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Sediment Management and Sustainable Use of Reservoirs

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CONTENTS

Abstract Reservoirs have traditionally been designed to operate for periods of 50–100 years without impairment by sedimentation. However, aging reservoirs are now experiencing sedimentation problems that were ignored by the original designers, and to sustain their utilization, it is now necessary to redefine operations and modify structures to manage sediment. This chapter outlines the basic concepts and strategies to consider in predicting and evaluating reservoir sedimentation, in determining the time frame and severity of the problem, and in selecting an appropriate course of action. Strategies from the watershed to the dam are described which can contribute to the achievement of long-term sustainable use.

Key Words Reservoir sedimentation • Sustainability • Sediment management • Reservoir flushing • Offstream reservoir.

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1. INTRODUCTION

Dams and reservoirs interrupt the transport of sediment along a river, trapping sediment in the low-velocity reach above the dam while the reach below the dam, which no longer receives coarse suspended or bed material, tends to erode. The fluvial system will eventually restore the sediment balance across the impounded reach by completely filling the reservoir and reestablishing sediment discharge below the dam. As an alternative, the impounded river reach can be managed to improve the balance between sediment inflow and discharge to sustain beneficial storage. The ultimate objective of sediment management in reservoirs is to retard storage loss and to achieve a sediment balance in an economical and environmentally responsible manner while maximizing sustained long-term benefits from the reservoir.

Ours is, above all, a hydraulic society, particularly from the standpoint of food production. Of global consumptive water use, consisting of water evaporated, incorporated into products or polluted, 86 % is appropriated by agriculture, with only 9 % and 5 % respectively attributed to industrial and domestic use [1]. Flow regulation by reservoirs adds about 460 km^3/year to the world's irrigation supply, a 40 % increase above naturally available supplies [2]. Additionally, about 20 % of the world's electricity is produced by hydropower, a non-consumptive use, but which also depends on reservoir storage to sustain hydropower production through the dry season. Even run-of-river plants need to maintain a limited volume of storage to supply power during daily periods of peak demand.

Reservoirs have traditionally been designed based on the "life of reservoir" concept. Under this paradigm, the designer estimates the rate of sediment inflow and provides storage capacity for 50–100 years of sediment accumulation, thus postponing the sedimentation problem. Not only does this approach ignore the long-term problem of storage loss, but at many sites sedimentation problems are occurring much earlier than anticipated because sediment yield was underestimated or, due to increased sediment yield resulting from changed land use. This traditional approach may also fail to anticipate rapid sedimentation in areas which interfere with recreational uses, intake function, etc. In multipurpose reservoirs, the normally empty flood control pool may receive little sediment, while the conservation pool at the bottom of the reservoir loses capacity rapidly. But most importantly, many reservoirs have now seen more than 50 years of operation and are now beginning to experience sedimentation problems that were "pushed into the future" by the original designers.

Reservoir operation is not sustainable unless sedimentation can be controlled, and in our hydraulic society reservoirs may represent the most important class of non-sustainable infrastructure. Yet, despite increased knowledge of sedimentation processes and control methods, and the acknowledged need for sustainable design, most reservoirs continue to be designed and operated based on the traditional concept of a finite reservoir life, giving little consideration to maintaining long-term storage [3]. This chapter introduces strategies for managing sediments to maintain long-term reservoir capacity. This is a complex topic and only basic concepts are provided here. More comprehensive sources of information are listed at the end of this chapter.

2. RESERVOIR CONSTRUCTION AND SEDIMENTATION

The history of ancient dams has been reported by Schnitter [4], who listed over 12 dams which have seen over 2,000 years of service. The record for most years in operation appears to be held by Egypt's Mala'a reservoir constructed by King Amenemhet III (1842–1798/95 BCE) in the Faiyum depression about 90 km southwest of Cairo and reconstructed in the third century BCE with a dam 8 km long and 7 m high. This 275 Mm^3 off-channel impoundment stored water diverted from the Nile and remained in operation until the eighteenth century, a span of 3,600 years. The largest number of ancient structures was built by the Romans, and other long-lived ancient structures are reported in Greece, Sri Lanka, and China. If properly maintained, the life of a dam can be virtually unlimited. For example, the Proserpina reservoir at Mérida, Spain, constructed by the Romans in the second century, continues in use today. Reservoirs are the longest lived of all functional engineering works. Pyramids may be older, but they are monuments rather than functional engineering infrastructure.

Most dam construction has been undertaken during the last half of the twentieth century, which saw the worldwide increase in inventory of large dams (>15 m tall) from 5,000 to 40,000. During this same period in China, which is heavily dependent on irrigation supplies from reservoirs, the number of large dams increased from under a dozen to 22,000 [5]. China today has about half the world's large dams. However, the rate of dam construction declined dramatically worldwide toward the end of the twentieth century as many of the best available reservoir sites in developed regions were consumed, and resistance to dam construction grew from the increased competition for land resources inundated by reservoirs and in response to adverse social and environmental impacts.

In contrast to the decline in the rate of new dam construction, the rate of storage loss from sedimentation has been steadily increasing. Estimates of average global rate of storage loss worldwide vary from Mahmood's [6] estimate of 1 % to White's [7] estimate of 0.5 %. Sedimentation is now estimated to reduce global reservoir capacity at the rate of 40 km^3/year, or about 0.6 % annually based on the current global reservoir capacity of approximately 7,000 km^3 [8]. Using the International Commission on Large Dams (ICOLD) database, Basson [8] estimated that about 1,400 km^3 of capacity has already been lost to sedimentation, equivalent to 20 % of total original storage capacity (Table 5.1). Reservoir storage is now being lost much faster than it is being created.

Rates of storage loss are highly variable, ranging from about 0.1 % per year in Great Britain to 2.3 % per year in China [7]. Within a given country or region, there is also a wide variation in the rates of storage loss; some reservoirs already have serious problems while centuries of unimpaired operation remain at others. Average rates of storage loss in different regions of South Africa, for example, range from <0.2 % to 3 % per year [9], and the variation in loss rates for individual dams is far greater.

New reservoir construction to offset sedimentation is frequently not a viable option once reservoirs have been developed within a region. There are relatively few locations both topographically and geologically suitable for reservoir construction, lands both upstream and downstream have often become occupied, and heightening of the dam to add storage

Table 5.1
Summary of worldwide reservoir capacity and sedimentation, 2010 [8]

Type of use	Original reservoir volume, km^3	Percent of total storage volume
Water supply (irrigation, municipal, industrial)	1,000	14 %
Hydropower dead storage	3,000	43 %
Hydropower live storage	3,000	43 %
Total reservoir storage	7,000	100 %
Storage lost to sedimentation by year 2010	1,400	20 %
Annual storage loss	40	0.6 %

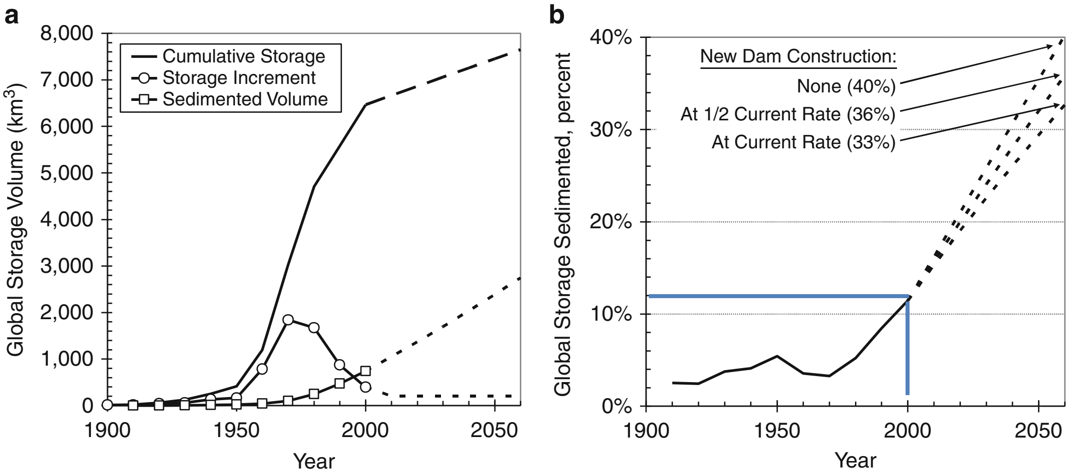


Fig. 5.1. (**a**) Cumulative reservoir storage, rate of reservoir construction, and cumulative volume loss due to sedimentation, assuming new dam construction at half the present rate. (**b**) Projected loss of global reservoir volume due to sedimentation under three different scenarios of new dam and reservoir construction rates. Percentage of global storage which is sedimented declines when the rate of new dam construction exceeds the rate of storage loss.

may not be viable due to both structural and upstream land use limitations. Development of a new reservoir at a distant site may not be economically viable, and water is costly to transport long distances, even if the political and environmental conditions allow such development and water transfers.

Due to the lack of available undeveloped sites, the problem of storage loss by sedimentation cannot be solved by new reservoir construction. This can be appreciated by viewing the global data [10] summarized in Fig. 5.1. Storage volume increases rapidly during the initial period of rapid dam construction. During this period, the rate of storage loss by sedimentation increases slowly. However, once the new construction rate declines, storage loss by sedimentation will exceed the rate that volume is added by new construction and declining capacity becomes the predominate trend. Similar patterns also result from plotting regional or national data. Two additional trends worsen the impact of the stagnation and subsequent decline in reservoir capacity. First, population is increasing, which means that the storage capacity on a per capita basis will decline much more rapidly than total storage capacity. Because of population increase, the volume of storage on a per capita basis began declining even before overall storage capacity began to decline. Second, climate change is ushering a period of more extreme weather, particularly drought severity. This means that the yield available from reservoirs will decline, not only because of storage loss, but also as a result of increased climatic variability. The developed world cannot return to high rates of new reservoir construction because a large inventory of undeveloped dam sites no longer exists. With new construction constrained, to sustain long-term capacity requires that existing reservoirs be actively managed to reduce the rate of storage loss.

Most dams are relatively young, and engineering experience to date has focused primarily on structures not yet experiencing significant sedimentation problems. However, this situation is changing as sediment accumulates, and the twenty-first century will see water resource engineers increasingly focus on the management of existing dams and reservoirs to achieve sustainable operation.

3. RESERVOIRS AND SUSTAINABILITY

3.1. Economic Analysis and Sustainable Use

Although economic analysis has long been the basis for decision-making in the water resources sector, it has important well-known limitations in counting impacts to affected third parties, including future generations, and to nonmarket values such as the environment. Financial analysis discounts future cash flows as compared to current income or expense, logically representing our preference for immediate rather than future income by expressing future value as a time-discounted present value. The present value (PV) for an income or expense amount A, which occurs N years in the future, may be computed for an annual discount rate, i, expressed as a decimal value (i.e., 7 % = 0.07) by

$$\mathrm{PV} = A/(1+i)^N \tag{5.1}$$

Use of discounting helps focus development activity on projects with near-term benefits as opposed to projects with less-certain distant future benefits. However, discounting removes economic incentives to incur costs today for actions to sustain long-term operation. This will be illustrated by an example.

Consider the two cash flows shown in Fig. 5.2 which compares Project #1 with benefits initially at \$100/year but declining to zero at year 30, against Project #2 with a sustainable benefit of \$90/year which extends indefinitely into the future. Using a 30-year horizon for financial planning and a 7 % discount rate, the present value of Project #1 is higher than

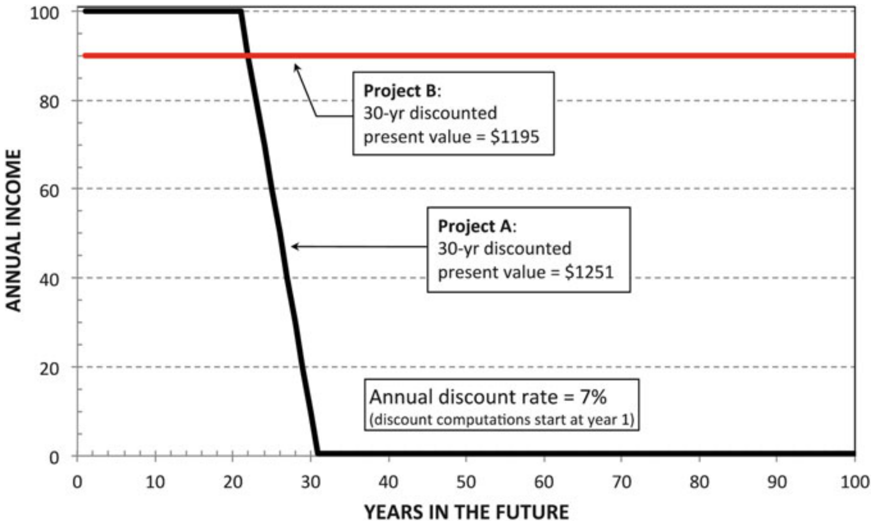


Fig. 5.2. Present values of two future income streams with a 7 % annual discount rate.

Project #2, and from a financial standpoint Project #1 is preferred over the sustainable option. This illustrates the effect that financial analysis can have in directing investment toward measures with near-term benefits but lacking long-term sustainability.

3.2. *Sustainability Criteria*

Public policy in the form of legislation and regulations is used to protect third parties and the environment from failings of the economic marketplace. The concept of sustainable development attempts to establish a more holistic framework for project decision-making and specifically includes issues of intergenerational equity, those long-term consequences of today's actions that will affect our children and grandchildren but which may be discounted out of project financing decisions.

The 1987 report to the United Nations by World Commission on Environment and Development titled "Our Common Future" [11] explicitly brought the rights of and our obligations to future generations, stating: "Humanity has the ability to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." An international team of experts reviewed the implications of sustainability to water resources projects, stating that "Most definitions of sustainable development include three broad notions: justice to nature, justice to future generations, justice within our generation" [12]. Economic performance is not excluded from the sustainability equation, but is recognized as one of several complementary factors which, together, result in sustainable activities. Despite widespread agreement on the general form of sustainability goals, it has been most difficult to establish specific project criteria. The issue of sustainability associated with dam construction has been addressed by the World Commission on Dams (WCD) [5] and the International Hydropower Association (IHA) in its

Hydropower Sustainability Assessment Protocol [13]. While the WCD gives greater emphasis to social and equity issues, the IHA's approach is more closely aligned with achieving economic performance and efficiency. However, neither the WCD nor IHA explicitly focuses on long-term sustainable use. For example, the IHA defines "long term" as "the planned life of the hydropower project."

Reservoirs are expected to serve not only the present but the future as well, and cities and societies are built using water from reservoirs based on this assumption. A sustainable approach to reservoir design and management does not accept as inevitable obsolescence by sedimentation, but rather seeks to design and actively manage reservoirs to sustain long-term beneficial use, even though the long-term benefits may differ in both magnitude and character from the original design purpose. Nevertheless, it is not always appropriate to sustain the operation of every reservoir, as benefits may not always justify the cost of sediment management. Facility retirement and removal should always be considered as a management option. Sediment management also plays a major role in the abandonment and removal of dams, since dam removal can release large volumes of sediment with significant downstream consequences. For example, retirement of the small San Clemente dam on the Carmel River, impounding less than 2 Mm^3 of volume, is expected to cost over $75 M, with the largest cost component associated with management of the 1.9 Mm^3 of sediment that now occupies most of the original reservoir storage volume [14].

4. SEDIMENTATION PROCESSES AND IMPACTS

4.1. Longitudinal Sedimentation Patterns

A definition diagram showing the idealized configuration of sediment deposits in reservoirs is presented as Fig. 5.3. Based on analysis of data from hundreds of reservoir surveys, Ferrari [15] noted that most sediment inflow tends to deposit either in the delta or along the reservoir thalweg. Deltaic deposits consisting of coarser sediment dominate in some reservoirs, while in others delta deposits may be essentially absent and most volume loss will consist of finer sediment, often transported by turbid density currents. More typically reservoirs will exhibit some combination of these two patterns. This general pattern can be complicated by the effect of sediment inputs from multiple tributaries and the reworking of sediment as reservoir level varies, plus the effect of extreme floods and reservoir drawdown which may carry coarser sediment deeper into the reservoir. It is important to determine where sediment is being deposited since even a small percentage of capacity loss can be problematic if deposited in front of outlet works, in navigation channels, and in the delta creating backwater flooding. In multipurpose reservoirs sedimentation will affect different beneficial pools to varying degrees.

Longitudinal profiles characteristically show a rapid initial change in the bottom configuration in the delta and also near the dam when turbidity currents are important. This initial rapid change in the reservoir profile corresponds to the deposition of material in zones of the reservoir with only limited storage capacity. Thus, if 30 m of sediment depth has been

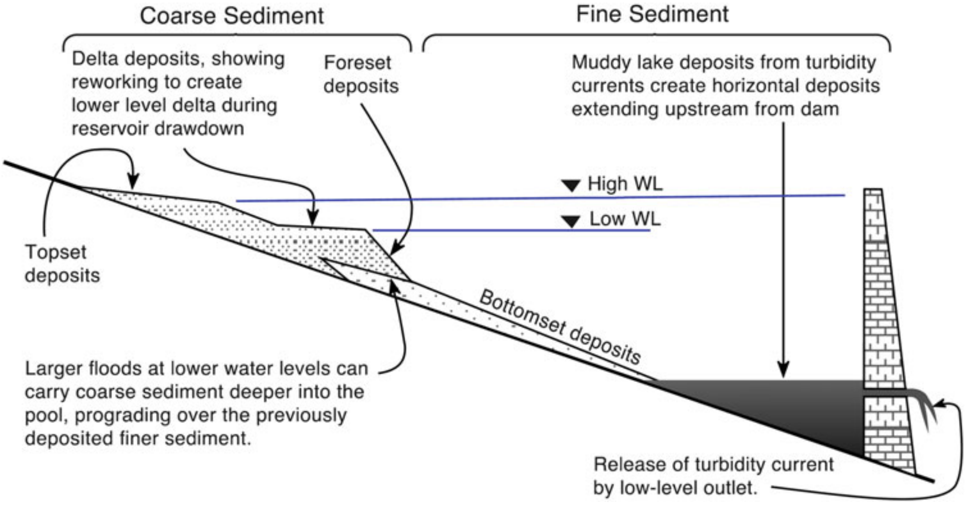


Fig. 5.3. Generalized pattern of reservoir sedimentation showing development of delta containing coarse sediment at two different levels corresponding to periods of two different water levels, and the accumulation of fine-grained deposits downstream of the delta.

deposited in front of the dam in the first 20 years of operation, the top of the sediment bed will not rise an additional 30 m during the next 20 years; the rate of rise will decline over time because each depth increment requires more volume to fill. Compaction of fine sediment can also reduce the subsequent rate of volume loss.

