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CHAPTER 12

Reservoir Sedimentation

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12.1 INTRODUCTION

Manual 54 was originally published in 1975, toward the end of a period of intensive dam building worldwide. Sedimentation investigations at that time focused primarily on computing rates of sediment inflow, predicting sediment-induced shifts in the stage–storage curve over time, sizing dead pools typically equivalent to 50 or 100 years of sediment storage, and determining the "life of the reservoir." Today an increasing number of dams are reaching the end of their "design life," and their operation is increasingly affected by long-term sedimentation issues ignored at the time of construction.

Dams represent a unique category of engineered infrastructure because their eventual obsolescence is determined by the geologic processes of erosion and sedimentation rather than by engineered works themselves, which can be continually rehabilitated. When sedimentation is controlled, dams can have useful lives greatly exceeding any other type of engineered infrastructure. For example, Schnitter (1994) lists 12 ancient dams that had operational periods exceeding 2,000 years. Four of these are still in operation, five have been rehabilitated and are operating again, and only three are no longer operational. However, absent sediment control, today's dams represent an unsustainable pattern of water resource development.

There are over 75,000 dams in the United States, of which over 7,000 are classified as large dams having a height of at least 15 m. Most U.S. rivers have been essentially fully developed with respect to dams, and the rate of dam construction in the U.S. and worldwide has decreased dramatically since the 1970s (Fig. 12-1).

Dam sites are limited, and the best sites, which were developed first, are accumulating sediment. New dams can replace silted reservoirs in some cases but not others, with the largest and most important reservoirs being virtually irreplaceable. Siting obstacles to new reservoirs are formidable, and even when technically feasible alternative dam sites exist, they may not be feasible from the economic, social, political, or environmental standpoint. This leaves today's owners and engineers facing long-term sedimentation issues ignored in the original project concept.

In 1946, Brown recognized that major reservoirs are irreplaceable, and at the brink of the most active period of dam construction in U.S. history, he wrote,

> If the contemplated public and private reservoir construction programs are carried out, we shall have utilized by the end of this generation a very substantial portion of all the major reservoir sites. . . . We cannot discover new reserves, as we will of oil. Nor can we grow new resources, as we can of forests. To whatever degree we conserve the capacity of the reservoirs built on these sites, to just that degree shall we conserve this indispensable base of our national strength and prosperity.

Whereas the twentieth century focused on dam construction, the twenty-first will focus on sustaining the function of existing infrastructure as it becomes increasingly affected by sedimentation.

Most natural river reaches are approximately balanced with respect to sediment inflow and outflow. Dam construction dramatically upsets this balance by creating a quiescent reach that accumulates sediment until the balance between sediment inflow and outflow is again reestablished. The objective of sediment management is to manipulate the river–reservoir system to achieve sediment balance while retaining as much beneficial storage as possible and minimizing environmental impacts and socioeconomic costs.

In addition to determining the rate of storage loss, sedimentation issues today are becoming increasingly focused on issues such as (1) continuation of reservoir operation beyond the original design life despite sediment accumulation,

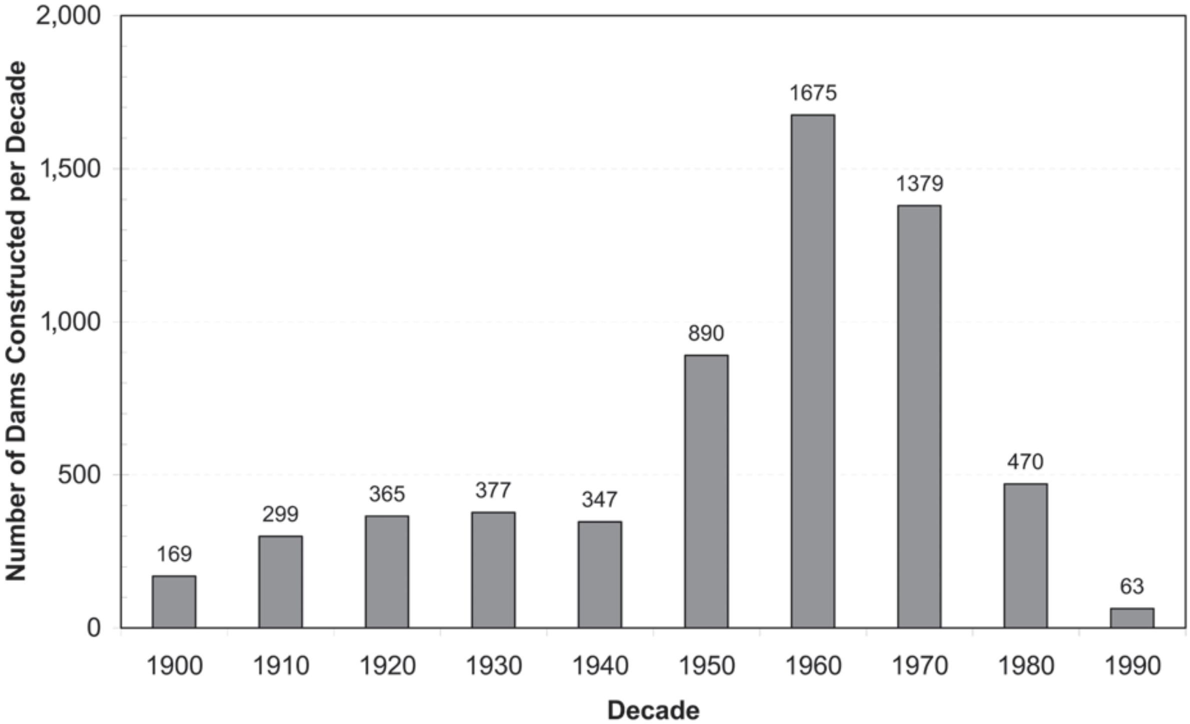

Fig. 12-1. Rate of large dam construction in the United States (data from USCOLD 1994).

