combined for any given storm frequency series to obtain trap efficiency on a time basis. A trap efficiency value for a period of years can be misleading without also presenting storm data. We should also study a wide range of the important influencing parameters, such as various discharge systems. Similarity of data may obscure the importance of some parameters.

Comment

Reservoir-sediment trap efficiency is a very important area of research because we need to design each reservoir to accomplish specific objectives. Such objectives can be accomplished by knowing how to control the movement of sediment in a reservoir and then carefully designing the reservoir so that it will have the necessary characteristics to control sediment trap efficiency.

In future trap efficiency research, we need to carefully characterize and study: (1) the inflowing water and sediment, (2) the dimensions and configuration of the reservoir storage, and (3) the discharge spillway location and capacity. We should study reservoirs larger than 80 ha drainage area (because of more uniform sedimentation patterns), study and measure reservoir performance on a storm basis, cover a wide range of parameter magnitudes, and focus on soil particles in the silt and clay size ranges. The sand-size particles will probably settle out after 60-90 m of travel in any reservoir. Reservoirs primarily vary in the ability to trap sediment in response to their availability to trap the silt and clay particle sizes.

After being satisfied by or restricted to pure empirical relations for estimating reservoir-sediment trap efficiency, for many years it is enlightning to see the recent research directed more toward the physical processes of sediment entering and moving through a reservoir, with a good balance between field and purely theoretical efforts. Such research should soon enable us to greatly improve our predictions of reservoir-sediment trap efficiency.

REFERENCES

American Society of Civil Engineers, 1975, *Sedimentation Engineering,* American Society of Civil Engineers Manuals and Reports on Engineering Practice No. 54.

Beer, C.E., Farnham, C.W., and Heinemann, H.G., 1966, Evaluating sedimentation prediction techniques in Western Iowa, *Transactions, American Society of Agricultural Engineers,* 9, 828-833.

Bondurant, J.A., Brockway, C.E., and Brown, M.J., 1975, Some aspects of sedimentation pond design, in *Proceedings, National Symposium on Urban Hydrology and Sediment Control, University of Kentucky, Lexington,* C-35 - C-41.

Borland, W.M., Reservoir Sedimentation, in *River Mechanics,* ed. Shen, H.W., (Water Resources Publications, Colorado State University, Fort Collins, Colorado), 29-1 - 29-38.

Brown, C.B., 1943, The control of reservoir silting, *US Department of Agriculture, Miscellaneous Publication,* No. 21.

Brown, C.B., 1944, Discussion of "Sedimentation in Reservoirs" by B.J. Witzig, *Transactions, American Society of Civil Engineers,* 109, 1080-1086.

Brune, G.M., 1953, Trap efficiency of reservoirs, *Transactions, American Geophysical Union,* 34, 407-418.

Brune, G.M., and Allen, R.E., 1941, A consideration of factors influencing reservoir sedimentation in the Ohio Valley region, *Transactions, American Geophysical Union,* 22, 649-655.

Camp, T.R., 1945, Sedimentation and the design of settling tanks, *Proceedings, American Society of Civil Engineers,* 71, 445-486.

Chen, C.N., 1975, Design of sediment retention basins, in *Proceedings, National Symposium on Urban Hydrology and Sediment Control, University of Kentucky, Lexington,* 58-68.

Churchill, M.A., 1948, Discussion of "Analysis and use of reservoir sedimentation data" by L.C. Gottschalk, in *Proceedings, Federal Inter-Agency Sedimentation Conference, Denver, Colorado, 1947,* (US Bureau of Reclamation), 139-140.

Curtis, D.C., and McCuen, R.H., 1977, Design efficiency of stormwater detention basins, *Proceedings, American Society of Civil Engineers, Journal of Water Resources Planning and Management Division,* 103, 125-140.

Dendy, F.E., 1974, Sediment trap efficiency of small reservoirs, *Transactions, American Society of Agricultural Engineers*, 17, 898-908.

Gottschalk, L.C., 1965, Trap efficiency of small flodwater-retarding structures, *ASCE Water Resources Engineer Engineering Conference, Mobile, Alabama,* preprint 147.

Guy, H.P., *et al.*, 1958, Sedimentation yield from small watersheds and its retention by flood retarding structures, *Report of Progress to June 1957*.

Hazen, A., 1904, On sedimentation, *Transactions, American Society of Civil Engineers*, 53, 45-71.

Hazen, A., 1914, Storage to be provided in impounding reservoirs for municipal water supply, *Transactions, American Society of Civil Engineers*, 77, 1539-1640.

Heinemann, H.G., and Reynolds, L.E., 1962, Interim findings on trap efficiency of small flood retarding reservoirs, in *Manual of papers prepared for Joint Sedimentation Workshop conducted by ARS-SCS, Panguitch, Utah.*

Pennell, A.B., and Larson, C.L., 1976, Effects of design factors on sedimentation basin performance, *Paper 76-2020 presented at the ASCE Annual Meeting, Lincoln, Nebraska.*

Rausch, D.L., and Heinemann, H.G., 1975, Controlling reservoir trap efficiency, *Transactions, American Society of Agricultural Engineers*, 18, 1105-1113.

Roehl, J.W., 1975, Procedure - Sediment storage requirements for reservoirs, *US Department of Agriculture, Soil Conservation Service Engineering Division, Geology Technical Release*, No. 12.

Schiebe, F.R., and Dendy, F.E., 1978, Control of water residence time in small reservoirs, *Transactions, American Society of Agricultural Engineers*, 21.

US Department of Agriculture, Agricultural Research Service, 1975, *Present and prospective technology for predicting sediment yields and sources,* US Department of Agriculture, Agricultural Research Service Publication No. ARS-S-40.

Ward, A.D., Haan, C.T., and Barfield, B.J., 1977a, Simulation of the sedimentology of sediment retention basins, *University of Kentucky Water Resources Institute Technical Report 103.*

Ward, A.D., Haan, C.T., and Barfield, B.J., 1977b, The performance of sediment detention structures, in *Proceedings, National Symposium on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky*, 58-68.

Ward, A.D., Haan, C.T., and Barfield, B.J., 1977c, Prediction of sediment basin performance, *Paper No. 77-2528, presented at the 1977 Winter meeting of ASAE.*