4.2. *Reservoir Deltas*

When a river enters a reservoir the velocity rapidly diminishes. Bed material transport stops and the coarsest fraction of the suspended load settles rapidly, creating a deltaic depositional pattern which begins at the upstream end of the reservoir and advances downstream. Gravels and cobbles may dominate delta deposits in steep mountain streams, but deltas may consist of fine sand and coarse silts in reservoirs impounding low-gradient streams. The downstream limit of the delta deposit is delimited by a change in grain size and also by its geomorphic expression as a slope change, although the characteristic delta shape is not always evident in reservoirs with limited bed material transport or wide variations in water level [16]. Delta deposits can be extensively reworked and coarse material moved further into the pool by reservoir drawdown or large floods. The topset slope of reservoir deltas is frequently about half the original channel slope [17]. Deltas can also advance upstream, raising backwater levels and causing deposition to occur above the maximum pool level.

An example of deltaic type deposition is illustrated in the sedimentation study of Peligre hydropower and irrigation reservoir in Haiti [18]. At this reservoir, the predominant grain size outside of the river channel is classed as silt based on sedimentation velocity in native water and without using a dispersant to deflocculate clays. Constructed in 1956, the reservoir had lost 50 % of its total capacity by 2008. The longitudinal pattern of sediment deposition is

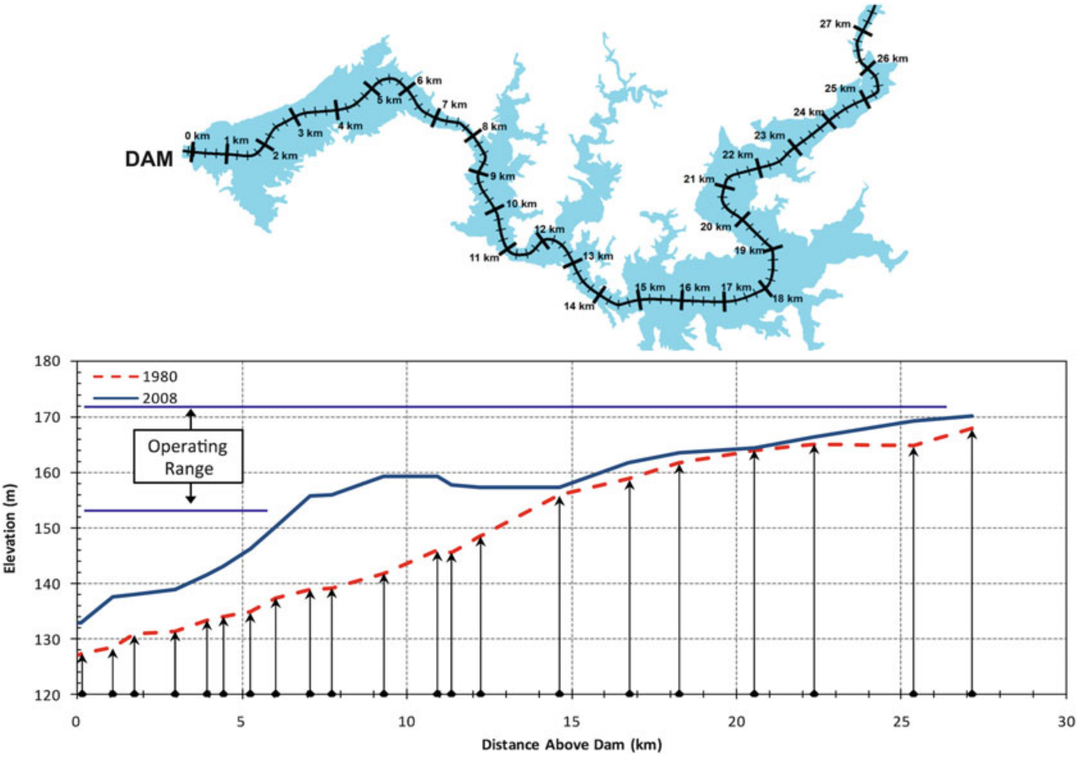


Fig. 5.4. Longitudinal profile of Peligre reservoir, Haiti, showing advance of delta-type deposition [18].

observed in Fig. 5.4, showing deposits advancing toward the dam, but the top of the delta deposit is well below the maximum pool level. A photograph of the reservoir bed during a seasonal drawdown (Fig. 5.5) shows the following: (1) seasonal utilization of exposed sediment for agriculture, (2) river channel meandering across seasonally submerged sediment deposits, and (3) focusing of sediment along the banks of the channel with less deposition along the margins of the reservoir. The concentration of sediment deposits along the main flow path, with less deposition in the reservoir branches, may also be observed in other heavily sedimented reservoirs.

4.3. Turbid Density Currents

In many reservoirs the coarse sediment which deposits into the delta comprises less than 10 % of the inflowing load, and most inflowing sediments consist of fines smaller than 0.062 mm (smaller than sand) which can be transported along the floor of the reservoir by turbid density currents. Turbidity currents are created by the density difference between the sediment-laden inflowing load and the clear water in the reservoir. Suspended sediment can easily create density differences much greater than those resulting from temperature differences, and the resulting gravity-driven current can carry sediment long distances along the

Fig. 5.5. Photograph of deposits in Peligre reservoir during seasonal drawdown for power production (photo: G. Morris).

bottom of the reservoir. For example, turbid density currents were documented to carry sediment-laden water 129 km along the bottom of Lake Mead prior to construction of Glen Canyon dam upstream [19]. Turbid density currents are particularly important in explaining both the mode of transport and the observed deposition patterns for fine sediment, and high-velocity turbidity currents can also redistribute fine sediment within reservoirs by scouring submerged material and transporting it closer to the dam. For example, scouring of submerged deposits by turbidity currents having velocities as high as 2.5 m/s has been documented at the Luzzone reservoir in Switzerland [20].

Several characteristics and indicators of turbid density currents are illustrated in Fig. 5.6. When turbid flow enters a reservoir and plunges this underflow pulls along with it part of the clear water impounded in the reservoir, thereby inducing a surface countercurrent of clear water at the plunge point. The downstream river flow and the induced upstream flow converge at the plunge point and floating debris carried into the reservoir will be trapped at this point of flow convergence. Floating material such as woody debris and logs can accumulate as massive debris dams blocking the entire width of the reservoir at the plunge point. Muddy surface water will be observed upstream of the plunge point, but surface water will be clear downstream of this point. The release of turbid water from low-level outlets, such as deep power intakes, while water on the surface of the reservoir at the dam remains clear, is a visual indicator that turbid density currents are reaching the dam. Another indicator is given by bathymetric data. If horizontal sediment beds extend upstream from the dam, this indicates that turbid currents are transporting a significant sediment load to the dam to create a

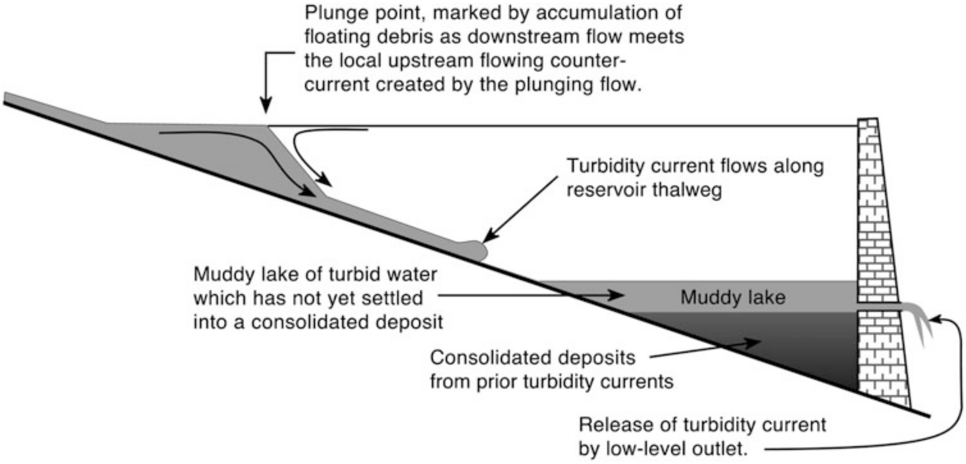


Fig. 5.6. Generalized pattern of turbidity current flow through a reservoir and accumulation as horizontal deposits extending upstream from the dam. Because of turbidity currents, it is not uncommon for muddy water to pass through low-level outlets although the surface water in the reservoir is clear.

submerged muddy lake from which the sediments have settled to create horizontal deposits (see Fig. 5.6). Turbid density currents can also be responsible for sedimentation near the dam even when the deposition pattern does not create horizontal beds. Turbid may not form if the reservoir is not deep enough or has insufficient concentration of fine sediment. In reservoirs with cold deep water, turbid inflows may be much warmer and lack sufficient suspended sediment to plunge beneath the cold bottom water. In this case, the turbid water may stay on the surface or may plunge only to the level of the thermocline separating warm surface water from deeper cold water.

The gravity-driven forward motion of the turbidity current creates turbulence which sustains sediment in suspension, but as sediment settles out the density difference and gravitational force driving the current diminish causing it to slow down. This allows more sediments to settle, further diminishing the density difference and the forces driving the current forward. By this means, the current may dissipate before reaching the dam while delivering sediment along the bottom of the reservoir. Sediment deposited by these currents as they flow along the reservoir thalweg infills the cross section from the bottom up to create flat-bottomed cross sections (Fig. 5.7). Flood discharge, suspended sediment grain size, and concentration all vary over the duration of a flood, and consequently turbid density currents are unsteady with respect to discharge, sediment concentration, grain size distribution, velocity, and thickness.

Turbidity current velocities vary with changes in both sediment concentration (density of the turbid flow) and bottom slope. The propagation of turbidity currents along the bottom of the reservoir is dependent on the submerged geometry, and their behavior can be greatly modified by changes in subsurface geometry through sedimentation or modification of sediment deposits by reservoir flushing or dredging. When the reservoir is newly impounded,

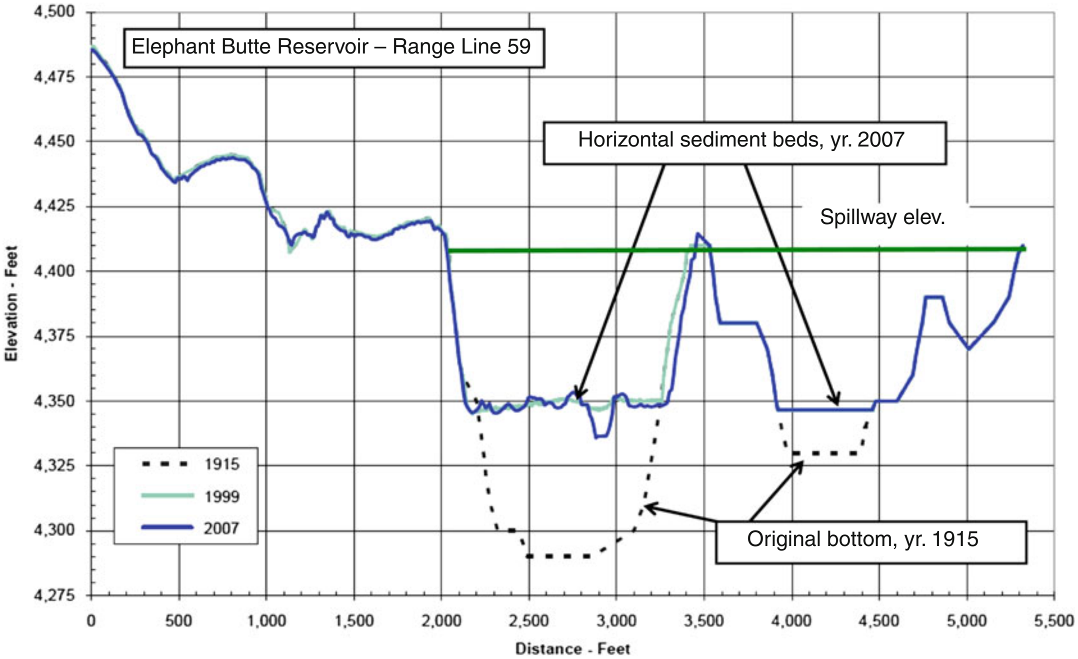


Fig. 5.7. Sediment deposited in horizontal beds in the bottom of Elephant Butte reservoir despite complex subsurface geometry [21].

the turbidity current can flow along the original river channel, producing a thick and compact current with a low wetted perimeter. However, as the original channel is filled, the reservoir bottom becomes wide and flat, and the turbidity current itself becomes wide and shallow, greatly increasing the frictional effects on both the top and bottom of the current, retarding its motion. This effect was noted as early as 1954 by Lane [22], who observed that turbidity currents reached Elephant Butte dam on the Río Grande in New Mexico during the initial years of impounding but thereafter dissipated before reaching the dam. Turbidity currents can also overflow submerged barriers such as a submerged cofferdam.

4.4. *Reservoir Volume Loss and Reservoir Half-Life*

The loss of reservoir volume by sedimentation can reduce water supply yield or flood control benefits. Sediment accumulation can also cause coarse sediment to be delivered to or clog intakes, obstruct navigational channels and access to marinas or other shoreside facilities, reduce recreational value, and modify reservoir ecology including loss of fish habitat and conversion of open water first into wetlands and then to uplands. When the reservoir is drawn down, fine sediment deposits dried and exposed to wind can produce noxious dust storms. Reservoirs with turbid density currents have experienced operational problems at intakes near the dam due to sedimentation after losing only a few percentage of their capacity. Because the original design purpose of the reservoir will become seriously affected once half the original

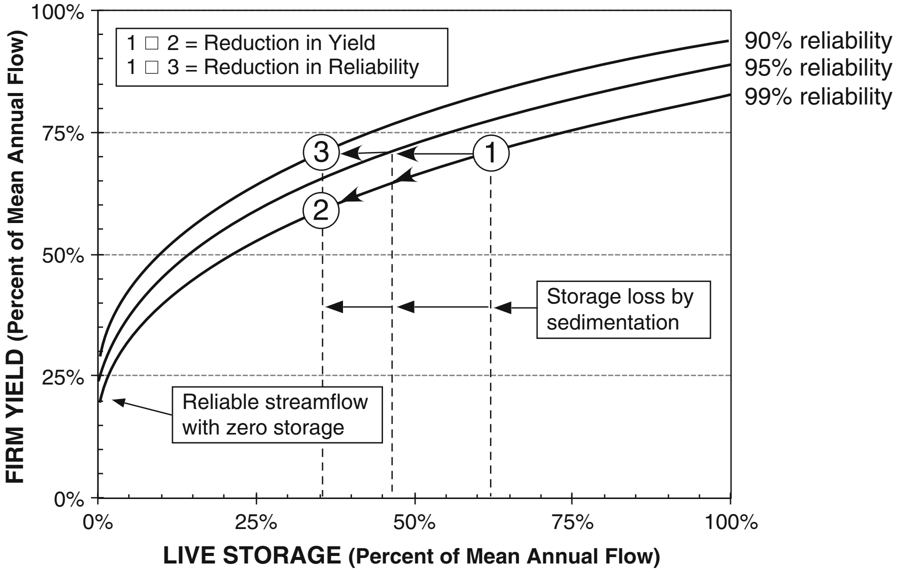


Fig. 5.8. Characteristic pattern of a reservoir storage-yield curve. Initial volume loss due to sedimentation has much less impact on firm yield than an equivalent volume loss when the reservoir capacity is diminished. Volume loss by sedimentation results in either a reduction in reliability, firm yield, or some combination of the two, depending on reservoir operation.

capacity is lost (if not much earlier), reservoir *half-life* (1/2 of original volume filled with sediment) is a much better indicator of the period of operational utility than is “reservoir life” based on 100 % storage loss.

Absent flow regulation by reservoirs, firm yield is limited to the natural minimum streamflow, which in arid regions may seasonally decline to zero. On a given stream, and at a given level of water supply reliability, an increase in storage volume will produce an increment in yield. The relationship between storage volume and water supply yield can be expressed by a storage–yield relationship. These curves exhibit diminishing marginal yield increments as reservoir volume increases, resulting in curves having the shape shown in Fig. 5.8. Reliability may be expressed as the percentage of days that the water supply is available at the stated yield. Different curves can be computed for different levels of reliability. As illustrated in Fig. 5.8, loss of storage by sedimentation will result in a decline in reliability if the normal withdrawal rate is sustained, or a reduction in firm yield if the withdrawal rate is reduced to sustain a given level of reliability. Reliability will also decline as climate variability increases, which adversely affects the ability of a given reservoir storage volume to either provide a sustained water supply yield or to provide the design level of flood control. Increased climatic variability will produce a new lower curve in Fig. 5.8, with diminished benefits at all storage volumes.

The impact of storage loss on reservoir function will vary widely from one site to another. High hydropower dams constructed primarily to produce hydraulic head may see little impairment until much of the storage volume has been lost, whereas at other sites functional impairment will occur much earlier. For instance, data reported by the US Army Corps of Engineers in 2010 revealed that in dams reporting operational impairment up to 10 % of the time due to sedimentation, 80 % of these had experienced less than a 25 % capacity loss [23]. In reservoirs with multiple uses, such as water supply, hydropower, and flood control, each use will be affected to a different degree by sedimentation. For example, because the flood control volume necessarily occupies the top portion of the reservoir pool which is normally empty, it will typically experience a low sedimentation rate, while more sediments will be deposited into the conservation pool. Pool reallocation will need to be performed at regular intervals if the impact of volume loss is to be apportioned equally among the different beneficial pools.