(2) modification of existing structures and operating rules to minimize sedimentation impacts, (3) design and management of new reservoirs to minimize sediment accumulation, (4) dredging and other sediment removal techniques, (5) sediment impacts associated with dam decommissioning and removal, and (6) sediment management to minimize or mitigate environmental impacts. Environmental issues associated with reservoir sedimentation include the consequences of altered sediment supply and regulated flows on the morphology and ecology of downstream channels. Sediment management is also a primary environmental issue associated with the decommissioning of dams because dam removal will expose deposits to scour and can potentially release large volumes of sediment and any included contaminants to the downstream channel.

There are three basic themes in this chapter. First, basic sustainable use concepts pertinent to dams and reservoirs are introduced. Second, concepts of sediment delivery processes and sampling are introduced. This topic is presented because sediment management for sustainable use requires a more detailed understanding of sediment delivery processes than the traditional approach of simply determining long-term yield to compute the rate of sediment accumulation. The third theme describes basic sediment management strategies applicable to reservoirs.

This chapter presents only a summary introduction to this complex topic, and additional resources should be consulted. The following references represent a useful starting point. Morris and Fan (1998) provide a comprehensive treatise on sediment management in reservoirs and regulated river systems, including background descriptions of measurement, monitoring and modeling techniques, case studies, and an extensive bibliography. The World Bank's emerging approach to Reservoir Conservation (RESCON) is described by Palmieri et al. (2003) and Kawashima et al. (2003). An overview of reservoir-flushing techniques is provided by Atkinson (1996) and White (2001). Strand and Pemberton (1987) present a summary of reservoir sedimentation techniques used by the U.S. Bureau of Reclamation, and Corps of Engineers procedures are outlined by the U.S. Army Corps of Engineers (1989). Additional information is provided by Annandale (1987).

12.2 SEDIMENTATION RATES

12.2.1 Sedimentation Rates Worldwide

Sedimentation rate may be expressed as of the percentage of total original reservoir volume lost each year. Crowder (1987) estimated the rate of storage loss in the coterminous 48 states in the United States at 0.22% per year. Data on U.S. reservoirs compiled by Dendy et al. (1973) showed that storage loss tends to be more rapid in smaller reservoirs than in larger ones due to generally higher capacity: inflow ratios and lower specific sediment yields in the latter. The rate of storage loss in other parts of the world is generally higher than in the United States, and Mahmood (1987) estimated that storage capacity worldwide is being lost at an annual rate of 1%,

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Table 12-1 Worldwide Rates of Reservoir Sedimentation

Region	Inventoried large dams	Storage (km^3)	Annual percent storage loss by sedimentation
China	22,000	510	2.3
Asia excluding China	7,230	861	0.3–1.0
North America	7,205	1,845	0.2
Europe	5,497	1,083	0.17–0.2
South and Central America	1,498	1,039	0.1
North Africa	280	188	0.08–1.5
Sub-Sahara Africa	966	575	0.23
Middle East	895	224	1.5
Worldwide	45,571	6,325	0.5–1.0

Source: Adapted from White (2001).

and estimates compiled by White (2001) are summarized in Table 12-1. The world is now losing reservoir capacity much faster than new capacity is being constructed.

Within a given geographic region, there are wide variations in the rate of storage loss. For example, Gogus and Yalcinkaya (1992) examined data from 16 reservoirs in Turkey and computed a mean annual rate of storage loss of 1.2%, but the rates for individual reservoirs ranged from 0.2% to 2.4%. In India, Morris (1995) estimated an annual rate of storage loss of 0.5%, meaning that about half of India's total reservoir capacity will be lost during the twenty-first century. However, the least affected 20% of the reservoirs will not lose half their capacity until after the year 2500. Thus, the problem is highly site specific, and new reservoir construction at a geographically distant location will not solve a local water supply problem stemming from sedimentation. Only in the case of hydropower can a distant new site offset local problems because, unlike water, electricity can be transported for long distances at low cost.

12.2.2 Reservoir Half-Life

Common practice has been to compute "reservoir life" by dividing total reservoir volume by annual sedimentation volume during the early years of impoundment, thereby estimating the number of years to completely fill the reservoir. However, in most reservoirs, sediment will seriously interfere with design functions by the time half the storage pool is lost (Dendy et al. 1973; Murthy 1977). *Reservoir half-life,* the time required to lose half the original capacity to sedimentation, is thus a much better approximation of when sedimentation problems will become truly serious. At many sites, sediments will seriously interfere with reservoir function when much less than half the original capacity has been lost. For example, Loehlein (1999) describes problems including hindered floodgate operation and clogging of hydropower and water supply intakes due to sedimentation at several Corps of Engineers flood control reservoirs in Pennsylvania, with only 6% storage loss.

12.2.3 Reservoir Life

Reservoir life has traditionally been conceptualized based on the continuous filling of the usable storage pool, presumably followed by abandonment of the structure. However, the "life" of a reservoir is better described based on the three distinct stages:

Stage 1: *Continuous sediment trapping*. During the first stage of reservoir life, continuous sediment trapping occurs during all inflowing flood events. A cross section perpendicular to the axis of the reservoir in continuously impounded areas will reveal a depositional sequence that fills the deepest part of the cross section first, eventually producing sediment deposits that are essentially flat (Fig. 12-2).