4.5. *Sedimentation Impacts Above Pool Elevation*

Delta deposits will cause flood levels to rise above the backwater profile computed in the absence of sedimentation, and sediment deposits can extend well upstream of the reservoir's normal pool level. This can produce upstream flooding and waterlogging of adjacent agricultural soils, bury upstream intakes and stream diversions beneath sediment, increase tailwater elevation at upstream hydropower plants, reduce freeboard beneath bridges affecting both flood hazard and navigational clearance, and promote avulsion of the upstream channel. Sedimentation of the main channel will also affect tributaries. In the case of Niobrara, Nebraska, for example, aggradation of the delta created by the sand-laden Niobrara River where it discharges into Lewis & Clark reservoir on the Missouri River increased flood levels to the extent that it became necessary to relocate the entire town to higher ground [24]. Recreational facilities and marinas in areas affected by delta deposition may become seriously affected very early in the sedimentation process.

4.6. *Sedimentation Impacts Below the Dam*

The river channel below the dam is impacted by elimination of the coarse suspended and bed material sediment supply due to trapping in the reservoir, and also by the diminished flood peaks which reduces sediment transport capacity below the dam. These factors tend to counteract one another. The first factor usually predominates, resulting in downstream channel incision and armoring. However, when a large reservoir greatly diminishes downstream transport capacity, and tributaries below the dam supply a heavy sediment load, the downstream channel can aggrade, as occurs along the Río Grande downstream of Elephant Butte reservoir in New Mexico [25]. The remainder of this section describes the more common situation, channel degradation.

Reservoirs trap virtually all coarse sediment, cutting off the supply of new bed material to the channel below the dam. Because discharges from the dam will continue to transport bed material downstream, and because smaller grains are transported at a higher rate than the larger material, the channel bed below the dam will progressively coarsen, incise, and may become armored. Armoring can reduce or eliminate habitat. Channel incision will accelerate bank failure and streambank erosion, and downcutting of the main channel can trigger incision of its tributaries due to the lowered base level. Hydropower peaking operations which produce large fluctuations in streamflow can further destabilize channel banks. These impacts are lessened by the reduction in peak discharges caused by flood detention in the impoundment, which occurs even in reservoirs not designed for flood control. Downstream impacts can extend from the dam to the sea and can affect coastal erosion. For example, a study in California [26] estimated 10 Mm^3/year of sand reached the coast prior to dam building, but dams on coastal rivers have reduced this by 23 %. The impacts are greatest in southern California where 50 % of the sand flux is now trapped by dams.

4.7. *Sedimentation Impact Thresholds*

Sedimentation impacts do not occur in a linear manner. Impacts to intakes, navigation, and recreational uses will typically have critical thresholds. While reservoir storage–yield relationships do not have specific thresholds, they are characterized by a nonlinear relationship as illustrated in Fig. 5.8. As reservoir capacity declines, the firm yield (or reliability at a fixed yield) also declines, but in a nonlinear manner, and the yield reduction per unit of storage loss (the yield elasticity) will increase as storage volume declines. When sedimentation is focused in the bottom of the reservoir, without reducing surface area, the surface-to-volume ratio will change thereby increasing the relative importance of evaporative losses, and in dry climates this can further increase the impact of sedimentation on yield loss [27]. While exact threshold values may be difficult to define, it is important to realize that thresholds do exist and to incorporate them into decision-making related to sediment management.

5. PREDICTING FUTURE CONDITIONS

Beneficial uses of reservoirs become increasingly constrained as sedimentation progresses, making it prudent to determine the time frame over which different beneficial uses may be impacted or when significant impact thresholds may be encountered. Sedimentation rates and future reservoir capacity may be predicted for individual reservoirs or at the regional or national level based on aggregate data.

5.1. *Reservoir Surveys to Measure Sedimentation*

Successive bathymetric reservoir surveys provide information on the historical rate and pattern of sediment accumulation at a reservoir, information needed to answer questions concerning the timing, characteristics, and magnitude of sedimentation impacts. Data from reservoir surveys are used to update the storage–elevation and storage–area relationships. Changes in the storage–elevation relationship over time will indicate the extent to which sedimentation affects different storage-dependent uses. These surveys also provide the data required to calibrate models to predict future sedimentation patterns and analyze management alternatives. Data on the volume of sediment trapped can also be used to estimate watershed sediment yield following correction for sediment bulk density and reservoir trap efficiency. Examples of bathymetric surveys and procedural guidelines can be downloaded from the US

Bureau of Reclamation website (http://www.usbr.gov/pmts/sediment/) and in Chap. 9 of the bureau's *Erosion and Sedimentation Manual* [28].

The interval between reservoir surveys should be established to track the rate and pattern of deposition, and at sites where the annual rate of storage loss is low the survey interval will be longer than at a reservoir with a high sedimentation rate or where deposition creates a significant problem. A survey interval corresponding to each 5–10 % increment in volume loss may be adequate, but more frequent surveys may be appropriate at critical sites and in smaller reservoirs following an extreme flood that transports a large sediment volume.

Volume surveys are subject to errors, especially when measurement techniques change. The pre-impoundment reservoir volume may have been computed from topographic mapping or by a photogrammetric survey biased by errors in estimating vegetation height. Cross-sectional surveys made during impounding may estimate volume from a very limited geometric dataset. Survey errors become evident when a detailed post-impoundment survey volume is larger than the initial volume, despite decades of impounding. Errors in the other direction can also occur but their detection is not so obvious. To minimize these problems, a detailed bathymetric survey should be performed soon after initial impounding to establish a baseline volume to be compared against future surveys.

Reservoir capacity surveys are best performed with the reservoir full using sonar connected to a GPS, mounted in a boat which then conducts multiple traverses to obtain the data density required to construct a contour map and compute capacity. If the reservoir is drawn down, part of the area may be traversed by vehicle or on foot or mapped by aerial methods such as LIDAR. In delta areas sediment can be deposited above the pool elevation, and it is important to survey the upstream delta growth to complement data from within the reservoir pool.

Large datasets can now be processed easily by computer, and the cost of the reservoir survey is primarily determined by the field data collection effort. Boat speed during bathymetric survey is normally limited to less than about 8 km/h, as higher velocities can induce cavitation on the sonar transducer and also increase the spacing of data points. At this speed, significant field effort will be required for complete mapping at large reservoirs, even when multi-beam sonar is used. Because sediment tends to accumulate in two areas, in the delta or along the submerged thalweg, once the depositional patterns are documented, the reconnaissance technique described by the US Bureau of Reclamation [15] can be used to remap large reservoirs, limiting data collection to those areas where most sediment accumulates. This technique requires prior survey data of the entire reservoir to confirm sediment deposition patterns and to plan the survey navigational tracks.

The range line method was used in older reservoir surveys, prior to the availability of automated GPS survey techniques. It continues to be used today in larger reservoirs when the budget does not allow the density of field data required for a contour survey or as a cost-effective method to monitor sedimentation rates at selected ranges. The range line method involves measurement of a series of representative cross sections and computing the volume change between adjacent range lines by formulas based on cross-sectional areas and surface area. Range line techniques are described by Strand and Pemberton [17] and by Morris and Fan [29]. As a word of caution, different survey methodologies and computational algorithms (pre-impounding vs. post-impounding, range line vs. contour) will produce different results. For example, a study of comparative measurement techniques at the Kremasta reservoir in Greece [30] found that at this site the range line method underestimated the volume of deposited sediment by 18–32 % as compared to a digital terrain model, depending on the number of range lines used. Different algorithms used to compute range line data also affect accuracy, and methods such as the surface area – average end area method [29] are expected to be more accurate than the end area method. When changing computational algorithms, or from range line to contour methods, computations from the same dataset should be made by both methods to document the volume change attributed to changed methodology. Small errors in volume estimate can produce very large errors in the estimated rate of volume loss by sedimentation.

5.2. Future Sedimentation Rate and Pattern

Future reservoir volume can be estimated by extrapolating the trend of volume depletion documented by successive reservoir surveys and incorporating any corrections as appropriate for the future compaction of fine sediment and change in trap efficiency as volume declines. However, the rate of sediment delivery to the reservoir is often not constant over time, being influenced by factors such as upstream dam construction plus changes in land use and climate. For proposed reservoirs, or existing reservoirs without survey data, future sedimentation rate must be predicted from secondary data. The rate of volume loss can be estimated from three parameters: sediment yield, sediment-trapping efficiency, and dry bulk density of the trapped sediment. These are each briefly described in subsequent sections.

Information on the future sediment deposition pattern will indicate the timing and severity of impacts to beneficial uses and reservoir infrastructure such as intakes. Prediction of depositional patterns is best performed by sediment transport modeling using tools such as the Bureau of Reclamation's SRH-1D model, the sediment transport component of the HEC-RAS model available from the US Army Corps of Engineers, or others. A sediment transport model requires, as a minimum, the following: initial pool geometry, a long-term inflow hydrograph, inflow sediment rating curve, sediment grain size distribution (hydraulic size of fines determined by sedimentation velocity), and the reservoir operating rule. When determining the grain size distribution of sediment containing clays, it is important to determine the sedimentation velocity using native water and without the aid of a deflocculant. Use of standard geotechnical laboratory techniques (deflocculant and distilled water) will determine the clay fraction of the sample, but not the true sedimentation velocity, since clays frequently experience flocculation in natural waters and may settle at velocities characteristic of silts. However, differentiation between silt and clay must be known for the purpose of evaluating cohesion in the sediment deposits and the potential for sediment compaction.

The empirical area-reduction method estimates the sedimentation pattern by predicting the future form of the elevation-volume curve. It is an approximate method to estimate the distribution of sediment within a reservoir based on the allocation of inflowing sediment at different depth increments within the reservoir [17]. It does not take into account the grain size distribution of the inflowing sediment and should not be used as the basis for design of a new reservoir. It is best used at existing reservoirs to project future conditions once the sediment distribution pattern has already been documented by bathymetric studies and when resources do not allow the use of modeling techniques.

5.3. Sediment Yield

Sediment yield is the mass of sediment delivered to a particular point in the stream network over a stated period of time and is always less than total erosion. Because there are relatively few long-term suspended sediment gaging stations, the long-term mean daily suspended sediment concentration or load is typically computed by a sediment rating equation which correlates either concentration or load to discharge. This empirical rating equation is derived from operation of a suspended sediment gage station for several years of representative flows. Given the importance of the rating equations in computing variations in suspended sediment discharge over time, and given the many potential sources of error, several concepts relating to collection and analysis of suspended sediment data are presented in this section.

Erosion refers to the process of soil detachment and initiation of particle motion. Erosion rates are measured on small plots, and these data are used to calibrate erosion models such as the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP) model. These models are then used to estimate erosion rates on larger land areas ranging from individual farms to entire catchments based on factors including soil type, soil slope, slope length, rainfall intensity, and type of soil cover or management treatment. The *sediment delivery ratio* expresses the ratio of sediment yield to erosion. Sediment yield is typically an order of magnitude less than the erosion rate because most soil particles are redeposited close to the point of dislodgement, at the base of the slope, in an aggrading channel, or on a floodplain, before exiting the catchment [31]. In practice, sediment yield is measured by gaging stations or reservoir surveys, but the erosion rate is estimated by modeling, and the sediment delivery ratio compares the modeled erosion rate to measured sediment yield. Erosion, sediment yield, and the sediment delivery ratio all vary greatly from one runoff event to another, and long-term average values obscure the wide variability that exits among the individual events. Floods are of primary interest in sedimentation management as they are responsible for much of the sediment delivery to reservoirs. Erosion models can be used to determine the erosion potential of different soil and land use combinations, thereby identifying areas to focus erosion control practices to yield the greatest benefit. However, lacking reliable methods to determine the sediment delivery ratio, erosion rates are of limited utility in estimating sediment yield [32, 33].

Sediment yield may be expressed in units of T/year, and the specific sediment yield per unit area may be expressed as T/km^2/year. Long-term sediment yield within a region may be best quantified by bathymetric surveys of reservoirs to document the cumulative sediment volume captured, following adjustment to account for trap efficiency and sediment bulk density. Reservoir data are particularly useful because reservoirs capture sediment from all events following dam closure, including extreme events which may be inadequately sampled or absent from gage station records.

Table 5.2
Factors evaluated in the PSIAC model [29]

Parameter	Characteristics considered
Geology	Durability and weathering of parent material
Soils	Erodibility and extent of soil cover
Climate	Rainfall intensity (storm types) and frequency of convective storms
Runoff	Runoff volume and peak discharge per unit of watershed area
Topography	Slope and extent of floodplain deposits
Ground cover	Extent of ground cover and soil litter
Land use	Percentage of disturbed land, especially row crops, overgrazing and fire
Upland erosion	Extent of rill, gully, and landside erosion
Channel erosion and sediment	Amount and frequency of channel bank erosion

To document timewise variations in sediment yield requires suspended sediment gaging and employing transport equations or empirical methods to correct for the unsampled bed load. It is important to insure the dataset includes adequate sampling of large events which are responsible for a disproportionate amount of sediment yield, since datasets lacking such events can seriously underreport yield. The potential for error is particularly large in mountainous watersheds and smaller watersheds where sediment delivery is dominated by large events of short duration and extreme events (e.g., hurricanes) may be difficult or impossible to sample accurately.

Sediment yield data are usually sparse, particularly in less developed areas, making it necessary to estimate yield by other techniques. In areas of low rainfall or Mediterranean-type climates, the PSIAC and similar methods which evaluate the factors responsible for the generation and delivery of sediment at the watershed scale (Table 5.2) have been found to give good indicators of sediment yield when evaluated across an entire watershed within a GIS framework. Application of this approach has been reported by several authors [34–38].

In analyzing sediment yield data it may be useful to prepare a plot of yield vs. drainage area from multiple sources within the same physiographic environment to help provide a range of reasonable sediment yield values (Fig. 5.9). Yield estimates which fall significantly outside of other regional values should be closely evaluated. Although it has been generally accepted that specific yield declines as watershed area increases [17], this is not always true. In plotting sediment yield data it should not be automatically assumed that specific yield will decrease as watershed area increases, as in some regions there is no clear relationship between these two parameters [38].

5.4. Climate Change and Sediment Yield

Long-term changes in sediment yield can occur due to construction of upstream dams; modification in soil cover resulting from land use changes; exhaustion of the supply of available sediment by soil denudation; climate change which can modify temperature,

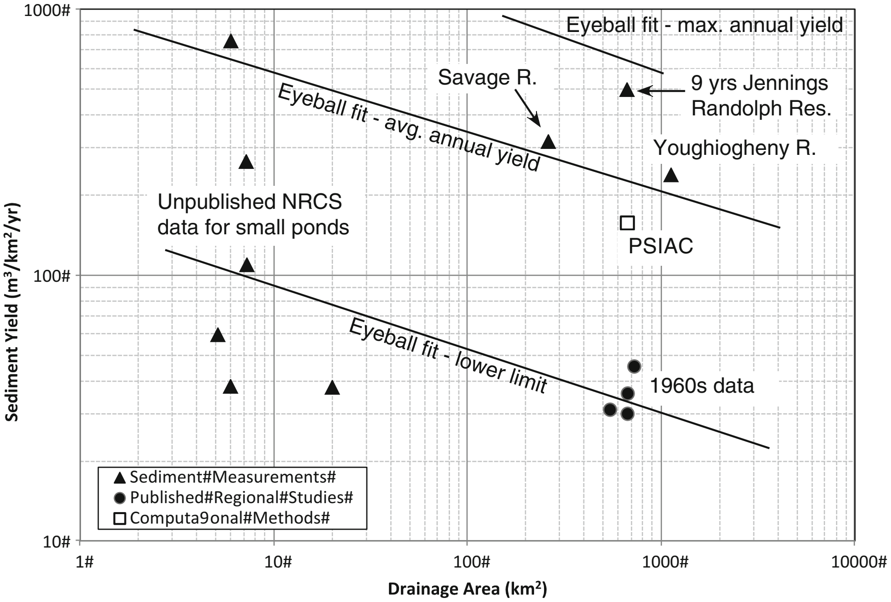


Fig. 5.9. Plotting data from multiple sources to better understand the range of estimates of sediment yield within a region. Redrawn from Burns and MacArthur [39].

precipitation, and evaporation and promote glacial retreat; and changes in erosional power from modification in rainfall intensity and runoff volume. The overall effects of climate change on sediment yield are complex, and it may be difficult to separate out climate effect from other factors. For example, increasing aridity of itself will reduce vegetative cover and make the soil more susceptible to erosion, but the reduced precipitation reduces runoff and thus sediment transport capacity, other factors remaining equal. However, a decrease in vegetative cover due to increased temperatures, coupled with increased rainstorm intensity, also related to climate warming, may significantly increase sediment yield. Walling [40] provides an overview of current knowledge on climate change and its potential impact on erosion and sediment transport by rivers. Evidence from around the world indicates that the principal factors affecting sediment yield have been land clearing, which increases sediment yield, and dam construction and flow abstraction which decreases yield, all modified by the impact of instream mining. Walling concluded that, "In most rivers, it is likely to prove difficult to disentangle the impacts of climate change or variability from changes resulting from other human impacts and existing evidence suggests that, in most cases, these human impacts are at present most likely to be more significant."

Erosion rates can change as a consequence of both climate and management techniques. For example, studies of the Midwestern USA indicate that a combination of increased precipitation coupled with a bias toward more intense storms, anticipated climatic trends already being observed, will increase both runoff volume and soil erosion [41]. About half of the increased precipitation is associated with the most intense 10 % of storms, causing both rainfall erosivity and erosion rate to increase more rapidly than total precipitation [42]. However, farmers are expected to respond to climate modification by changing cropping patterns and management techniques, which will itself effect erosion rates. Modeling studies for 11 regions within five Midwestern states of the USA by O'Neal and coworkers [43] took these factors into consideration and concluded that soil loss might increase by a factor ranging from 33 % to 274 % in ten of the regions and would decrease slightly in the eleventh. However, as pointed out by Walling [40], a relatively small percentage of the erosion may actually find its way into downstream reservoirs due to redeposition near the point of erosion, at the base of slopes, in upstream impoundments, in channels and wetlands, or on floodplains. Although it will be difficult to quantify future changes in sediment yield associated with climate change, the combination of climate change plus land use impacts from continued population increase is expected to sustain or increase sediment yields over time, especially in regions undergoing development and deforestation. Finally, it is worth noting that climate models generally agree that the climate will become more variable, with more intense floods and droughts. Reservoir storage exists to smooth out this hydrologic variability. An increase in hydrologic variability produces an impact on reservoir yield or flood protection similar to reducing storage volume and will further reduce reservoir benefits beyond that due to sedimentation alone.

5.5. *Reservoir Trap Efficiency*

Trap efficiency refers to the percentage of the inflowing sediment load retained within a reservoir. Trap efficiency varies greatly from one event to another. All sediment from a small inflow event may be captured, while a large inflow event producing a short hydraulic residence time in the reservoir may transport much of the finer sediment through the impoundment and beyond the dam with a low trap efficiency. The average long-term trap efficiency may be estimated from a reservoir's hydrologic size, expressed as ratio of total reservoir capacity to mean annual inflow (the capacity:inflow or C:I ratio), based on the empirical Brune relationship shown in Fig. 5.10 [44]. The three curves represent an envelope of conditions ranging from reservoirs having a lower average trap efficiency (reservoir emptied annually, slowly settling sediment) to reservoirs having a higher average trap efficiency (continuously impounding, coarser sediment inflow). A significant decline in trap efficiency does not occur until a reservoir's C:I ratio becomes quite small. The following equation can be used to plot the Brune curve for the case of "normal ponded reservoirs" [45]:

$$T_e = (R)/(0.012 + 1.02 \times R) \tag{5.2}$$

where T_e = trap efficiency and R = capacity:inflow ratio. Brune's curves should be used only for normally ponded reservoirs, not for floodwater-retarding structures, debris basins, semidry reservoirs, or reservoirs where sediment-release techniques are employed. Heinemann [46] modified Brune's relationship for smaller agricultural impoundments, using data for 20 normally ponded surface discharge reservoirs with catchment areas ranging from 0.8 to 36.3 km^2

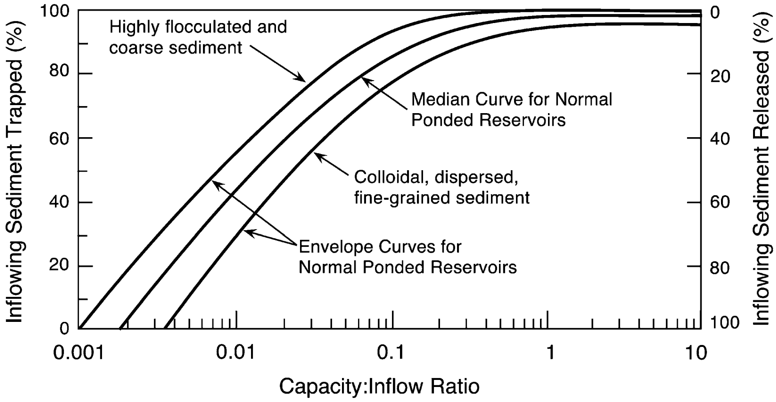


Fig. 5.10. Trap efficiency as a function of reservoir capacity:inflow ratio as proposed by Brune [44].

and volumes from 0.031 to 4.1 Mm^3. The Heinemann curve can be expressed by the following equation:

$$T_e = -22 + 119.6\,(R)/(0.012 + 1.02 \times (R)) \tag{5.3}$$

For this size range, his curve predicted a lower trap efficiency than the Brune relationship.

The Brune curve is widely used due to its limited data requirements. However, the best tool for examining sedimentation history and predicting future sedimentation behavior is by mathematical modeling. A properly validated model can simulate the contribution of each discharge event to the sedimentation process, as well as the sediment management benefits of alternative operational measures such as routing of sediment-laden floods through the reservoir.

5.6. *Sediment Bulk Density*

Dry weight per unit of submerged sediment volume may be termed either *specific weight* or *dry bulk density* (g/cm^3, T/m^3). To determine sediment yield from reservoir surveys it is necessary to convert sediment volume to sediment mass. This can be determined by analysis of sediment cores, being careful not to compact soft sediment during the sampling. Because sediment composition varies from one point to another in a reservoir, sampling should be spaced so each core represents a known fraction of the total deposit volume, to enable the volume-weighted dry bulk density to be computed. The volume-to-mass conversion can also be estimated by empirical methods. Lara and Pemberton [47] presented a method to compute initial bulk density, and the Lane and Koelzer [48] method adjusts for compaction of fine sediment over time. These methods are described in Morris and Fan [29] and Strand and Pemberton [17]. Representative values of bulk density are summarized in Table 5.3.

Table 5.3
Representative values specific weight for reservoir sediments in T/m^3 or g/cm^3

Dominant grain size	Always submerged	Aerated
Clay	0.64–0.96	0.96–1.28
Silt	0.88–1.20	1.20–1.36
Clay–silt mixture	0.64–1.04	1.04–1.36
Sand–silt mixture	1.20–1.52	1.52–1.76
Sand	1.36–1.60	1.36–1.60
Gravel	1.36–2.00	1.36–2.00
Poorly sorted sand and gravel	1.52–2.08	1.52–2.08

Source: Geiger [49].

5.7. *Preliminary Sedimentation Assessment for a Single Reservoir*

A preliminary assessment of sedimentation rate and potential future impacts can be undertaken by following the approach outlined below. This approach will help identify the types and timing of possible impacts, help determine when sedimentation will become problematic, and identify the appropriate data collection and management strategies.

1. Compile available bathymetric data, plot reservoir storage volume over time, and estimate annual rate of storage loss. Several surveys are required to reliably define the overall pattern of storage loss. Comparison of the reported pre-impoundment volume against a single bathymetric survey data point is not a reliable measure of sedimentation rate due to errors inherent in the use of two measurement methodologies.
2. Predict future rate of storage loss considering any variation in trap efficiency due to loss in reservoir volume or any upstream reservoir construction which may affect sediment yield.
3. Plot longitudinal thalweg profiles and superimpose the location of intakes or other critical structures. Also plot representative cross sections giving particular attention to locations near potentially affected infrastructure or properties.
4. A preliminary estimate of the shift in the stage-storage curve can be made by the empirical area-reduction method based on data from prior sedimentation surveys. Sediment transport modeling is recommended to achieve more reliable results.
5. Determine the extent to which beneficial users may be affected in the future. In a storage reservoir, for example, this would entail projecting future loss in firm yield based on storage–yield relationship or by simulation modeling of supply reliability or power production under scenarios of declining volume.

These data should provide the type of information needed to determine the nature and timetable of beneficial uses to be affected by sedimentation and form the basis for identifying and scheduling the next actions to be taken. Next actions may range from a continuation of reservoir surveys in the future to the execution of more detailed sustainability analysis to better define and address any sedimentation issues revealed by the preliminary assessment

Table 5.4
Corps of engineers reservoirs with operations reportedly affected by sedimentation, by authorized purpose [23]

Authorized use	Percent of reservoirs affected	Notes
Water supply	<10 %	Most of these in Tulsa District
Fisheries	10 %	Most in Tulsa and Omaha Districts
Navigation	2 %	1/3 of reservoirs are authorized for navigation
Hydropower	2 %	
Recreation	15 %	
Flood control	11 %	
Water quality	6 %	Over half of these in Tulsa District

5.8. *Regional Analysis*

A national, regional, or institution-wide analysis of sedimentation at multiple reservoirs can help determine the extent of existing problems and identify priority sites for sediment management. However, regional analysis is often constrained by sparse sedimentation data, and the available data may be geographically scattered and in inconsistent reporting formats. Two strategies may be used to assess and prioritize regional sedimentation issues: data-call and regional sediment balance model.

Data-call. The data-call method consists of querying each dam operator for information on sedimentation data and to identify existing or anticipated sediment-related problems. This approach was used by the US Army Corps of Engineers [23] to compile sedimentation information on the 609 dams under corps jurisdiction nationwide. It revealed that less than 5 % of their reservoirs had lost more than 25 % of their capacity by sedimentation. Nevertheless, a significant percentage of the sites reported one or more authorized purposes were experiencing "moderate" restrictions due to sedimentation, defined as "sedimentation limits a specific purpose up to 10 % of the time" (see Table 5.4). Not all reservoirs are authorized for all types of use, and some reservoirs report impacts in multiple authorized uses. Data collected will feed into a larger national database hosted by the USGS which contains data on over 6,000 sites [50].

Data-call results may be biased by differences in data availability and by differing interpretations and levels of interest by the respondents. The data-call approach can also include questions about problems which may exist below the dam resulting from cutoff of the sediment supply, although these may be of less concern to dam operators. A serious deficiency in the data-call approach is the nonuniformity of response quality.

Regional reservoir sediment balances. Many watersheds have multiple dams, and sediment accumulation is affected both by sediment trapping in upstream dams plus the change in trap efficiency over time as each impoundment loses storage. To obtain an accurate regional

Table 5.5
Cumulative loss of existing reservoir volume computed by alternative methodologies (adapted from Minear and Kondolf, 51)

Methodology to estimate sedimentation	Cumulative percent storage loss	
	Year 2000	Year 2100
Using total basin area and 100 % trap efficiency	16 %	70 %
Correcting for trap efficiency and upstream dams	4 %	15 %

picture of long-term sedimentation impacts and trends requires evaluation of these parameters for all reservoirs within the studied watersheds. For example, California's state database lists 57 dams above Folsom Dam on the American River, and to predict future sedimentation at Folsom requires that all of these upstream sites be considered.

A spreadsheet model for prediction of sedimentation rates at all reservoirs within a region considering these factors was described by Minear and Kondolf [51], who analyzed 1,382 reservoirs in California. This methodology requires the following: (1) estimates of specific sediment yield by physiographic region; (2) location of each reservoir and its watershed limits overlain on the physiographic regions to estimate sediment load from the unregulated watershed above each dam; (3) hierarchy of reservoirs within each watershed and construction dates and volume for each site to account for changes in sediment trapping over time; and (4) a procedure to estimate sediment-trapping efficiency at each reservoir, since trap efficiency declines as reservoir capacity diminishes. A GIS database which locates each dam on a digital elevation map with an overlay for physiographic regions was used to facilitate computation of watershed areas and sediment loads. Brown's equation was used to estimate trap efficiency based on watershed area:

$$T_{a,t} = 1 - 1/[1 + 0.00021 \times K_{a,t-1}/A] \tag{5.4}$$

where $T_{a,t}$ = decimal trap efficiency of reservoir a at time step t, A = watershed area, and $K_{a,t-1}$ is capacity or reservoir a at time step $t-1$. The Brune relationship based on the capacity:inflow ratio could not be used because data on mean annual inflow were not available at about 80 % of the sites. The results of this analysis (Table 5.5) showed the critical importance of accounting for both trap efficiency and upstream dams when assessing long-term sedimentation impacts.

6. CLASSIFICATION OF SEDIMENT MANAGEMENT STRATEGIES

Strategies for sediment management in reservoirs may be broadly classified as follows: (1) methods to reduce sediment inflow from upstream, (2) methods to pass sediment through or around the impoundment to minimize sediment trapping, and (3) methods to recover, increase, or reallocate storage or to modify intakes or other structures, after sediment has been deposited. Specific techniques available under each strategy are shown in Fig. 5.11 and

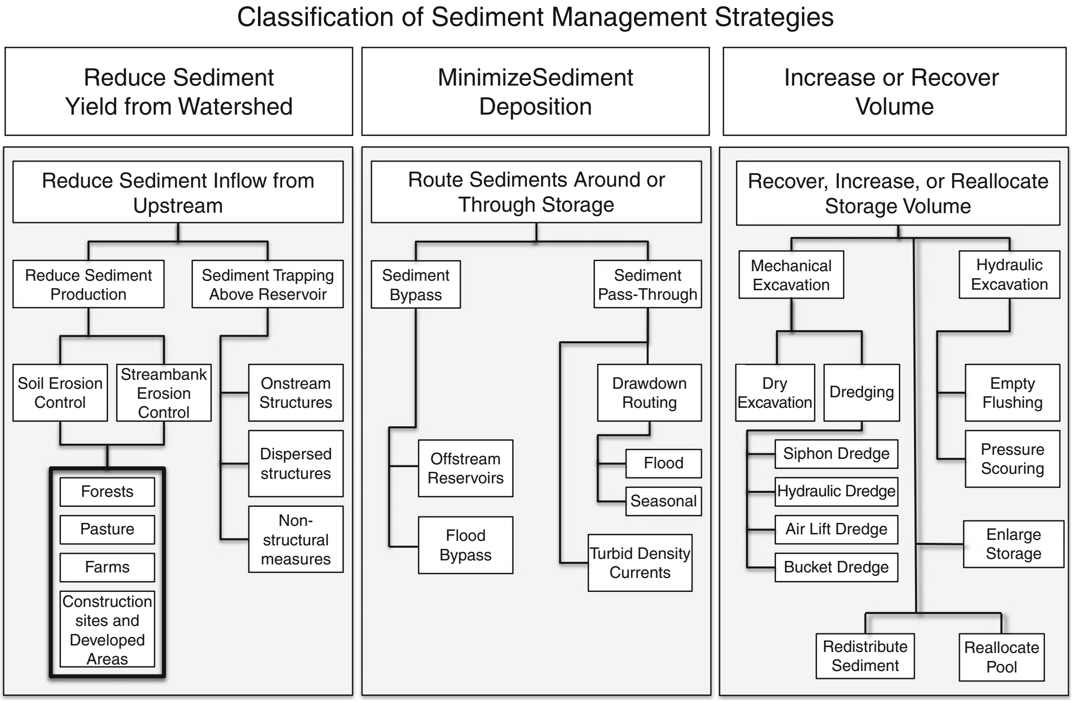


Fig. 5.11. Classification of sediment management alternatives.

Table 5.6. These can be used as a preliminary checklist to confirm that the gamut of control strategies has been considered. Some authors have classified management techniques based on management location rather than process [52, 53]. A combination of management strategies will typically be employed, and the techniques suitable for implementation will change over time. For example, the venting of turbidity currents may be the only feasible technique to pass sediment through a hydrologically large reservoir, but this method may no longer work and other routing approaches become feasible when reservoir volume has been diminished by sedimentation. A long-term sediment management strategy may consist of a sequence of different techniques to be applied sequentially as volume diminishes.

7. REDUCE SEDIMENT INFLOW FROM UPSTREAM

All watersheds export sediment, but the natural sediment yield can be greatly accelerated by land use changes which remove vegetative cover, destroy soil structure, concentrate the hydraulic energy of flowing water, initiate stream incision, and accelerate streambank erosion. For example, isotope analysis of sediment deposits in a Mississippi oxbow lake documented a 50-fold increase in sediment yield initiated by land clearing in the late nineteenth century and sustained to the present day [54]. In developing areas, land use often changes after dam construction as extension of the road network enables farmers to

Table 5.6
Classification of sediment management strategies

Strategy	Description
Reduce sediment inflow from upstream	• *Erosion control* to reduce sediment yield • *Upstream trapping* of eroded sediment in structures ranging from small check dams and farm ponds to major reservoirs
Route sediments around or through storage	• *Bypass sediment*, sediment is passed around the storage zone, for example, by constructing an offstream reservoir or sediment bypass tunnel • *Sediment pass-through*, routing sediment through the impounded reach by venting turbidity currents or reservoir drawdown. The lowered water level accelerates flow velocity, transporting sediment beyond the dam
Recover, increase, or reallocate storage volume	• *Flushing*, use hydraulic action to scour out previously deposited sediment. Flushing requires full reservoir drawdown to be effective. Pressure scouring occurs with water ponded in the reservoir and only removes a scour cone in front of the flushing outlet • *Dredging*, removal of sediment from underwater by mechanical means • *Dry excavation*, removal of sediment from an empty reservoir by conventional earthmoving equipment • *Increase storage* by raising the dam or constructing additional storage reservoirs • *Modify structures*, modify intakes or other structures to avoid areas of sediment deposit • *Redistribute sediments*, manipulate water levels to deposit sediment in areas of the pool where impacts are reduced • *Reallocate available storage*, distribute sedimentation impacts among the beneficial uses to maximize the utility of the remaining volume

move into previously unpopulated areas above the dam, producing rates of erosion and sediment yield much higher than originally anticipated. Two broad strategies can be used to reduce the sediment load reaching a reservoir: reduce the erosion rate from the land surface or stream channels, or provide upstream storage to trap eroded sediment.

7.1. Reduce Sediment Production

Soils are held in place primarily by vegetation and the associated soil ecosystem, and the principal objective in the control of soil erosion is to maximize vegetation coverage. Vegetation and leaf litter physically protect soil from the direct impact of raindrops which can dislodge particles from the soil matrix. Organic materials produced by fungi and bacteria in the soil ecosystem act as a binding agent that causes fine particles to agglomerate, thereby resisting dislodgement and retaining soil structure which enhances infiltration. Roots, worms,

Table 5.7
Median erosion rates as function of land use, Río Guadiana Basin, Puerto Rico (modified from ref. 54)

Land use	Median erosion rate, T/km^2/year	Percent of surface area in the watershed	Percent of total erosion
Bare soil	53,400	0.6	21
Dense urban (impervious)	100	1.7	0.1
Rural residential	1,500	9.4	9.2
Agriculture	2,200	0.3	0.4
Pasture	1,700	16.6	18
Open canopy forest	2,600	14.5	25
Closed canopy forest	700	56.9	26

Note: Forests occupy lands having higher slopes.

and burrowing insects all loosen the soil, enhancing infiltration and reducing erosive overland flow. Vegetation, soil litter such as leaves and twigs, and minor soil surface irregularities all retard the velocity of surface flow, reducing erosive energy and trapping sediment eroded from upslope. Interventions which disrupt or destroy these natural processes at and beneath the soil surface can accelerate soil erosion rates by two orders of magnitude, as illustrated by the data in Table 5.7 from a 22 km^2 moist mountainous tropical watershed. Modeling showed that conversion of 5 % of the most-erosive land use to forest would produce a 20 % reduction in erosion rate. The average sediment delivery ratio in this watershed was computed as 17 % [55].

Soil erosion control is typically recommended to control reservoir sedimentation. Erosion control success depends on identifying the areas of accelerated soil loss, implementing effective erosion control measures, and then sustaining these controls or land use changes indefinitely. Nevertheless, some areas have experienced sustained high rates of sediment yield despite substantial reductions in soil erosion. In practice, a significant reduction in sediment yield may not be seen in a river system for years or decades following erosion control treatment because much eroded sediment will become trapped at the base of slopes as colluvial fill or may accumulate in channel bars or on floodplains, creating a large reservoir of sediment to be transported downstream for many years after soil erosion is reduced at the source [56, 57]. This should not be interpreted to minimize the long-term benefits of erosion control, which also include enhanced soil fertility and moisture retention, environmental recovery, and other benefits which exist independent of reservoirs. Rather, it is to point out that while erosion control is an excellent long-term strategy, it will not necessarily produce an immediate and measurable reduction in sediment yield.