Stage 2: *Partial sediment balance*. During the second stage, the reservoir transitions from a continuously depositional environment to a mixed regime of deposition and removal. If sedimentation is allowed to proceed uninterrupted, the reservoir at this stage will become largely filled with sediment, and a channel–floodplain configuration will develop in the former pool area. The inflow and discharge of fine sediment may be nearly balanced, but coarse bed material continues to accumulate. Sediment management techniques, such as drawdown to pass sediment-laden flood flows through the impounded reach or periodic flushing, can produce a partial sediment balance to help preserve useful reservoir capacity.

Stage 3: *Full sediment balance*. A long-term balance between sediment inflow and outflow is achieved when both the fine and the coarse portions of the inflowing load can be transported beyond the dam or artificially removed on a sustainable basis. However, sediment movement through the impounded reach is not necessarily the same as the preimpoundment condition because sediment may accumulate during smaller events and be washed out during large floods or may be removed at intervals by dredging or flushing.

Most reservoirs worldwide are in Stage 1, continuously trapping sediment. Only a handful of reservoirs worldwide have been designed to achieve sediment balance. A notable example is the large (more than 600 km long) Three Gorges reservoir on China's Yangtze River, designed to reach full sediment balance after about 100 years.

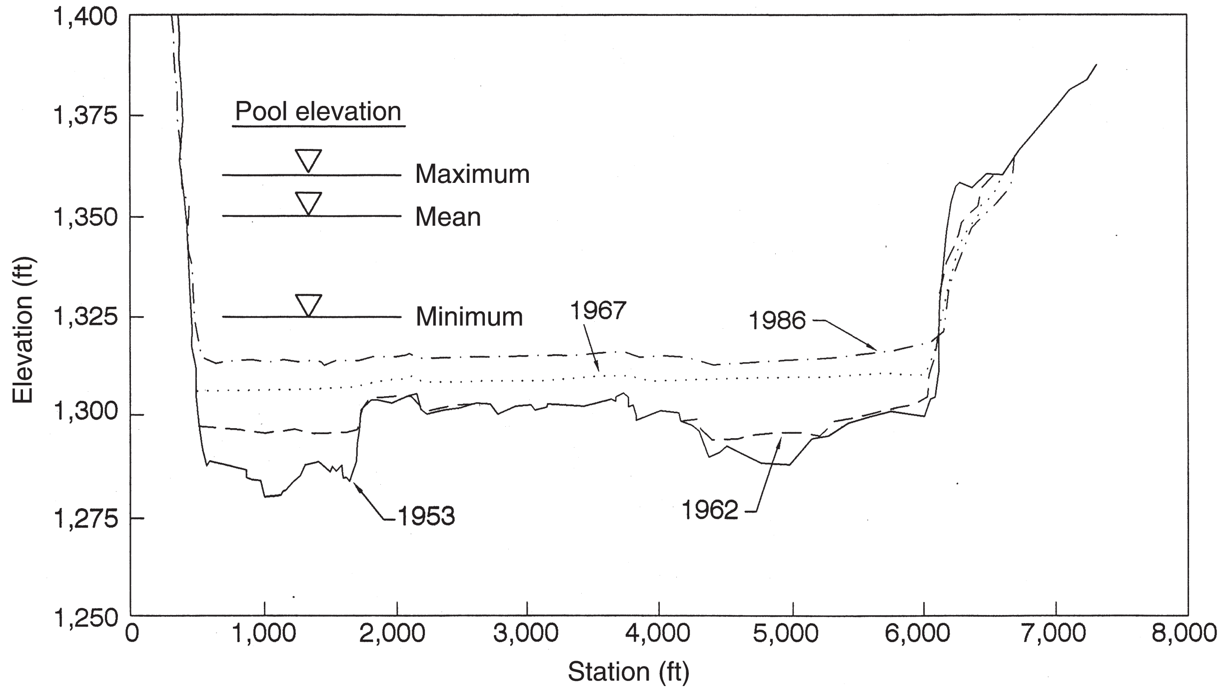

Fig. 12-2. Successive cross sections of Lake Francis Case on Missouri River above Ft. Randall Dam, showing the deposition of sediment in flat beds (Stanley Consultants 1989).

12.2.4 Capacity–History Curves

Reservoir volumetric capacity will steadily diminish in a reservoir that is continuously impounded, although the rate of storage loss will tend to decrease as the reservoir's hydrologic size and trap efficiency diminish (Brune 1953). Sediment management can retard or reverse this trend, and storage capacity can increase over time as sediment is removed. Capacity–history curves may be drawn to illustrate historical and anticipated changes in usable storage volume under different management options.

Illustrative capacity–history curves are given in Fig. 12-3, illustrating the case where sediment management is initiated when half the reservoir capacity has been lost. This example compares dredging alone versus dredging in combination with pass-through routing of major sediment-producing floods. The rate of sediment accumulation eventually decreases under the do-nothing alternative because of the declining capacity to inflow ratio (Brune, 1953). Similar curves may be constructed for other types of sediment management operations and can be useful in visualizing the impacts of alternative strategies on the long-term evolution of the reservoir.

12.3 SUSTAINABILITY

12.3.1 Sustainability and Economic Analysis

The underlying concept of sustainable development is that the welfare of future generations (including our own children and grandchildren) should logically figure into the project decision-making process. This concept arose from the recognition that many development and resource utilization patterns could not be sustained in the long term, coupled with the failure of conventional economic analysis to formally consider impacts over periods as short as a single human life span. Reservoirs arguably represent today's most important class of nonsustainable infrastructure.

Definitions of sustainable development have proliferated, but the following basic concepts are most relevant from the standpoint of water resource infrastructure: (1) Today's patterns of infrastructure development should not compromise the ability of future generations to access these same resources. (2) Maintain biological diversity and environmental integrity. (3) Minimize the potential for catastrophic disasters resulting from infrastructure failure or obsolescence. (4) Avoid activities that create a legacy of environmental restoration or infrastructure rehabilitation obligations that fall disproportionately on future generations.