Erosion modeling in a GIS environment can be used to determine erosion rates for the purpose of focusing erosion control efforts and to better understand the possible sources of sediment entering a reservoir. For example, the European Environment Agency applied the Revised Universal Soil Loss Equation (RUSLE) to the entire Alpine area, including parts of

6 different countries, to estimate soil erosion rates on a 100 m grid, mapping soil erosion rates in eight classes from <50 to >5,000 T/km^2/year [58]. Modeling can also be used to estimate the benefits of management measures.

In agricultural areas, erosion control strategies can include minimizing soil disturbance (no-till), maximizing soil cover by vegetation and mulch, sediment trapping by vegetated buffer strips, management of runoff water with grassed waterways, and construction of farm ponds. In general, maximize vegetation and mulch coverage while keeping runoff flows as dispersed as possible, thereby maximizing the potential for infiltration and reducing the erosive energy of concentrated flows. Vegetated swales and hardened structures can be used to carry concentrated flows across slopes without gullying. In promoting the implementation of erosion control measures by farmers, it is essential that they see on-farm benefits from soil conservation activities; otherwise, these activities will not be self-sustaining. On-farm benefits may include enhanced infiltration and retention of water leading to higher yield and income, reduced fertilizer inputs, etc. Effective erosion control typically requires effective and sustained intervention with hundreds to thousands of landowners and users, an undertaking not likely to be successful absent a strong organizational presence. For example, in the USA, the Natural Resource Conservation Service and local soil and water conservation districts provide both technical services and directed incentives to land users. There is an abundance of literature and technical guidance concerning soil erosion and its mitigation on agricultural soils available from the US Natural Resources Conservation Service website (http://www.nrcs.usda.gov/), the Soil and Water Conservation Society (http://www.swcs.org), and many other organizations.

In forested areas a dense network of roads and skid trails may be constructed for logging. Erosion and slope failures associated with the construction and use of unpaved roads are typically the most important long-term contributors of sediment from logged areas. After logging ends these roads may fall into disrepair while simultaneously experiencing increased traffic for which they were not originally constructed. For example, the US Forest Service has more kilometers of roads than the US Interstate Highway System and has seen use of its forest roads increase 18-fold over 50 years, and timber harvest now accounts for only 0.5 % of forest road use [59]. Whereas sediment yield from the forest floor can quickly diminish after logging, road erosion will remain as a long-term source of sediment which can potentially increase over time, especially if hydraulic structures fall into disrepair. The US Forest Service's Treesearch online library (http://www.treesearch.fs.fed.us/) has an extensive research library relating to sediment yield and erosion control, and numerous region-specific best management practice (BMP) guidelines for timber harvesting, logging roads, and related topics are available on the Internet from local extension services and national forestry services.

Urban development will dramatically increase onsite erosion and sediment yield as vegetation is removed and earth movement destroys soil structure and exposes destabilized soils to erosive energy. However, sediment yield declines dramatically after construction is completed, as soils become vegetated or covered with impervious surfaces, and drainage is routed through hard structures. For example, Warrick and Rubin [60] analyzed 34 years of data from the semiarid Santa Ana River watershed in California and found that conversion to urban land use produced a 20-fold reduction in suspended sediment concentration with respect to discharge and a sixfold increase in discharge. However, when the increased peak discharge reaches a downstream natural channel, the increased erosive energy will accelerate channel incision and bank erosion. Thus, urbanization moves the problem of accelerated erosion into the channels downstream of the impervious areas. Urban erosion control typically focuses on implementing best management practices (BMPs) for erosion control on construction sites through combined local and federal regulatory frameworks.

Urban stormwater detention basins have been used to compensate for the increase in peak discharge due to impervious surfaces, but these structures have traditionally focused on treating only the larger and more infrequent “design storms,” while the smaller and frequent events responsible for the great majority of runoff pass through the basins with little attenuation. The current emphasis in the management of post-construction runoff from urban areas is to mimic, insofar as possible, pre-construction hydrologic behavior. This strategy of Low Impact Development (LID) focuses on maximizing opportunities for evaporating, detaining, and infiltrating water, trapping sediment and other contaminants as far upstream as possible within the catchment and before entering drainage structures with concentrated high-velocity flow. This is reminiscent of the 1930s motto of the Civilian Conservation Corps: “Stop the water where it falls.” Online documentation and links are available from the Low Impact Development Center (http://www.lowimpactdevelopment.org).

Alluvial stream channels naturally meander across their floodplain, eroding the exterior of channel bends while simultaneously depositing sediment on point bars located opposite the eroding banks. However, natural streambank erosion rates may be greatly accelerated as a result of human intervention and become an important contributor to increased sediment yield. Causes of accelerated channel erosion include increased peak runoff due to upstream deforestation, overgrazing, and urbanization; removal of streambank vegetation; channel straightening which increases channel slope and erosion rate; and channel incision induced by activities such as upstream dam construction or removal of channel sediment by instream aggregate mining. In built-up environments, even natural stream meandering is usually the object of control since any lateral movement will quickly threaten property and infrastructure. Traditional approaches for the treatment of bank erosion have focused on the extensive use of rip rap. A more environmentally sustainable and potentially less costly channel management approach focuses on developing an understanding of the geomorphically stable stream form, and to establish this form along the stream channel, rather than using patch-in-place channel bank hardening which can itself contribute to further stream destabilization [61]. More comprehensive information is given in the Stream Restoration Design Handbook compiled by the US Natural Resources Conservation Service which incorporates inputs from multiple federal agencies and the private sector and is available on the Internet [62].

In summary, several factors are critical to successfully reduce sediment yield from an impacted watershed.

- *High erosion areas*. Identify priority areas or priority land uses to be treated. Determine the types of soils and corresponding land use practices which create high rates of erosion over sufficient land surface to significantly influence sediment yield and which can be expected to be amenable to treatment. In unstable streams, identify treatment strategies which lead to long-term channel stability.

- *High sediment delivery ratio*. Focus treatments on areas which have the highest potential to deliver sediment to the reservoir. While it is difficult to assess the sediment delivery ratio, the following factors will tend to increase the delivery ratio from a catchment: close proximity to the reservoir, high soil and channel slopes, small alluvial floodplains or wetlands to trap sediment, mostly fine sediment, few farm ponds or other impoundments, high drainage density, and gullying.
- *Sustained community participation*. Identify erosion control practices suitable to the local technical, economic, and institutional environment, and which can be expected to be sustained because they generate visible benefits to the local community. Identify and partner with local grassroots organizations or institutions having presence and credibility within the watershed. Reduction of erosion and sediment production within a watershed can generate substantial and sustained benefits to many members of the community including farmers who retain their soil, recreational users who have cleaner water, and environmentalists.

Although land use changes are not easy to achieve, the benefits can be both broad based and long lasting. The realization of tangible benefit by the local community is essential for both initiating and sustaining changed land use practices.

7.2. *Sediment Trapping Above the Reservoir*

Sediment inflow into a reservoir can be reduced by the construction of upstream sediment-trapping storage facilities. It is relatively rare to construct an upstream reservoir for the sole purpose of trapping sediment, other than the construction of debris basins designed to trap coarse sediment that would otherwise collect in and impair the operation of a downstream flood channel. However, upstream impoundments of all sizes can act as efficient sediment-trapping structures, and the presence of upstream dams is one of the most important factors modifying sediment loads downstream. In considering the effect of upstream dams, not only are large dams important, but numerous small structures, including those as small as stock watering ponds, can also act as efficient sediment taps. For example, in the conterminous USA, Renwick et al. [63] estimated that there are at least 2.6 million, and possibly as many as 8 or 9 million, small impoundments capturing runoff from about 21 % of the total drainage area in the lower 48 states. Total sediment capture in these ponds was estimated to equal between 25 % and 100 % of the total sedimentation in the 43,000 reservoirs listed in the U. S. National Inventory of Dams.

8. ROUTE SEDIMENTS

Sediment discharge is highly concentrated in time, and *sediment routing* refers to a family of techniques that take advantage of this timewise variation in sediment discharge, managing flows during periods of highest sediment yield to minimize sediment trapping in the reservoir. These strategies include the following: (1) selectively diverting clear water to an offstream impoundment and excluding sediment-laden flood flows, (2) sediment bypass around an onstream reservoir, (3) reservoir drawdown to pass sediment-laden floods through the impoundment at a high velocity to minimize deposition, and (4) release of turbid density currents through a bottom outlet. In all cases, the objective is to release sediment-laden water and impound clear water.

8.1. Timewise Variation in Sediment Yield

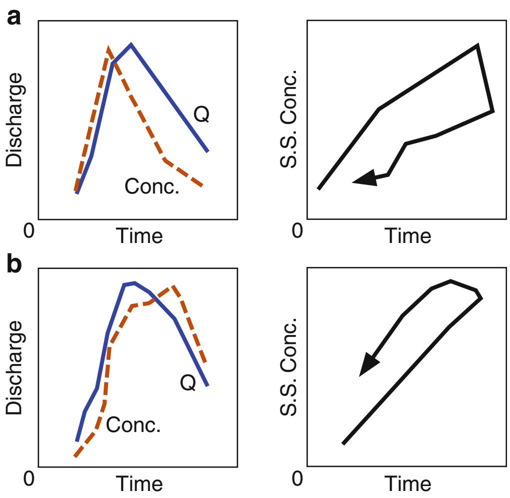
Sediment yield is highly variable over all time frames. It is necessary to understand this variability to properly interpret sediment data and devise efficient management strategies. These strategies take advantage of the timewise variation in suspended sediment concentration to capture and impound flows having relatively low suspended load while passing high-concentration flows through or around the impoundment.

Most sediment is transported by floods, and the intervening period of normal or low flows typically transports relatively little sediment. Using data from the USA, Meade and Parker [64] showed that for many rivers in the USA about two percent of the days account for about half the annual sediment load. In smaller watersheds and mountainous areas sediment discharge can be even more concentrated in time. Because so much sediment can be discharged by large floods, sediment yield can vary dramatically from year to year, reflecting variation in hydrologic conditions and timewise variations in sediment availability within the watershed. In mountainous areas landslides can contribute over half the sediment load during extreme events, and the onset of widespread landslide activity may be associated with an intensity-duration threshold [65]. In mountainous watersheds the role of extreme events can be particularly important, and a single catastrophically large event can generate sediment loads, including debris flows, equivalent to many decades of "normal" events. Such events may not be reflected even in decades of gage record [66].

The finer fraction of the total sediment load, the *wash load*, consists of sediment smaller than the smallest 10 % contained in the stream bed material. This finer material is "washed" through the system without appreciable interaction with the stream bed because the hydraulic energy is large enough to transport all the fine sediment delivered to the stream. It is delivered to the stream primarily by soil erosion in the watershed, and delivery rate to the stream is dependent on rainfall-runoff processes. However, transport of the coarser material that composes the predominate fraction of the stream bed, the *bed material load*, is driven primarily by stream hydraulics rather than the delivery rate from the watershed. Thus, in a sand or gravel bed stream, a storm early in the flood season may have a high total suspended load with a high component of fine wash load, while a late-season storm having the same discharge may have a much lower suspended sediment concentration of fines, while the rate of bed material transport remains unaltered. The late-season suspended sediment yield from watershed erosion may be reduced by factors such as increased ground cover as vegetative grows, plus the seasonal exhaustion of readily mobilized sediment. Where a consistent timewise sediment delivery pattern exists, it may be possible to route sediment-laden water through or around the reservoir at the start of the season and to fill the reservoir with late-season discharge having a lower sediment concentration.

Suspended sediment concentration will also typically exhibit a systematic variation within the duration of a single runoff event, producing hysteresis effects in concentration–discharge

Fig. 5.12. Conceptual hysteresis loop in concentration–discharge data from flood events showing (**a**) clockwise loop with the concentration preceding the discharge peak and (**b**) counterclockwise loop.



(C–Q) graphs. If multiple samples are collected over the duration of a flood event, a graph of sediment concentration vs. discharge rarely produces a straight line relationship [67]. The more common pattern is for sediment concentration to peak before discharge peaks, producing a clockwise concentration–discharge (C–Q) hysteresis loop (Fig. 5.12). This can occur when the first part of the flood washes out readily mobilized sediment, leaving the latter portion of the hydrograph relatively deficient in sediment. Counterclockwise loops can occur when more distant areas of the watershed have more erodible soils or when landslides develop as soils become oversaturated as the storm progresses. The hysteresis pattern is not necessarily a fixed watershed characteristic, and different storms can produce different timewise patterns in the same watershed.

8.2. *Sediment Rating Relationships*

Sediment yield can be measured by suspended sediment gaging stations operated for a sufficient number of years to obtain suspended sediment concentration and discharge data over a wide range of flows. These data may be used to define a *sediment rating curve* which correlates discharge to suspended sediment concentration, and by applying this rating curve to a longer streamflow record, the sediment discharge may be estimated over the entire period of stream gage record. It is critical that floods be adequately sampled because they have both high sediment concentration and flow rates, and thus discharge a disproportionate amount of the total load. Bed load is infrequently measured and is instead computed by a transport equation or estimated as a fixed percentage of suspended load.

Sediment rating relationships are characteristically developed as a power function having the form

$$\mathrm{SSC} = bQ^{c} \tag{5.5}$$

where SSC = concentration (mg/L), Q = discharge (m^3/s), b = coefficient value, and c = exponent which is often in the vicinity of 1.5. While this equation implies an intercept of zero concentration at zero discharge, use of a nonzero intercept may be appropriate in some datasets to better represent the flow range of interest.

There is typically considerable scatter in a graph of sediment concentration vs. discharge due to variations in watershed and sediment delivery processes over time, and it is quite common for sediment concentration to vary by more than an order of magnitude at a given discharge. Horowitz [68] noted that “The key to a good rating-curve-derived flux estimate appears to be how well the regression averages out the ‘scatter’ in the data, rather than how well the curve actually fits all the data points.” When a regression equation is used to fit a curve to the logged discharge and concentration data, the resulting regression can underestimate the true rating curve by as much as 50 % [69, 70]. Comparative analysis of data from Europe by Asselman [70] indicates that curve fitting by nonlinear least squares produces the best overall fit. To check that the rating curve accurately averages out the scatter, perform a period-of-record *total load comparison* in which the total sediment load computed by the rating equation is compared to the measured total load in the original sediment dataset. The rating equation should be adjusted if these two loads do not match closely. Considerations for constructing rating curves are discussed by Glysson [71].

When analyzing reservoir management techniques such as sediment bypass, in which only the lower-discharge events are diverted into the reservoir, it is critical that the rating curve reflect as accurately as possible the concentration–discharge relationship for the range of flows to be diverted. An equation that reproduces the total load in the original dataset will not necessarily produce an unbiased fit over the range of flows that contribute most of the diverted water volume. To protect against this error, a total load comparison (computed vs. dataset load) should be performed over discrete discharge intervals to insure against rating equation bias in any critical flow range (Fig. 5.13). Similarly, the rating curve may produce concentrations too high when extrapolated to large discharges beyond the range of the original dataset. In these cases, it is appropriate to use a multisegment rating curve incorporating more than one equation, as also shown in Fig. 5.13. Manual preparation and adjustment of rating curves should be performed to achieve a good overall fit to the data when mathematical equations do not adequately represent the dataset.

8.3. Sediment Bypass by Offstream Reservoir

Sediment bypass may be accomplished by constructing an *offstream* or *off-channel reservoir*, diverting water having low sediment concentration into storage by either gravity or pumping while allowing large sediment-laden floods to bypass the storage pool (Fig. 5.14). Water supply reservoirs fed by gravity have been constructed specifically for sediment management in Taiwan [72] and Puerto Rico [73]. Offstream reservoirs provide other benefits in addition to sediment control. Exclusion of floods greatly diminishes spillway size, offsetting the cost of the intake and diversion works. Offstream reservoirs also avoid environmental problems associated with the construction of onstream dams by minimizing impacts to aquatic species and riparian wetlands, by maintaining the transport of bed material along

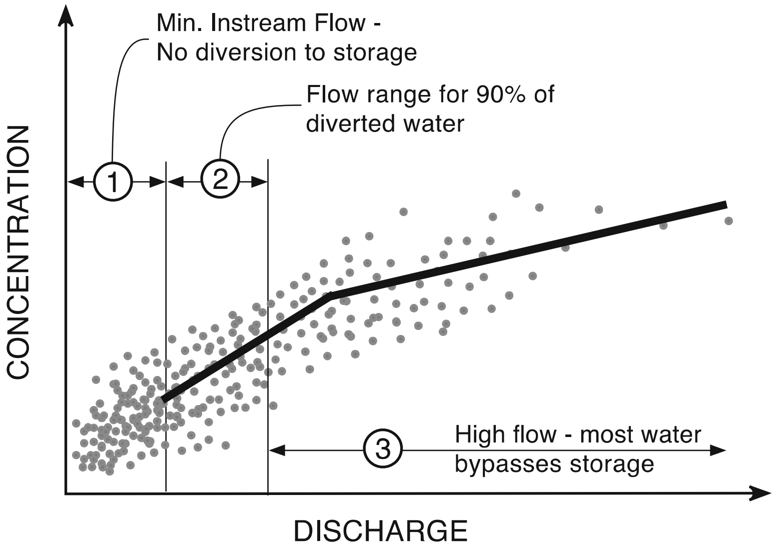


Fig. 5.13. Conceptual diagram showing adjustments in a sediment rating curve to produce an unbiased estimate of the discharge–concentration relationship for the ranges of flows to be diverted into off-channel storage. In computations for sediment bypass, it is critical to insure that the rating curve accurately reflects sediment concentration in the flow range "2" which contributes most of the diverted water and sediment inflow into the impoundment.

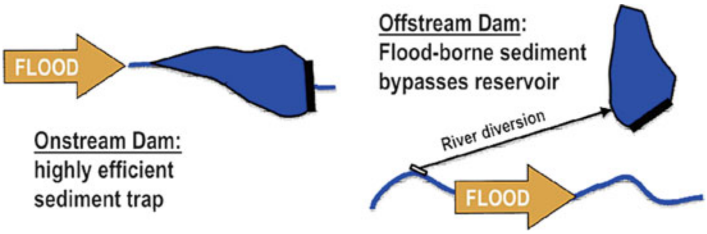


Fig. 5.14. Schematic of offstream reservoir supplied by a diversion dam, which allows sediment-laden floodwaters and bed material load to continue downstream without entering the impoundment.

the natural stream channel, and it also improves the quality of water delivered to users such as hydropower and water filtration plants. The ability to sustain bed material transport along the stream is particularly important as it avoids the problem of channel incision, accelerated bank erosion, and riverine habitat loss that plagues river reaches below instream dams.

Sediment enters an offstream reservoir either as suspended inflow from the diverted stream or by erosion from the watershed tributary to the dam. Simulations for the gravity-fed Río Fajardo offstream reservoir in Puerto Rico showed that 26 % of the total streamflow can be diverted into the reservoir with only 6 % of the suspended sediment load. Additionally, the intake design excludes 100 % of the bed material load. However, sediment eroding from the small watershed tributary to the dam will be trapped with essentially 100 % efficiency, since the reservoir is operated to avoid spills. For this reason, in developing

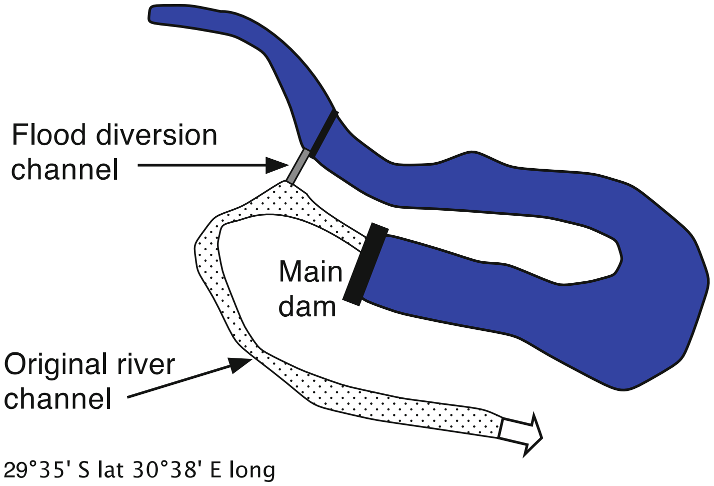


Fig. 5.15. Configuration of Nagle dam and reservoir in South Africa showing the flood bypass channel.

offstream reservoir sites, it is important to minimize the catchment area above the dam and to undertake strict land use controls or convert the catchment to permanent forest to minimize long-term sediment yield. At both offstream reservoirs in Puerto Rico the entire catchment area tributary to the dam was acquired and dedicated to natural forest, generating reservoir half-lives in excess of 1,000 years [73] despite naturally high sediment yields. The firm yield of an offstream reservoir is related to both storage volume and diversion capacity. In moist areas of Puerto Rico where rainfall is rather well distributed throughout the year, it is possible to achieve a firm yield almost equal to that possible from an onstream reservoir of the same volume with a diversion capacity equal to 140 % of mean annual flow [73]. Under other hydrologic settings, with more episodic runoff events, the required diversion capacity may become too large to make offstream storage economically attractive.

8.4. Sediment Bypass at Onstream Reservoirs

Under favorable conditions it is possible to divert sediment around an onstream reservoir, bypassing sediment-laden flows using a channel or tunnel which discharges below the dam. Taking advantage of river meanders, the Nagle reservoir in South Africa (Fig. 5.15) was designed to pass sediment-laden floods around the main pool using a flood-diversion dam and a flood bypass channel upstream of the storage pool [74]. In mountainous areas of Japan, several bypass tunnels have been constructed to pass gravel-sized bed material from the upstream limit of the reservoir to below the dam with the objective of maintaining the continuity of coarse bed material flow along the river to prevent stream incision and maintain gravel beds for environmental purposes. The Japanese systems have a small diversion dam at the upstream limit of the pool which directs bed material into the bypass tunnel (Fig. 5.16). To date, bypass tunnels have been used primarily on mountain reservoirs which allow for tunnel slopes of at least 1 %, and the maximum tunnel length reported to date is 4.3 km. When the

Fig. 5.16. Upstream area of Asahi reservoir, Japan, showing entrance to gravel bypass tunnel on the right and cofferdam which directs flood flows into the tunnel (photo G. Morris).

tunnel entrance is located at the upstream limit of the reservoir pool, the tunnel's entrance sill is set slightly below the riverbed elevation, followed by a short steep entrance reach to accelerate flow before transitioning to a long reach at constant slope. If the tunnel is located within the reservoir pool, the entrance may be set below the normal reservoir level and water is diverted during a sediment-bypassing flood event by opening a normally closed gate. These tunnels are characteristically designed to achieve supercritical flow to maximize the discharge per unit area, but the resulting combination of coarse sediment and high velocity can produce substantial scour damage to the floor of the tunnel [75]. At the Solis reservoir in Switzerland, a physical model study was used to support the design of a 900 m bypass tunnel which included a skimming barrier at the tunnel entrance to exclude floating logs [76].

8.5. Turbid Density Currents

A turbid density current occurs when sediment-laden water enters an impoundment, plunges beneath the clear water, and travels downstream along the submerged thalweg toward the dam. Figure 5.6 illustrates characteristics of a turbidity current passing through a reservoir showing the plunging flow, movement through the impoundment, accumulation as a submerged "muddy lake," and release through a low-level outlet at the dam. As the current travels downstream it will deposit the coarser part of its sediment load, and if enough sediment is deposited the current will dissipate before reaching the dam.

Turbidity current forward motion is facilitated where a thick current can flow along a defined channel, but as the submerged channel is infilled with sediment the geometry of the

Table 5.8
Sediment balance for Cachi reservoir, Costa Rica, during an average hydrologic year [29, 77]

Sediment distribution	Tons/year	Percent of total
Throughflow, turbidity currents through turbines and spills	148,000	18
Deposited on submerged terraces	167,000	21
Bed load trapped in reservoir	60,000	7
Turbidity current deposits removed by flushing	432,000	54
Total	807,000	100

reservoir bottom becomes flat and wide. This causes the turbidity current to spread out, becoming wide and shallow, increasing frictional resistance along both the top and the bottom of the current. This lowers the velocity and results in the deposition of transported sediment. For this reason, turbidity currents which reach the dam after initial impoundment may dissipate after the bottom configuration is modified by sedimentation. Regular flushing can maintain a submerged channel conducive to the propagation of turbidity currents to the area of the dam. The impact of turbidity current release on the sediment balance in a reservoir is illustrated by data from the Cachi hydroelectric reservoir in Costa Rica (Table 5.8). This reservoir was being flushed each year, thereby maintaining a normally submerged channel along the reservoir which facilitated the flow of turbidity currents to the low-level power intake at the dam where the turbid water was vented with the turbine flow.

Under the most favorable conditions some reservoirs in China's Yellow River basin have reported that turbidity currents transporting silts have discharged more sediments than the inflow, a result of scouring and then transporting unconsolidated bed sediments. For example, at the narrow 40 km long Liujiaxia hydropower and flood control reservoir on China's upper Yellow River, a major sediment-laden tributary named the Tao River (Taohe), discharges only 1.5 km above the dam. This tributary contributes 30 % of the inflowing sediment load, consisting primarily of silt, but provides only 2 % of the reservoir's storage capacity. Partial drawdown during floods allows inflow along the Taohe to scour sediment from the bed, transporting it to the outlet at the dam in the form of a turbid density current. By entraining additional sediment by scour, it was possible to release over 100 % of the inflowing sediment load during 13 of 25 density current release events during 1995. Over a 10-year period, 37 % of the inflowing Toahe sediment was released [78].

The release of turbidity currents is dependent on successfully predicting the arrival time at the dam and operating outlets to minimize the settling period in the muddy lake. Hydropower facilities with low-level power intakes may be well suited to release these currents if the dispatch schedule adopts sediment managed operation to allow continuous power production during sediment-laden inflow events when only fine sediments reach the dam, since these will not normally abrade hydraulic machinery.

8.6. Sediment Routing by Reservoir Drawdown

The strategy for drawdown pass-through (often termed sluicing) is to route sediment-laden inflows through the impounded reach at the highest velocity possible, maintaining sediment in suspension and minimizing deposition in the reservoir. High-velocity flows are achieved by reservoir drawdown, and the reservoir is refilled with water having lower sediment concentration toward the end of the inflow event. Because this strategy entails substantial drawdown and refilling of the reservoir, it is only suitable for reservoirs with a small storage capacity in relation to annual streamflow. It also requires large-capacity low-level outlets.

Sediment pass-through was first employed in a large reservoir at the Sanmenxia dam on China's Yellow River, where serious sedimentation problems required reconstruction of the outlet works to permit seasonal emptying at the beginning of the flood season to generate riverine flow along the length of the reservoir, not only passing inflowing sediment but also scouring out sediment accumulated from the prior year's impounding [29, 79]. The best-known example of this strategy is the Three Gorges Reservoir in China, which also employs a seasonal drawdown [29]. At smaller reservoirs the drawdown may be performed for individual flood events, instead of seasonally, refilling the reservoir's storage pool at the end of each pass-through event. A sediment routing operation of this type in a reservoir with a smaller watershed is schematically illustrated in Fig. 5.17. The management system consists of real-time rain and stream gage stations with attendant software to monitor and predict inflow rate

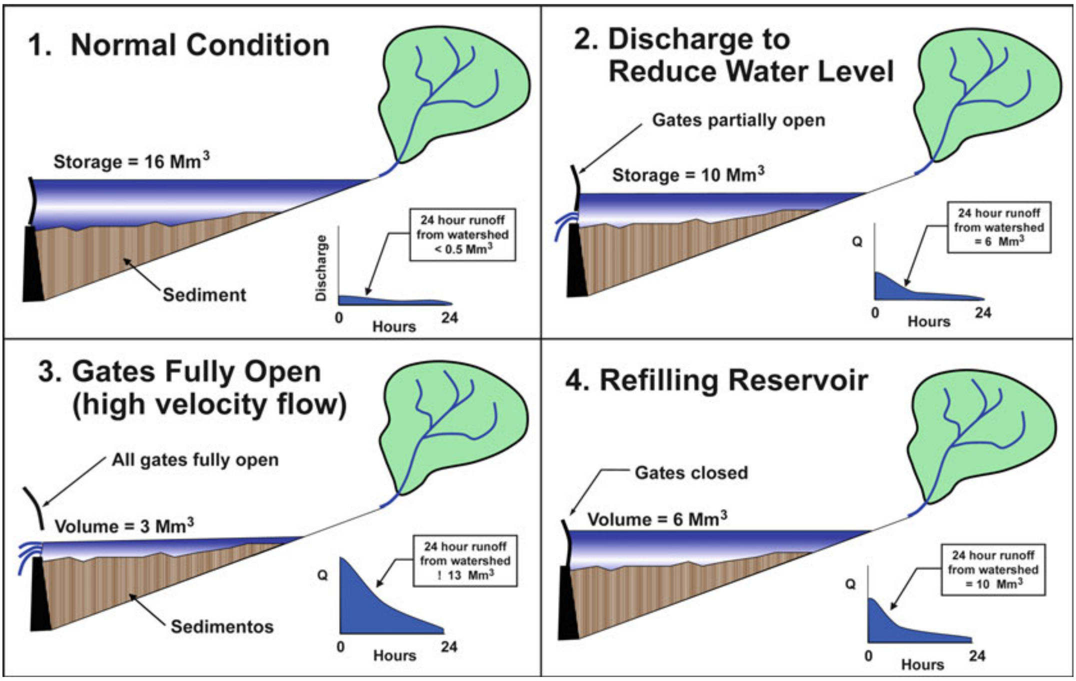


Fig. 5.17. Conceptual operation of a reservoir for sediment pass-through. (1) Normal operation, (2) initiation of drawdown as precipitation is received in the watershed, (3) gates fully open and high-velocity flow developed through the length of the reservoir, and (4) when precipitation diminishes gates are closed to refill the reservoir.

and volume. This operation may be described in a sequence of four steps. (1) During periods of normal weather the reservoir maintains storage for water supply and the hydrologic forecast system continuously updates flood forecast parameters such as antecedent soil moisture. (2) At the onset of a large rainfall event, reservoir gates are opened to draw down the storage pool at a rate not exceeding the accumulation of runoff volume in the watershed as determined by hydrologic modeling based on received rainfall and corroborated by discharge measurements at upper watershed stream gages. The total volume in the system, consisting of the volume in the reservoir plus the predicted 24-h inflow volume from the watershed, is never allowed to drop below the reservoir capacity, thereby ensuring the storage pool can always be refilled. (3) During a large volume flood, reservoir gates are fully opened and high-velocity riverine flow occurs through the impoundment, transporting flood-laden sediment beyond the dam. (4) When the hydrologic model indicates that the runoff volume under the predicted hydrograph has declined to that required to refill the reservoir, gates are closed and the reservoir is refilled. While this method may mobilize and remove some of the previously deposited sediment, its main focus is to minimize deposition, particularly since the velocity required to maintain cohesive sediment in suspension is much less than that required to scour sediments which have already been deposited. Maintaining sediment transport through the impounded river reach during floods avoids the environmental impacts that accompany strategies such as flushing, which releases high-concentration flows with limited discharge, and thus requires particular attention to environmental mitigation. A key feature of sediment pass-through is that it maintains the natural flood hydrograph and its associated sediment transport along the river system.

9. RECOVER, INCREASE, OR REALLOCATE STORAGE VOLUME

Sediment removal can be undertaken by opening a low-level outlet to produce hydraulic scour and remove sediments, a process termed *flushing*. There are two basic types of flushing operations: *pressure flushing* occurs when a low-level outlet is opened while the reservoir pool is held at a high level, and *drawdown flushing*, *empty flushing*, or more commonly simply *flushing*, occurs when the reservoir is completely emptied and riverine flow runs along the entire length of the reservoir and out the bottom outlet [79].

The term *sluicing* refers to any method which removes sediment through a low-level outlet (a *sluice gate*), and the term *sluicing* has been used by different authors to refer to sluicing (venting) of turbidity currents, sluicing by partial drawdown (sediment pass-through), sluicing through a tunnel (sediment bypass), and sluicing by reservoir emptying (flushing). Given its multiple interpretations, use of this term is not recommended.

Sediment can also be removed mechanically from beneath the water while the reservoir is inundated (dredging) or with the reservoir empty (dry excavation). Mechanical methods to excavate sediment are well known and are invariably suggested to “solve” sedimentation problems. However, to rely solely on mechanical equipment and fuel to sustain a sediment balance across a reservoir can rarely be considered a sustainable strategy, and the mechanical management of sediment should normally be evaluated as a complement to other measures rather than as a stand-alone practice.

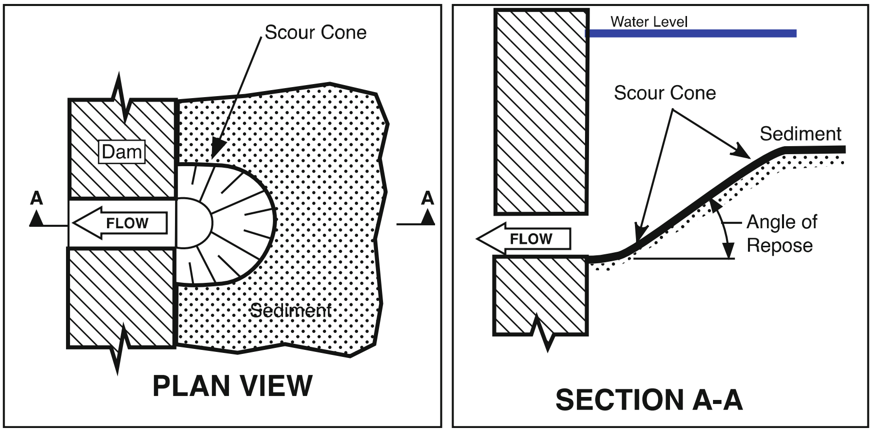


Fig. 5.18. Definition sketch for pressure scouring.

9.1. Pressure Flushing for Localized Sediment Removal

Pressure flushing will release only a relatively small volume of sediment in the immediate vicinity of the flushing outlet. If an intake is located immediately above or adjacent to a low-level outlet operated for pressure flushing, it will be possible to maintain the intake area free of sediment. With reference to the definition sketch in Fig. 5.18, in granular sediment, the angle of repose of the scour cone under continuously submerged conditions will approximate the submerged angle of repose of the sediment, on the order of approximately 30°. In the case of cohesive sediment this angle can be much steeper, and operators at some sites have found it necessary to dredge cohesive sediment in front of the intake to reduce clogging despite continuous hydropower releases. Based on laboratory experiments on scour cone formation using cohensionless sediment [80], it was reported that the half cone created centered on the outlet at the wall of the dam was nearly symmetrical and that the volume of the scour cone is increased (angle of repose decreased) by increased discharge, increased outlet diameter, or decreased water depth over the sediment deposit. When a reservoir is emptied, sediments will normally slump and the dewatered angle of repose can be less than half of the submerged value. When an outlet is buried in sediment it may be necessary to sink a small shaft (e.g., by water jet) to create a piping channel to initiate flow through the outlet.

9.2. Empty Flushing

Empty flushing entails opening a low-level outlet to completely drain the reservoir and scour out sediment. Flushing of this type inevitably occurs as a consequence of reservoir emptying for any reason, such as emptying to repair a low-level intake. The removal of sediment by flushing is an old technique dating to Moorish Spain over 500 years ago when emptying and flushing of irrigation reservoirs was scheduled at intervals of 4 years [81]. Today flushing is frequently undertaken on an annual basis and the flushing duration may vary from a few days to a few weeks, but its utilization is limited due to adverse downstream impacts. Empty flushing has primarily been practiced in hydrologically small

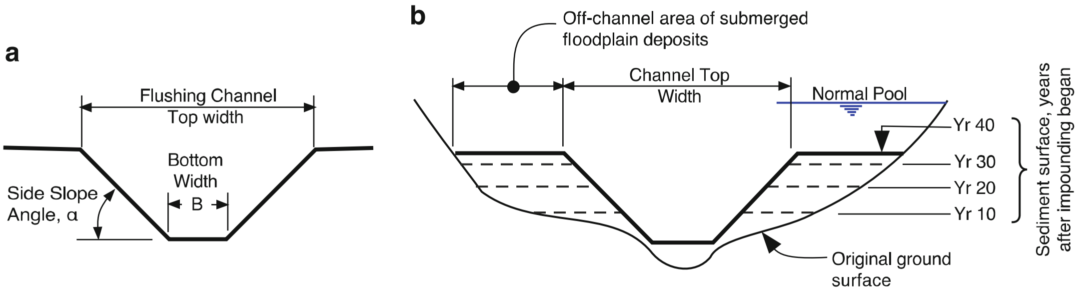


Fig. 5.19. Effect of flushing on reservoir geometry showing (**a**) definitional cross section of flushing channel in reservoir deposits, and (**b**) conceptual sequence of deposit configuration over time. This geometry is applicable only to deposits of fine sediment below the area of the reservoir delta.

reservoirs (low capacity:inflow ratio) on streams in mountainous areas. Maximum flushing effectiveness is achieved using the highest discharge that can be passed through the bottom outlet without backwater.