Hotchkiss and Bollman (1996) have emphasized the need to assess project configurations on the basis of long-term parameters rather than relying solely on limited-horizon economic performance. Project economic analysis is based on benefit-cost techniques in which the future streams of benefits and costs are time discounted. Using a discount rate of 7%, for example, the present value of a \$100 benefit 50 years in the future is only \$5.83, and end-of-project decommissioning costs are typically ignored. Traditional discounting procedures discourage additional construction costs aimed at sustaining long-term function, such as large low-level flushing outlets that do not produce quantifiable

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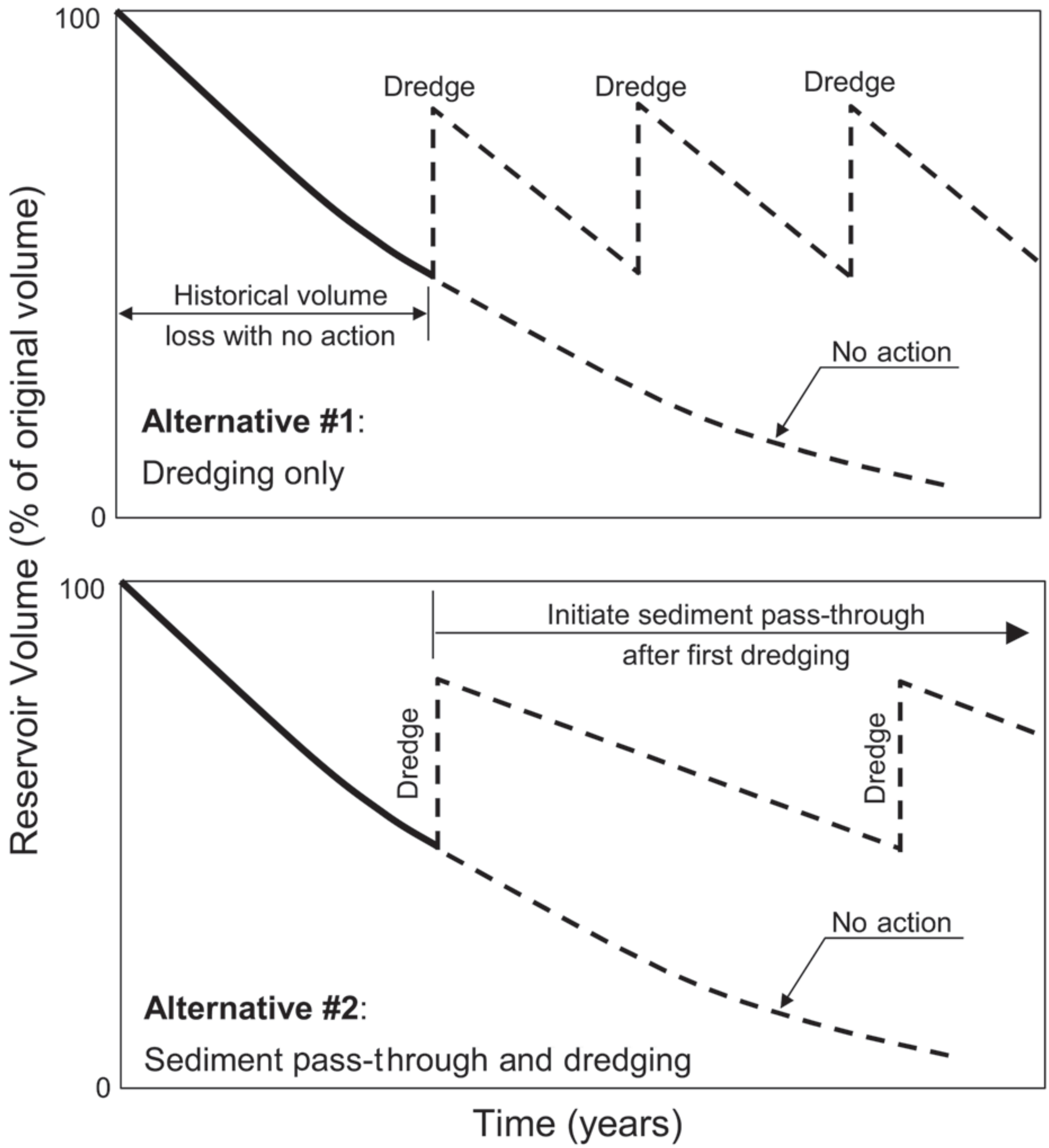

Fig. 12-3. Alternative storage history curves to conceptually illustrate sediment management alternatives, dredging only versus sediment-pass through with less frequent dredging.

economic benefits during the initial decades of reservoir life. Despite the logic behind sustainability considerations and the technical feasibility of a variety of preventive sediment management options, there is usually little economic incentive for an owner to invest today in strategies that reduce future sedimentation problems.

Cairns (1993) concluded that short-term economic gain overrides long-term sustainability or ecological considerations. He observed that historical development in the United States has followed this policy and that the same policy is definitely being pursued in developing countries. Weiss (1993) points out that market conditions also tend to be evaluated within the context of the present generation, and the needs of future generations are not explicitly represented. In addition to the problem posed by limited planning horizons, the benefit-cost analysis is not always appropriate for two other reasons: (1) incomplete information and improper valuation of impacts and (2) uncertainties in future markets. Most secondary impacts of reservoir sedimentation are not included in benefit-cost analysis. O'Neil

(1997) concluded that uncertain futures, both economic and technological, make the use of benefit-cost analysis for far-distant project impacts questionable.