When the river is allowed to run through the impoundment and exit through a low-level outlet it will scour a channel across the deposits, typically following the original river channel. The volume within the reservoir that can be sustained by flushing can be defined based on the width of the flushing channel and the side slope angle (Fig. 5.19). In narrow reservoirs flushing has been used to sustain most of the original reservoir capacity, but in wider reservoirs sediments deposited on either side of the flushing channel during impounding will not be removed and will create a submerged floodplain that continues to accumulate sediment and increase in elevation over time. Sediment removal during flushing can be increased by using mechanical equipment to push sediment into the flushing channel or by diverting smaller flows laterally across erodible floodplain deposits. This lateral erosion procedure has been used successfully in Chinese reservoirs where sediments are predominately erodible silts [82]. Where a significant clay content is present, consolidation of the cohesive sediment can impair erosion.

Regular flushing which sustains a defined channel along the length of the reservoir will facilitate the passage of turbidity currents to the dam where they can be released through low-level outlets. Also, turbidity currents will deposit their sediment into the submerged flushing channel from whence they can be readily removed during subsequent flushing events. The data previously presented for Cachí reservoir in Table 5.8 which showed high rates of sediment removal reflects the beneficial effects of the flushing channel which conducts turbidity currents to the power intake at the dam and which also focuses deposition of fine sediment from turbidity currents into the submerged flushing channel from which it is easily removed during the subsequent flushing event.

Flushing is much less efficient in removing coarse sediment from a reservoir. Bed material sediment is transported and deposited on the reservoir delta by floods with high hydraulic transport capacity, but flushing flows are typically limited by bottom outlet size and cannot generate the transport capacity required to remove the volume of bed material delivered to the delta area by natural inflows. Thus, while flushing may achieve a sediment balance for the fine fraction of the inflowing load, the coarse fraction may continue to accumulate in the reservoir (as occurs at Cachí reservoir per Table 5.8). For example, Sumi and Kantoush [83] reported that flushing at the Unazuki dam in Japan was effective in removing 73 % of the total sediment inflow but removed only 10 % of the annual load of coarse sediment >2 mm in diameter. Thus, the geometry of the flushing channel defined in Figure 5.19 may not be sustainable in the very long term because it does not represent the behavior of the continuously accumulating coarse sediment.

9.3. *Downstream Impacts of Flushing*

Flushing releases high sediment loads with limited water volumes, potentially producing downstream environmental impacts including reduced dissolved oxygen, high sediment concentrations that interfere with the function of gills and smothers stream benthos, reduction in visibility and light penetration, and channel morphological impacts such as infilling of pools and clogging of river gravels with fine sediment, thereby eliminating spawning sites and habitat. Social and economic impacts include the interference with water treatment processes for municipal or other users, sedimentation within irrigation canals if not designed to transport sediment, accumulation in heat exchangers which draw water from the river, reduction of recreational quality, impacts to fisheries of economic importance, accumulation in flood control and navigational channels, and impacts to coastal areas. While the total amount of sediment released is not different from that which would have been transported downstream absent the dam, the combination of high sediment concentrations during flushing, changed downstream hydrology due to the dam, and the potential to release sediment-laden water out of sync with natural biological cycles, can produce large adverse impacts.

The downstream impacts associated with flushing are related primarily to the release of high-concentration flows. Early in the process of reservoir drawdown for flushing much of the sediment scoured from the upper part of the impoundment will be redeposited before reaching the dam. Sediment eroded from within the impoundment is discharged as a high-concentration mud flow only as the reservoir approaches full drawdown. This causes the suspended sediment concentration in the released water to rapidly spike to a very high level, often in the range of 100,000–400,000 mg/L, if not otherwise controlled by limiting the release rate to match dilution flows. Typical variations in hydraulic parameters and suspended sediment concentration during flushing are illustrated in Fig. 5.20. The highest concentrations associated with flushing events occur in reservoirs with annual maintenance flushing because recent poorly consolidated sediments in the flushing channel can be readily mobilized as a thick mud flow as soon as free flow is established along the bottom of the reservoir.

Based on the experience at alpine reservoirs in Europe which are flushed to maintain capacity, the following measures have been identified as minimizing the adverse environmental impacts of reservoir flushing [84, 85]:

- *Timing of release*. The most important criterion for minimizing flushing impacts is the proper timing of the release. Flushing releases should be timed to coincide with natural high-flow events or releases from other reservoirs to provide dilution, and particularly flows from tributaries downstream of the dam. Also, if flushing coincides with the beginning of the wet season, there is

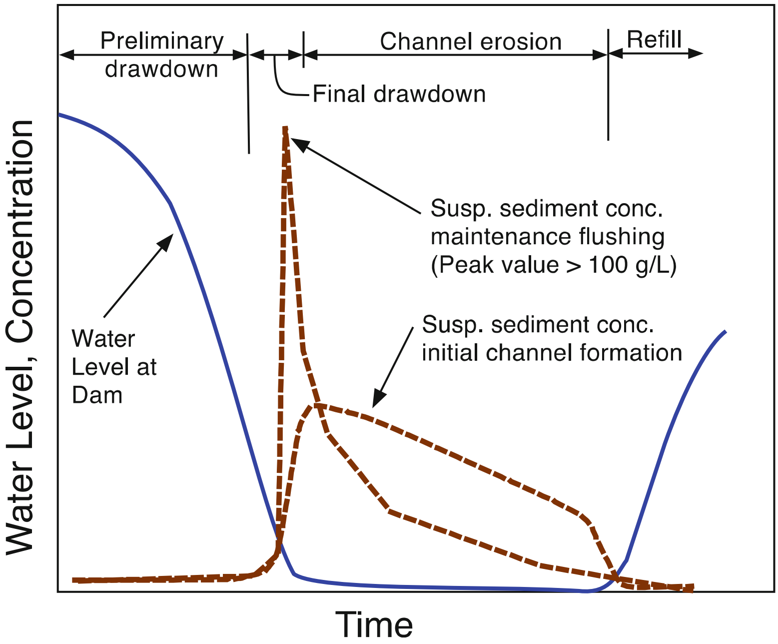


Fig. 5.20. Typical pattern of variation in suspended sediment concentration during flushing events. When a reservoir is flushed for the first time and a flushing channel is gradually eroded, peak suspended sediment concentrations are lower than when a reservoir flushed on a regular basis. With regular maintenance flushing, suspended sediments that accumulate in the flushing channel do not consolidate between flushing events and are discharged as highly concentrated mud.

the opportunity for subsequent floods to cleanse the river channel and gravel beds of fine sediment deposited by the flushing release. If flushing releases sediment when fish are using gravels for spawning or the recently emerged weak-swimming larvae are using gravels for refuge, the juvenile population may be decimated, making it important to use biological as well as hydrologic criteria in selecting flushing dates. Because natural populations of juvenile fish can experience significant cyclic fluctuations, it is important to understand and document population fluctuations due to natural or other impacts and separate them from the impact of reservoir management.

- *Duration of release*. At a number of sites, the volume required to flush sediment from a reservoir is significantly less than the volume required to transport the released sediment downstream in a manner which minimizes localized sediment accumulation [29]. The availability of tributary inflow and the ability to release clear water downstream to further transport the released sediment soon after the low-level outlet is closed are important mitigation factors.
- *Frequency of release*. More frequent releases can result in smaller sediment releases during each event, which would normally be considered favorable. For example, a review of data from flushing at the Dashidaira and Unazuki dams on the Kurobe River in Japan indicated that adverse downstream impacts to the river channel were limited because of frequent flushing, high stream slope which facilitated transport of the released sediment, and the short distance (<30 km) to the sea. To minimize water quality problems, the reservoirs were flushed as frequently as possible during periods of high flow to provide high dilution volumes, thereby reducing the peak suspended

> sediment concentration and sustaining higher oxygen levels in the stream below the dam [83]. Studies of flushing impacts in Italy [84] also emphasized the positive effect of frequent (annual) flushing which minimizes the amount of sediment release during any single event, in combination with the adequate release of clear water for dilution and cleaning the bed after the sediment release. Fish were impacted by both the high discharge and elevated sediment concentration, with juveniles being particularly susceptible.

Flushing has not been feasible in many areas of the world due to downstream water quality impacts, and only in recently years has significant attention been directed at developing flushing strategies to minimize these impacts.

9.4. *Flushing Equations*

A rough preliminary idea of flushing channel geometry can be defined by two equations, one to estimate the width of the flushing channel and the other to estimate the slope angle of channel banks [85], as previously defined in Figure 5.19. Channel bottom width can be estimated by

$$B = 12.8 Q_f^{0.5} \tag{5.6}$$

and the bank angle can be estimated by

$$\tan\alpha = \frac{31.5}{5}\gamma_d^{4.7} \tag{5.7}$$

The rate of sediment discharge during flushing based on data from Chinese reservoirs can be roughly estimated by the Tsinghua University equation [29]:

$$Q_s = \Psi \frac{Q_f^{1.6} S^{1.2}}{B^{0.6}} \tag{5.8}$$

where Q_s is sediment transporting capacity (T/s), Q_f is flushing discharge (m^3/s), S is bed slope, B is channel width (m), and Ψ is a constant determined by sediment type: 1,600 for loess sediments, 650 for other sediments with median size $<$0.1 mm, 300 for sediments with median size $>$0.1 mm, and 180 for flushing with a “low” discharge. These equations provide only a rough approximation of flushing performance, but they do show the importance of maximizing the discharge during flushing events. A tenfold increase in discharge increases the rate of sediment discharge by a factor of 20 and increases the channel width by a factor of 3, while cutting in half the volume of water needed to remove a fixed sediment volume. Reservoir flushing in China is frequently performed annually, meaning that the flushing channel refills with sediments which do not have time to consolidate before the next flushing event and making flushing very efficient in terms of water use. Atkinson [85] suggests that equation may overestimate the rate of sediment discharge by a factor of approximately three when flushing sediments that have had many years to consolidate or when flushing from a reservoir with sediments coarser than 0.1 mm diameter.

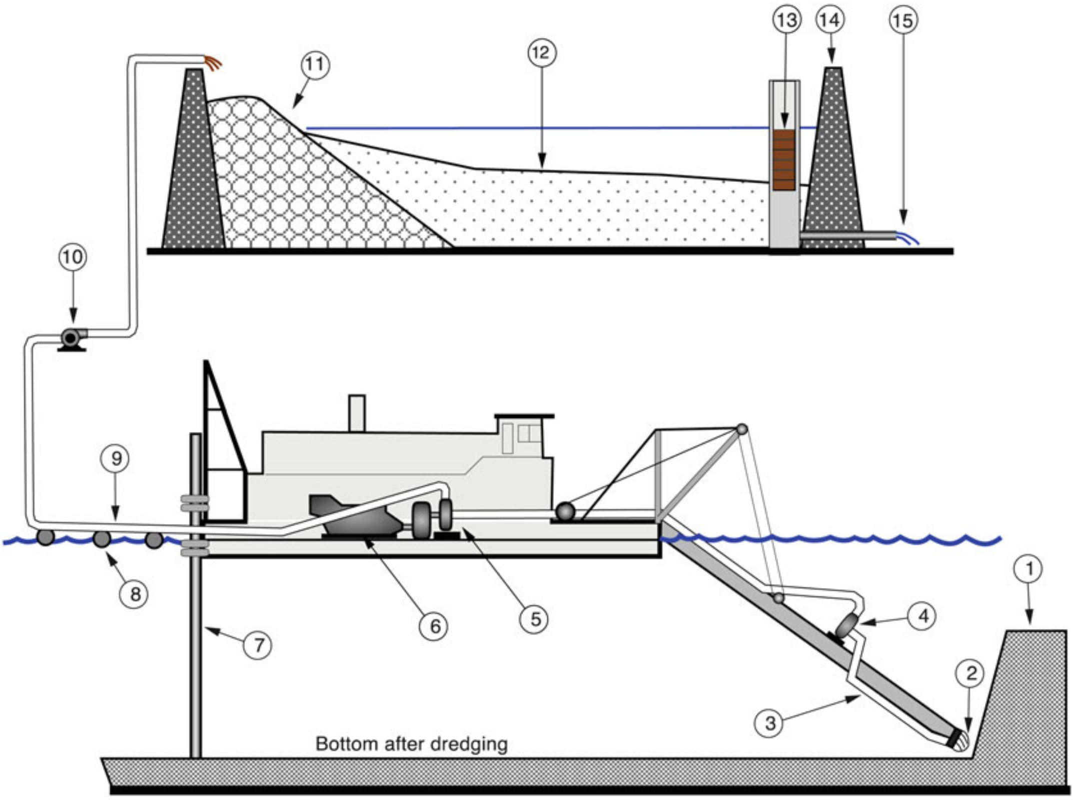


Fig. 5.21. Schematic of components of dredging system: (1) sediment to be dredged; (2) rotating cutterhead to cut and suspend sediment; (3) suction line connected to the ladder; (4) ladder pump; (5) main pump; (6) main drive, either diesel or electric; (7) spud; (8) pontoons to support discharge pipe; (9) discharge pipeline; (10) booster pump; (11) coarser material deposited near the discharge point; (12) fine sediment; (13) discharge weir with flashboards to allow elevation to be raised as the containment area is filled; (14) containment area dike; and (15) discharge of clarified water back to the reservoir or to other receiving body.

9.5. Dredging

Dredging refers to the excavation of material from beneath the water. There are broadly two types of dredging: mechanical dredging in which the dredged material is removed by buckets such as a clamshell, dragline, or bucket ladder dredge or hydraulic dredging in which sediment is excavated and transported as a slurry. Mechanical dredging is generally used in low-volume applications which focus on dredging of smaller areas and the removal of woody debris, such as the area around an intake, or for the removal of gravels and cobbles from the delta as this coarse material is inefficient to dredge hydraulically. Mechanical dredging in reservoirs typically entails haulage of the material to a disposal site by truck.

Volume-wise, most sediment is removed from reservoirs by hydraulic cutterhead dredges. The principal components of a hydraulic dredging system are illustrated in Fig. 5.21. Hydraulic dredges can achieve high rates of production, can handle a wide range of grain sizes, do not

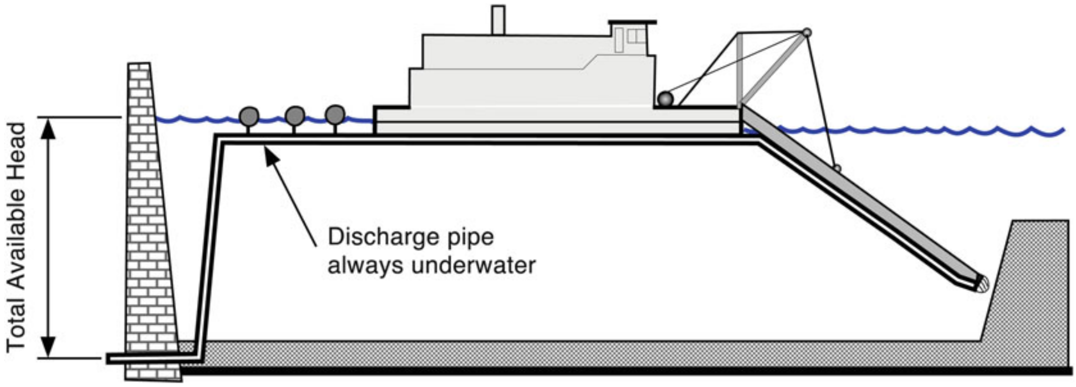


Fig. 5.22. Siphon or hydrosuction dredging configuration.

interfere with normal reservoir operation, and the slurry pipeline is a clean and low-impact means to convey dredged material to the disposal site.

A special type of hydraulic dredging developed only for reservoirs is the *siphon* or *hydrosuction* dredge [86], which does not use a pump but instead uses the difference in head between the reservoir water surface and a discharge point at the base of the dam as the energy source for slurry transport, as illustrated in Fig. 5.22. Because the amount of hydraulic energy available is fixed by the reservoir level, which may vary, high friction losses in the slurry pipeline typically limit the use of siphon dredges to the removal of sediment within about 2 km of the dam. A slurry pipeline must be designed to transport the largest grain sizes in the material to be dredged. The high velocity required to sustain sand or coarser material in suspension generates high friction loss, making it infeasible to transport coarse material over significant distances without energy input by pumping. Longer transport distances are feasible with uniformly fine material because they can be transported at lower velocities without sedimentation in the pipeline. The hydraulics of slurry pipeline transport of coarse materials for siphon dredging in reservoirs has been outlined by Eftekharzadeh [87].

Dredging is expensive and is typically much more costly than creating storage volume by dam construction. Dredging costs include engineering and permitting, costs associated with acquisition, and management of the dredged material placement site, plus the cost of dredging itself. Dredging costs vary widely, and 2013 reservoir dredging costs can be expected to run in the general range of \$5 to \$15/m^3, provided there are no unusual conditions such as contaminated sediments. The unit cost of reservoir dredging is typically higher than navigational dredging because dredges must be transported to the reservoir by land and are typically smaller than the equipment available for navigational dredging. Upland dredged material containment area costs may also be higher than in navigational dredging.