Requiring a reservoir life measured in terms of generations instead of decades will demand new methods of analyzing costs and benefits. Palmieri et al. (1998) demonstrate that "for a very wide range of realistic parameter values, sustainable management of reservoirs is economically more desirable than the prevailing practice of forcing a finite reservoir life through excessive sediment accumulation." They reach such a conclusion after comparing the salvage value of projects to the cost of continuing dam operation. They suggest than an annual contribution to a "retirement fund" or to an "insurance policy" will affect future salvage value and may extend the economic life of a reservoir indefinitely.

12.3.2 The RESCON Approach

The RESCON (REServoir CONservation) approach to sustainable reservoir management developed under the auspices of the World Bank is described by Palmieri et al. (2003), and its technical details are outlined by Kawashima et al. (2003). The methodology proceeds in three stages: (1) determine which methods of sediment management are technically feasible; (2) determine which alternatives are more desirable based on an economic analysis; and (3) incorporate environmental and social factors to select the best course of action for sediment management.

The RESCON methodology can be applied to proposed or existing dams and reservoirs to make a preliminary assessment of sustainable management alternatives, and to compare them to the nonsustainable alternative of allowing the reservoir to silt up and implement decommissioning procedures at the end of a dam's physical life. Should the latter choice be identified as the only feasible alternative, a sinking fund to pay for decommissioning should be established to ensure intergenerational equity?

The RESCON approach accounts for all major benefits and costs over the complete project life-cycle and, in particular, acknowledges the need for intergenerational equity. This is achieved by maximizing the algebraic sum of net benefits, capital cost, and salvage value, that is,

$$Maximize \sum_{t=0}^{T} NB_t \cdot d^t - C2 + V \cdot d^T,$$

subject to

$$S_{t+1} = S_t - M + X_t,$$

given the initial capacity S_0 and other physical and technical constraints, and where: NB_t = net benefit in year t; d = discount rate factor defined as $1/(1 + r)$, where r = discount rate; $C2$ = initial capital cost of construction (= 0 for existing facilities); V = salvage value; T = terminal year; S_t = remaining reservoir capacity (volume) in year t; M = trapped annual incoming sediment; and X_t = sediment removed in year t.

In the case of reservoirs, the salvage value V is usually negative as it represents the cost of decommissioning at terminal year T, should this prove the most economical solution. Allowance for intergenerational equity is made by creating a sinking fund that will create a large enough retirement fund to decommission the facility, if required. The annual investment, k, into the sinking fund is calculated as

$$k = -m \cdot V / \left[(1+r)^T - 1 \right]$$

where m = interest rate (which can differ from the discount rate r). When assessing the economic feasibility of a decommissioning option, k is subtracted from the net benefits on an annual basis.

12.3.3 Regulatory and Legal Aspects

Important sustainability criteria are already established by regulation or law rather than economic analysis, such as the requirements for environmental protection and dam safety. From the owner's standpoint, these may be viewed as onerous and uneconomic measures, and it is precisely this difference in perception between the owner and society in general that has given rise to socially protective regulations and engineering standards. From this standpoint, it may be logical for the engineering community to develop minimum standards for considering long-term sustainability in future design and management activity related to reservoir sedimentation.

A logical starting point would be to formally evaluate and incorporate to the extent possible measures to sustain long-term capacity in all designs for new reservoirs, or significant modifications to existing ones. These measures are not necessarily costly. For example, in a new reservoir having crest gates and where sediment pass-through may eventually be feasible, this future option is facilitated by the specification of bottom-opening gates, as opposed to bascule gates which are unsuited to passing sediment. Similarly, outlets for river diversion during construction might be closed, but not filled with concrete, to facilitate the installation of bottom gates at some point in the future.

Legal and liability considerations will also have impacts on sediment management activities. In addressing this issue, Thimmes et al. (2005) have pointed out that the dam owner may be liable for the accumulation of sediment within

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the reservoir that causes upstream flooding, as well as for impacts of sediment release downstream.

12.4 SEDIMENTATION IMPACTS

Sedimentation impacts not only the impoundment but also areas extending far downstream and short distances upstream of the design pool. Typical impacts are outlined in Table 12-2. Fig. 12-4 presents a highly simplified longitudinal profile along a reservoir, illustrating the various patterns of sediment deposition and associated impacts.

The primary sedimentation impact within a reservoir is storage loss that impairs water supply, hydropower, flood control, and both commercial and recreational navigation. The impacts of storage loss on water supply yield may be quantified as a gradual reduction in firm yield based on the storage–yield relationship for the site or as the increased risk (increased frequency) of water shortage with time when attempting to maintain a stated rate of withdrawal.

Coarse sediments (>0.6 mm diameter) can abrade hydromechanical equipment, and sediment deposits against the dam may increase the static loading on the structure. The presence of contaminants in sediments (Chapter 21) can greatly hinder any procedure that would release these sediments, such as dredging, flushing, or dam removal (Chapter 23).

Deltas can form where the main or side tributaries discharge into a reservoir, and these deltas will create backwater and bed aggradation above the normal pool level (Chapter 2). This deposition can create problems such as increased frequency and depth of flooding, decreased navigational clearance at bridge crossings, and sedimentation of upstream water intakes. Streambed aggradation will increase groundwater levels, which in turn can saturate vegetative root zones and waterlog riparian agricultural soils, increase soil salinity, and alter ecological habitats.

Below a dam, the river will adjust to both reduced sediment inputs and the altered stream flows produced by reservoir releases. Dams are highly efficient bed-load traps, and even reservoirs operated for sediment release may trap most of the inflowing bed material. Reservoir trapping of bed material encourages channel incision along the river reach below the dam, lowering the base level of the river. This can trigger processes much the opposite of those upstream: degradation of tributaries, destabilization and undercutting of streambanks, undermining of bridge piers and river training works, and sediment starvation of river bars and beaches important for both environmental and recreational benefits. Sediment starvation will also reduce aggregate supplies in the stream channel and contribute to coastal erosion.

Also, as the base level in the river incises in response to sediment trapping by the reservoir, channel degradation

Table 12-2 Sedimentation Impacts

Impact location and type	Impact description
Within-reservoir impacts:	
Storage loss	Reduced firm yield, hydropower, and flood-control benefits.
Reservoir operations	Sediment can clog intakes, interfere with gate operation, and abrade hydromechanical equipment.
Organic sediments	Oxygen demand can make bottom waters anaerobic.
Turbidity	Reduced euphotic zone and decreased primary productivity. Aesthetically unpleasant for recreation.
Navigation	Sedimentation of marinas and navigation channels. Interferes with recreational use and sport fisheries.
Air pollution	During drawdown, fine sediment exposed to air can dry out and be carried by wind.
Above-reservoir impacts:	
Delta deposition	Higher river levels flooding and reduce navigational clearance beneath bridges. Groundwater levels can rise causing soil waterlogging, salinization, and increased evaporation from vegetated deltas.
Below-reservoir impacts:	
Reduced bed-material load	Streambed incision and accelerated bank erosion. Bed may become too coarse for spawning. Structures such as bridges, intakes, and training works may be undermined. Cutoff of sand supply contributes to coastal erosion. Reduced supply of aggregate materials.
Reduced fine sediment load	Reduced nutrient delivery to downstream ecosystems. Increased water clarity will alter ecological conditions and benefit recreational use.

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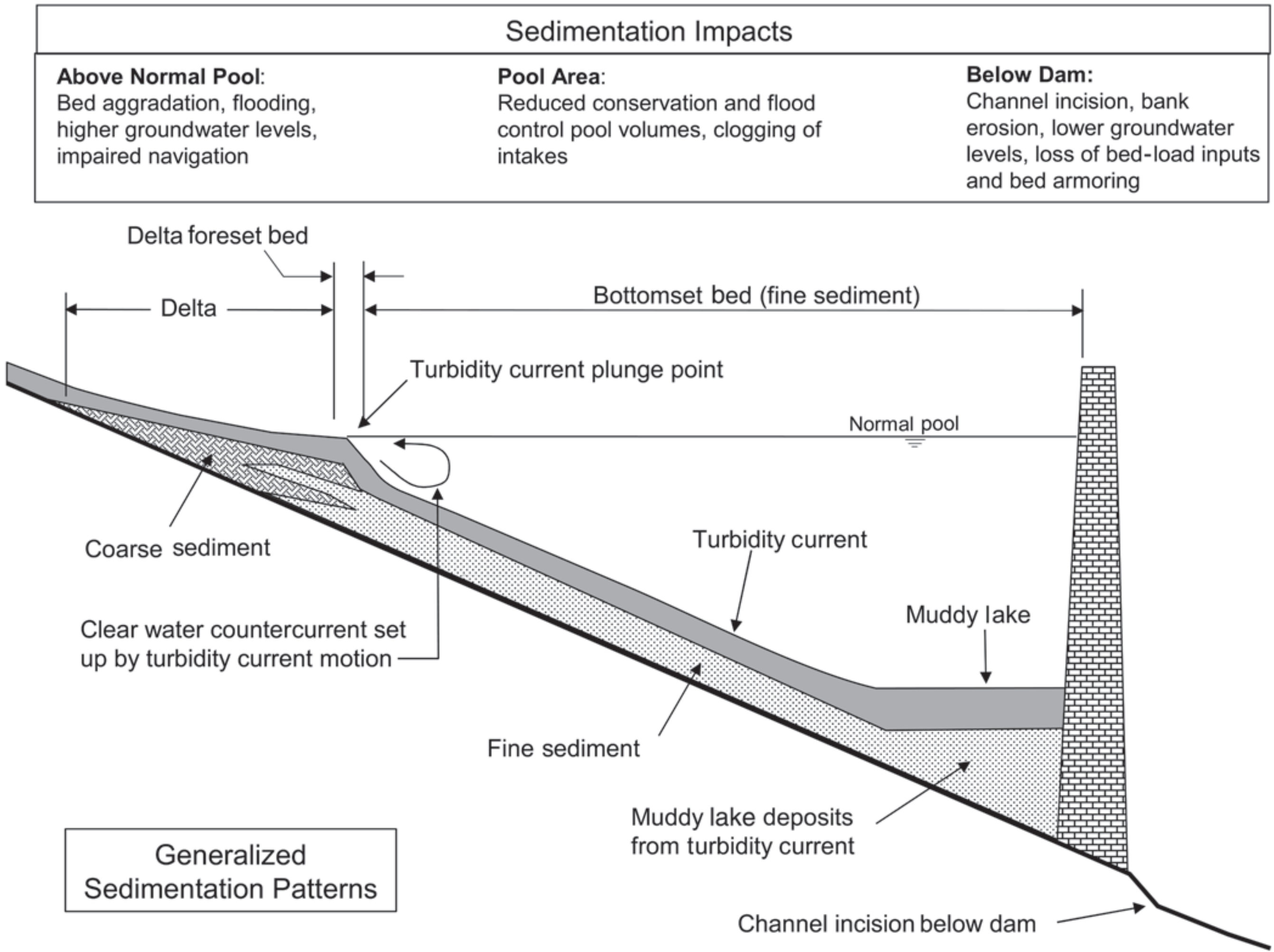

Fig. 12-4. Deposition patterns in reservoirs and classes of sediment-related impacts imposed by the dam.

can proceed upstream along tributaries and thereby affect stream reaches not themselves directly below the dam and thus unaffected by reservoir hydrology. Lower groundwater levels can result in loss of riparian vegetation and dewatering of wetlands. Fish habitats may degrade as a smaller fraction of the bed material is washed downstream, leaving behind an armored bed too coarse for fish spawning.