The availability of land for the disposal of dredged material is an important impediment to sustaining long-term reservoir capacity by dredging. Material removed by hydraulic dredging is subject to bulking, and if fines are present the volume of containment area must be proportionally larger than the in situ volume of the material to be dredged, as computed by the dimensionless *bulking factor*:

$$B = \frac{V_c}{V_i} = \frac{\gamma_c}{\gamma_i} \tag{5.9}$$

where V = volume, γ = dry unit weight, and subscripts c and i refer, respectively, to containment area and in situ values. The value of the bulking factors is 1.0 for pure sands, in the range of 1.3 for silts, but can exceed 1.5 for clays. Their value depends on the amount of consolidation in the area being dredged as well as the settling characteristic of the material. Thus, the bulking factor for older consolidated clay deposits may be larger than for recent clay deposits having a lower in situ dry unit weight. Column settling tests should be run for at least 15 days to better determine the anticipated settling characteristics of the material to be dredged. Over time the dredged material will dewater and consolidate, particularly when the material is dewatered and provided with good surface drainage and plant roots penetrate the material [88].

In some instances, it is permissible to discharge dredged material to the river channel downstream of the dam. Discharge below the dam is advantageous in that it sustains the flow of sediment along the channel, with the principal problem being that sediment is released continuously rather than being timed to coincide with natural discharge events. Nevertheless, at smaller dams in mountainous areas with frequent downstream releases, sediment discharge to the river below the dam can represent a good alternative, especially when coarse bed material can be placed below the dam to replenish the cutoff of sediment supply due to the dam. Small-scale downstream sediment replenishment in the Isa River, Germany, is described in Hartmann [90] and in the Nunome River, Japan, is described by Kantoush and Sumi [89]. When downstream discharge is not feasible, dredging can be sustained only as long as there is space available in containment areas which are sufficiently close to the reservoir to be economically feasible.

9.6. Dry Excavation

Dry excavation has been used in some instances to remove sediment from reservoirs. Unlike dredging, it requires that reservoir level be lowered or emptied to allow access to deposits by earthmoving equipment. At some sites with predictable seasonal water-level variation, dry excavation can be undertaken on a seasonal basis. Disposal area limitations similar to those associated with dredging apply, the difference being that sediment transport is typically by truck haulage with attendant damage to roads, public disturbance from traffic and dust, etc. Dry excavation can easily remove coarse material from the delta, but removal of deep deposits of poorly consolidated fine sediment presents significant difficulties absent a period for dewatering and consolidation.

9.7. Raise the Dam

Raising the dam to increase storage capacity can, in some cases, provide a volume increase sufficient to substantially delay sediment problems. Due to reservoir geometry, each height increment provides more volume than the prior increment, making even relatively small height increases potentially important. However, raising the dam is neither a simple nor inexpensive undertaking. In addition to structural and hydraulic considerations, raising the dam may entail additional land acquisition, upstream flood levels will increase, delta deposition will move further upstream, evaporative surface will be enlarged, etc. Raising the dam in combination with improvements to gates to facilitate sediment release may improve the long-term sediment balance. However, if the dam is raised to increase storage capacity without other sediment management measures, it may not contribute to a long-term solution.

9.8. Structural Modifications

Sedimentation can interfere with intake operation and can result in the entrainment of coarse sediment. For example, at the glacial-fed Gebidem hydropower reservoir in Switzerland, which maintains storage capacity by annual flushing, fine sands were being carried into the area of the low-level outlet and causing turbine abrasion. In this case a new intake tower was installed and provided with multiple-level inlets at higher elevations in the pool to avoid the entrainment of sand (290). When fine sediment accumulates in front of the dam that does not practice sediment removal, the intake may be raised to avoid the accumulating sediment. The disadvantage of this approach is that it will tend to maintain a high reservoir trap efficiency. In general, turbid density currents should be released insofar as possible, and passage of turbidity currents through turbines will typically not cause abrasion problems due to the small grain size of the transported sediment.

To minimize interference by sedimentation, intakes should be placed above or adjacent to a low-level outlet, so that operation of the outlet for either pressure or empty flushing will clean out the area in front of the intake. However, many reservoirs have intakes located at the side of a reservoir, a significant distance from either the low-level outlet or the channel which is created by flushing through a low-level outlet. In such cases it may be necessary to construct a normally submerged pipe or other conveyance structure from the intake to an area of the dam which can be maintained sediment-free by pressure flushing or to the location of the flushing channel. This conveyance structure should be sized to generate the velocities required to avoid sedimentation within the conveyance structure, based on the largest sediment size likely to be entrained. Relocation of the intake entrance by this method may increase the frequency with which turbid density currents are diverted into the intake.

9.9. Reuse of Reservoir Sediments

Reservoir sediments will reflect conditions in the upstream watershed, including the contaminants generated by upstream activities. If there is extensive upstream agricultural activity including the historical application of persistent pesticides, these may be found in the reservoir sediments and should be evaluated when considering reuse options. Similarly, upstream mining or industrial activity can result in sediment contamination. However, in general reservoir sediments do not present special hazards and can be readily reused for activities such as agriculture, fill, or construction materials if sediments are sufficiently coarse. Testing protocols to insure compatibility with intended uses will vary by jurisdiction and by intended use.

10. TOWARD ACHIEVING SUSTAINABLE USE

10.1. Modeling of Sediment Management Activities

Future sedimentation patterns and alternative sediment management activities can be best examined by simulation modeling. Depending on the situation, the appropriate tool may be a physical model, a numerical model, or both. Physical modeling is typically used to simulate the detailed behavior of 3-dimensional flow patterns, deposition, scour and the movement of floating debris in the vicinity of structures such as intakes, gates, and spillways. Numerical sediment transport models are currently used for both single-event and longer-term (e.g., 100-year) simulations focusing on larger-scale scour and deposition phenomena. Fundamental aspects of sediment transport are covered by Yang [91], and the mathematical basis for numerical models has been summarized by Simões and Yang [92]; this section will focus on several practical aspects of numerical modeling.

Numerical models may solve flow problems in one, two, or three dimensions. One-dimensional models have been in use for many years, and two-dimensional models are increasingly being used as computational capacity expands. Three-dimensional models remain, at this moment, more in the purview of academic research. Inasmuch as river-reservoir systems can frequently be simulated as one-dimensional systems, 1-D models have been employed in many situations to predict the timing and patterns of sediment deposition and scour. One-dimensional models available from US government agencies include SRH-1D available from the US Bureau of Reclamation and HEC-RAS (successor to the HEC-6 sediment transport model) available from the US Army Corps of Engineers. Both models can simulate the behavior of both coarse and cohesive sediment.

One-dimensional models are used to simulate the changes in bed profiles and the longitudinal variation in grain size as a result of changes in discharge, sediment load, and the influence of hydraulic structures which raise or lower water levels and sediment transport capacity. They cannot simulate situations involving secondary currents and transverse sediment movement, changes in stream morphology such as meandering, point bar formation, pool-riffle formation, and many plan form changes. They also cannot simulate the details of local deposition and erosion resulting from intakes, bridges, and other instream structures. Several types of reservoir sedimentation questions are commonly addressed using one-dimensional models. One question is to predict the future sedimentation pattern and particularly the evolution of the reservoir delta into the pool as well as deltaic aggradation upstream above the pool. A second question involves the extent to which the sedimentation rate and patterns will be modified by changes in factors such as sediment input or reservoir operation. A third question involves the effectiveness of sediment removal and the reservoir profiles resulting from reservoir flushing. A fourth question involves the response of the channel below the dam as affected by reduced sediment inflow from reservoir construction or from an increase in sediment inflow due to reservoir flushing, dam removal, or other management. Models may be run to examine the effects of a single flood event, multiple events, or long-term (>100 year) behavior, depending on the nature of the question to be addressed. Because most sediment is transported by floods, simulations frequently focus on these large events.

Input data required for numerical modeling include geometry, hydraulics, sediment, and operating rules. Model geometry is established using cross sections of the river-reservoir system. Hydraulic parameters include the inflow time series at the upstream boundary plus any tributaries, the downstream water surface boundary (subcritical flow), plus rating curves for any internal boundaries such as gates or weirs. Sediment data includes specification of the bed material size distribution, depth to bedrock at each cross section, sediment deposit density, and the inflowing load for each grain size as a function of discharge and density of sediment deposits. It is also necessary to select the appropriate sediment transport equation from the several that are available. Operating rules involve the management of water levels during inflow events, which directly influences the flow velocity and trap efficiency in the reservoir and which may also entail periods of reservoir drawdown for sediment flushing.

The simulation of sediment transport is usually undertaken with very limited data. For example, many locations will not have a suspended sediment gage station to provide data to construct a sediment rating curve, and bed material transport data are virtually never available. Furthermore, selection of one or another transport equation can change the transport rate by more than an order of magnitude. This makes model verification essential. When simulating sedimentation within an existing reservoir, the model can be exercised over the historical period and parameters adjusted until a reasonable fit is made to the observed depositional pattern and grain size distribution within the reservoir.

Calibration of a sediment transport model should start with the hydraulic elements, adjusting hydraulic roughness or other parameters until a reasonable match is achieved against any available hydraulic profile data. Calibration of a sediment transport model for an existing reservoir requires bathymetric data from at least two points in time, plus data on the grain size of deposited sediments as a function of location along the reservoir. Grain size samples should be taken using a sediment core, since grab samples from the surface of the sediment deposits will reflect only the most recent period of sedimentation rather than average conditions. The model is calibrated by starting with the pre-impoundment condition, and then run to simulate the documented post-impoundment geometry and grain size along the reservoir, while insuring that the resulting value of reservoir trap efficiency is reasonable. This may require adjustment of the amount and grain size in the inflowing sediment load and a change in the transport function. If simulating sedimentation in a proposed reservoir, the model may be run for a period of decades using the existing stream geometry to insure that it properly simulates the existing profile and grain size distribution along the river while transporting anticipated amounts of sediment through the system. However, this will verify only the coarse fraction of the load as represented in the bed material, but most reservoir sediments consist of fines which behave as wash load. This makes it important to have a good estimate of the suspended sediment rating curve, and lacking this the inflowing load will need to be approximated from other suspended sediment gages which may exist in the area, or based on volume of sediment trapped. Modeling cannot overcome errors in the estimate of the inflowing suspended sediment load.

An important factor limiting the reliability of sediment transport models is the availability of data for model calibration. Grain size will exhibit significant variation within a reservoir and may be locally influenced by the lateral inflows from minor tributaries. It is important that the modeler understand the sampling procedures that were used, obtain samples at multiple locations, and should ideally be personally involved in at least some sediment field work. It is also necessary to interpret results from transport models for overall reasonableness, since sediment calibration data are not themselves always consistent. The future conditions which are simulated should always be interpreted as a general guide rather than a precise prediction, taking into consideration limitations that exist in the calibration data, the uncertainty of future hydrologic conditions, and the limitations inherent in using a simplified model to study a complex process.

An example of the use of the SRH-1D model was given by simulations performed at the Peligre reservoir in Haiti [18], which had lost 50 % of its capacity after 50 years of operation. This reservoir produces hydropower and also delivers water to irrigators downstream in the Artibonite Valley. The configuration of this reservoir was previously shown in Figures 5.4 and 5.5. A study was undertaken for the Inter-American Development Bank to determine whether or not coarse sediments would enter the hydropower intake within the next 20 years. To address this question, the reservoir was surveyed to determine the existing (2008) configuration of sediment deposits, and sediment samples were collected to determine the longitudinal grain size distribution. The SRH-1D model was started with the 1980 bathymetry (the original reservoir configuration was not available) and calibrated against the 2008 bathymetry. Because there are no data on inflowing grain size data, the inflowing grain size distribution was adjusted to produce the grain size distribution observed in the reservoir from field samples. The calibrated model was then run 100 years into the future under the existing and alternative operating rules, including a rule which included periodic flushing using the existing outlets. Simulation results for the recommended operating rule are illustrated in Fig. 5.23 showing the simulation of delta advancement toward the dam. These results indicated that coarse sediment would not enter the intakes during the next 20 years. Furthermore, it was shown that by both raising the power intake level and using the recommended operating rule, it would be possible to sustain hydropower operations during the next 100 years with no reduction in energy production, although the reduction in storage would significantly impair the reliability of irrigation supplies. It also showed that absent a large low-level outlet to discharge large floods with significant reservoir drawdown, it will not be possible to flush a significant part of the delta sediment from the reservoir. However, when the reservoir capacity is greatly reduced, and by operating at the lowest possible level during flood events (sediment pass-through), the trap efficiency is reduced from 95 % to 50 % over the 100-year simulation period.

10.2. Implementation Steps

Reservoir operation becomes sustainable once a program is implemented to bring sediment inflow and outflow into long-term balance in a manner that produces significant net benefits to society while sustaining the integrity of ecological systems. Sustainable operation at a specific reservoir site may be achieved through a sequence of actions such as those listed below:

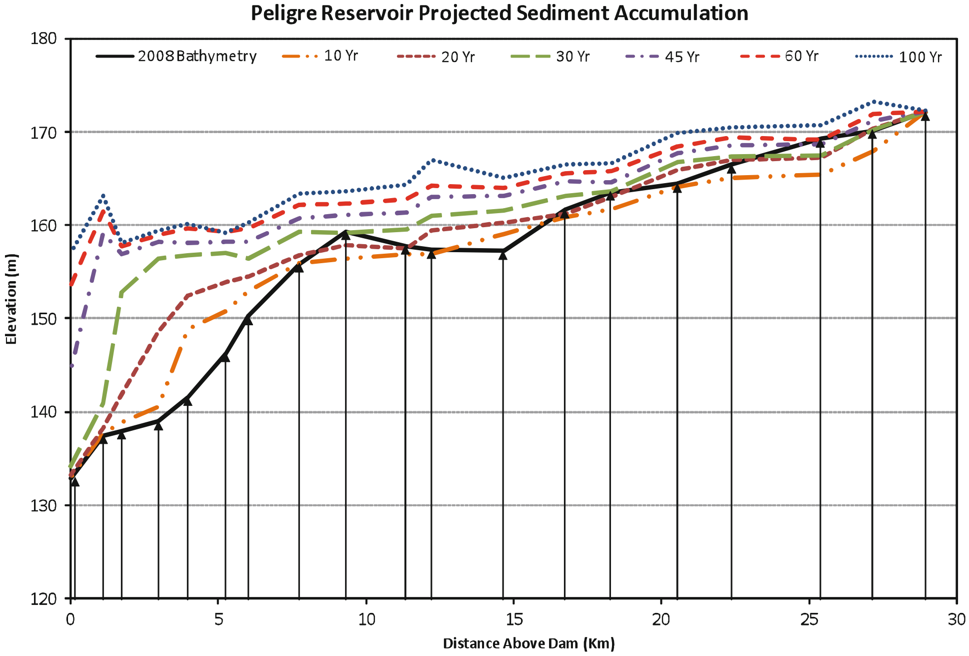


Fig. 5.23. Advancement of reservoir delta toward the dam over a 100-year simulation period, Peligre dam, Haiti [18].

1. *Data collection*. Perform bathymetric studies at regular intervals to document the pattern and trend of sediment accumulation and to identify those beneficial uses most threatened by sedimentation. Operate one or more sediment monitoring gage stations upstream of the reservoir to collect data for construction of a sediment rating curve including grain size distribution of the inflowing load, giving particular attention to monitoring flood events. The sediment rating curve is an important input for numerical modeling.
2. *Predict sedimentation patterns and impacts*. Use sediment transport modeling to predict long-term sedimentation patterns, identifying the benefits to be impacted and approximate time frames when sediment will interfere with specific operations.
3. *Adaptive measures*. Identify and implement measures to adapt to sedimentation. This may include measures at the reservoir such as pool reallocation, modification, or optimization of operating rules or offsite measures such as development of an alternative water supply and increased efficiency of resource use through water conservation, reuse, or loss reduction.
4. *Select long-term sediment management strategy*. Identify feasible strategies to manage sediment, assign action priorities based on the urgency and consequences of sedimentation, and establish an implementation timetable. The sedimentation impacts at some sites may be very large as loss of an essential water supply or flood protection may eliminate the livelihood of entire communities, and large consequences can justify aggressive sediment management actions. If sedimentation will lead to decommissioning of the dam, those implications and potential liabilities should also be considered.

The most appropriate strategies may change over time as the reservoir loses capacity; management measures such as sediment routing by drawdown may not be technically feasible early in the reservoir life, but will become feasible as storage volume diminishes. Conversely, the ability to release turbid density currents may diminish over time. If heightening or a new dam is selected as an alternative, land should be acquired or otherwise reserved for this eventual use.

5. *Implementation*. Initiate those activities required to support the long-term strategy. At sites without a significant near-term problem or mitigation opportunities, implementation may be limited to the data collection program. At sites with more proximate problems or immediate sediment management opportunities, implementation may include detailed analysis, design, environmental permitting, operational modifications, and construction activities. Even though some types of control measures may be delayed until sedimentation is more advanced, these should be identified and scheduled. The objective is to outline the path to sustainable operation and insure that all future activities are coincident with this path.
6. *Monitoring*. Monitor the impacts of implementation measures, and adjust sediment management activities as needed to maximize long-term benefits.

In summary, long-term stainable use requires that project design and operation look beyond the traditional planning horizons associated with project financing. It requires that owners and engineers actively pursue measures to establish a sediment balance across the impounded reach. In the same manner that dams are designed and managed to comply with dam safety and environmental criteria, sustainability should also be considered an essential component of the project, implementing to the greatest extent possible those elements that lead to a long-term sediment balance.

10.3. Additional Resources

This section lists several online resources which provide information and software, at no cost unless otherwise noted.

Intl. Assn. for Hydrological Research (many open access publications)	http://www.iahs.info/press.htm
Intl. Commission on Large Dams. ICOLD (publications, some free)	http://www.icold-cigb.net/
Reservoir Sedimentation Handbook (PDF download)	http://www.reservoirsedimentation.com
Erosion and Sedimentation Manual (PDF download)	http://www.usbr.gov/pmts/sediment/
US Army Corps of Engineers (publications and software)	http://www.hec.usace.army.mil/
US Bureau of Reclamation (publications and software)	http://www.usbr.gov/pmts/sediment/
USDA Natural Resources Conservation Services (publications, software, local offices)	http://www.nrcs.usda.gov/
US Environmental Protection Agency (water quality regulations)	http://www.epa.gov
US Geological Survey (online water data and publications)	http://www.usgs.gov/water/
US Geological Survey, reservoir/fluvial sedimentation website	http://ida.water.usgs.gov/ressed/

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