Dams reduce downstream flood peaks even in reservoirs not operated for flood control. This reduces the energy available to mobilize bed material, allowing an armor layer to form with smaller material than in the predam river channel (Chapter 3). This peak flow reduction and armoring will limit channel degradation below the dam, but without periodic mobilization of the armor layer and flushing of fines from the riverbed sediment, the immobilized bed can become useless for spawning and habitat. Although streambed degradation and bed-material coarsening below dams tend to occur in the first decades after construction, the process occurs erratically rather than as a uniform progression (Williams and Wolman 1984).

Channels below dams do not always degrade. When the dam significantly reduces downstream flows and sediment transport capacity yet below-dam tributaries continue to deliver large sediment loads to the river, the channel may aggrade, as in the case of Río Grande at Presidio, Texas, below Elephant Butte reservoir (Collier et al. 1995).

There is growing appreciation that the long-term impacts of dams on river systems have often been underestimated or even ignored, that dams can cause unnecessary environmental damage, and that the wise development and utilization of environmental resources is incompatible with the destruction of biological habitats. However, with proper management, these impacts can be greatly diminished. Environmental and related impacts of dams have been reviewed by Goldsmith and Hildyard (1984, 1985), McCully (1996), and Petts (1984).

River channels are maintained by periodic flood events, and the channel-forming event typically has a return interval of about 1.5 years (Leopold et al. 1964; Simon and Heins 2005). When downstream flood releases are reduced,

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the channel can no longer maintain its original size and is encroached on by vegetation, as shown in the example pictured in Fig. 12-5. Ligon et al. (1995) described impacts on the McKenzie River in Oregon by flow regulation in two Corps of Engineer dams that reduced peak discharges by over 50%. Reduced flows allowed channel simplification, channel stabilization, and vegetative encroachment, substantially reducing the areas of gravel suitable for salmon spawning. They also reduced the area of sloughs, backwaters, and traces of former channels created by meander cutoffs, habitat required for rearing juveniles.

The increased resistance of public and environmental organizations to new reservoir construction is a logical reaction to the extensive reservoir building that has already occurred and to the impacts of dams on free-flowing rivers, including impacts not necessarily understood by their original designers. By 1990, a total of 965,000 km of rivers had been submerged by dams in the United States, versus only 15,000 km protected under the Wild and Scenic Rivers Act (Graf 1993). Much of the "wild and scenic" river mileage is itself downstream of or sandwiched between dams.

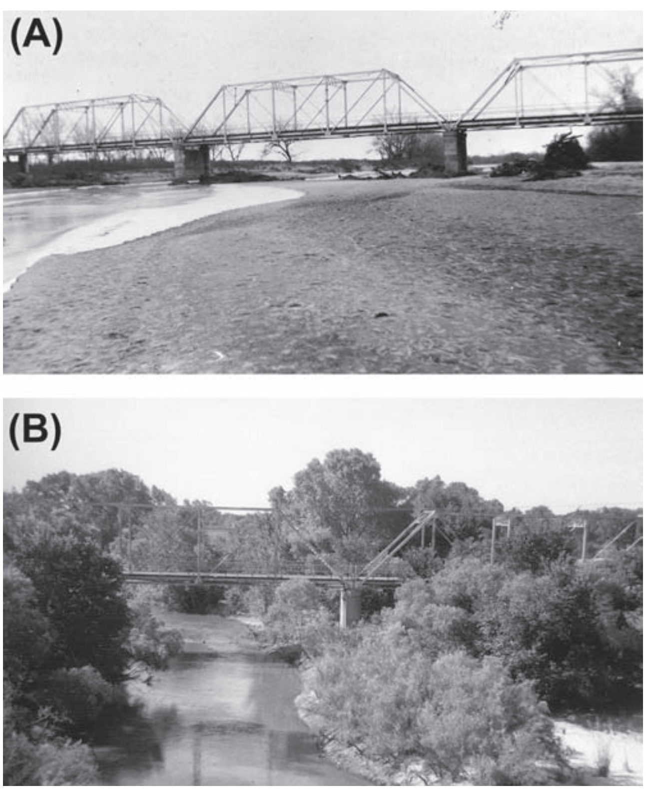

Fig. 12-5. Encroachment of vegetation into channels of North Canadian River 0.8 km below Canton Dam, Oklahoma, due to reduction in channel-maintaining flows. Photos taken in (A) 1938 and (B) 1980 (Williams and Wolman 1984).

12.5 SEDIMENT DELIVERY TO RESERVOIRS

Sediment yields vary remarkably over time and space, and this variability must be understood to properly interpret data, to predict sediment yields, and to successfully implement strategies for reducing sediment inflow or passing sediment-laden flows around or through the storage pool. This section outlines basic concepts of variability in sediment yield and delivery to reservoirs. The discussion focuses on suspended load because it is responsible for most sediment discharge worldwide, but basic concepts are generally applicable to the bed load as well.

12.5.1 Erosion and Sediment Yield

Erosion is the process of detaching particles from the soil matrix and initiating their transport away from the point of detachment. Erosion rates are measured using small plots, and the distance that a particle must travel before being counted as having been "eroded" may be a few meters or less. Erosion rates from farms and watersheds are computed by empirical models, such as the Universal Soil Loss Equation (USLE) and its variants (MUSLE, RUSLE), or the more complex physically based detachment and transport models, such as AGNPS, ANSWERS, CREAMS, SEDIMONT, and WEPP.

Sediment yield is the amount of sediment transported beyond or delivered to a specified point in the drainage network over a specified time period. It is always less than and typically much less than the amount of sediment eroded within a watershed due to redeposition prior to reaching stream channels or reservoirs. Watershed sediment yield is also addressed in Chapter 17.

Sediment delivery ratio is ratio of eroded sediment to delivered sediment. Because erosion rates are computed rather than measured, the sediment delivery ratio is actually the ratio of computed erosion to measured yield. Sediment yield estimates derived from erosion estimates are typically more sensitive to errors in estimating the sediment delivery ratio than to errors in erosion rate. For example, with a sediment delivery ratio equal to 10% of erosion, a 1% error in estimating sediment delivery ratio would have the same impact on computed sediment yields as a 10% error in the erosion estimate. For a good review of the problems associated with estimating sediment delivery ratio, see Walling (1983).

12.5.2 Spatial Variation in Sediment Yield

Sediment yield is highly variable over space, and a small part of the landscape unit will contribute a disproportionate amount of the total sediment yield. Dividing total sediment discharge by total basin area to obtain the average yield can be grossly misleading by masking the underlying variability in sediment yield (Campbell 1985). Variations in specific sediment yield, the sediment yield per unit of land area, can be particularly

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Table 12-3 Sediment Yield from Gauge Stations Worldwide

Yield Class (tn/km^2/year)	Number of Gauge Stations	Gauged Land Area (%)	Total Gauged Sediment Load (%)
0–10	230	21.3	0.3
11–50	285	25.6	1.8
51–100	172	11.9	2.1
101–500	426	25.6	14.7
501–1,000	145	6.9	12.0
>1000	179	8.8	69.1

Source: Jansson (1988).

Table 12-4 Median Suspended Sediment Characteristics of 1.5-year Discharge at USGS Gauge Stations, Selected U.S. Ecoregions

Ecoregion	Number of Stations	Concentration (mg/L)	Specific Yield ($tn/d/km^2$)
Northern Rockies	13	30.13	0.05
Arizona—New Mexico Plateau	40	4143	6.5
Middle Atlantic Coastal Plain	22	22.1	0.16
Mississippi Valley Loess Plains	33	2175	173

Source: Data from Simon and Heins (2005).

dramatic in watersheds subject to disturbance. For example, Megahan (1975) showed that, compared to natural conditions, logging increased specific sediment yield by a factor of 1.6 on forest soils subjected to tree felling and skidding but by a factor of 550 on logging roads subject to mass erosion. For this reason, erosion control on forestlands focuses foremost on logging roads. On a larger scale, Jansson (1988) analyzed data from 1,358 gauge stations worldwide with tributary watersheds between 350 and 100,000 km^2. These data, summarized in Table 12-3, show that only 9% of the land area accounts for 69% of the sediment load. Effectively targeting erosion-control efforts requires that the landscape units and land use practices responsible for most sediment delivery be identified.

Sediment yield is particularly sensitive to vegetative cover. Thus, in selecting data sets for use in the estimation of sediment yield at an ungauged site or to confirm the reasonableness of an available data set, data should be compared within ecoregion. Background material and GIS mapping products for North American ecoregions can be found on several sites by Internet search. The Holdridge life zone system of ecological classification, more widely used in tropical areas, may represent another suitable landscape classification method.

An example of suspended sediment variability in the United States is presented by Simon and Heins (2005). They examined suspended sediment characteristics of the effective discharge, defined as the discharge or range of discharges that transport the largest proportion of the annual suspended sediment load over the long term (Wolman and Miller 1960). The 1.5-year discharge ($Q_{1.5}$) approximates the effective discharge. The range of median concentration and daily load values corresponding to the $Q_{1.5}$ discharge for representative ecoregions are illustrated in Table 12-4. Although the highest concentrations occur in the semiarid Arizona–New Mexico area, the highest yield occurs in a moist environment with erodible soils.

The size of the area analyzed can have a significant impact on both delivery ratio and sediment yield. The long-term delivery ratio decreases as watershed area increases because the opportunity for sediment trapping increases as a function of the distance from the erosion source. As a result, both delivery ratio and sediment yield tend to vary as a log-log function of drainage area (Fig. 12-6), although this trend may not be evident in all data sets.

12.5.3 Temporal Variation in Sediment Yield

Suspended sediment concentration typically increases as a function of discharge, making sediment yield more concentrated in time than the discharge of water (Chapter 2). In their review of data from stream gauges in the United States, Meade and Parker (1984) found that 50% of the annual sediment load is discharged on 1% of the days. Extreme storms or cycles of wet and dry years can dramatically influence annual yield, and it is not unusual for a single large storm event to deliver more sediment than an entire year of average flows. Uncertainty parameters affecting annual sedimentation rates have been analyzed by Salas and Shin (1999).

That most sediment yield is high focused in time implies that large sediment reduction benefits can be achieved from control methods focused on these highest-discharge days. In hydrologically small reservoirs having a capacity–inflow ratio less than about 0.2, it may not be necessary to capture every runoff event; large but infrequent sediment-producing events may be passed around or through the storage pool.

Sediment yield is also heavily influenced by land use changes such as deforestation or reforestation, changes in grazing intensity, and urbanization and by climatic variation. For example, analysis of sediment cores covering 110 years of impounding at Fairfield Lake, North Carolina, revealed a several-fold increase in the rate of sediment deposition following relatively limited urban development activities in its 7.3-km^2 watershed.

Techniques for evaluating long-term sediment yield have been summarized by Strand and Pemberton (1987) and MacArthur et al. (1995). They are also considered in Chapter 17. Long-term trends can be visualized by constructing a cumulative mass curve for water and sediment,

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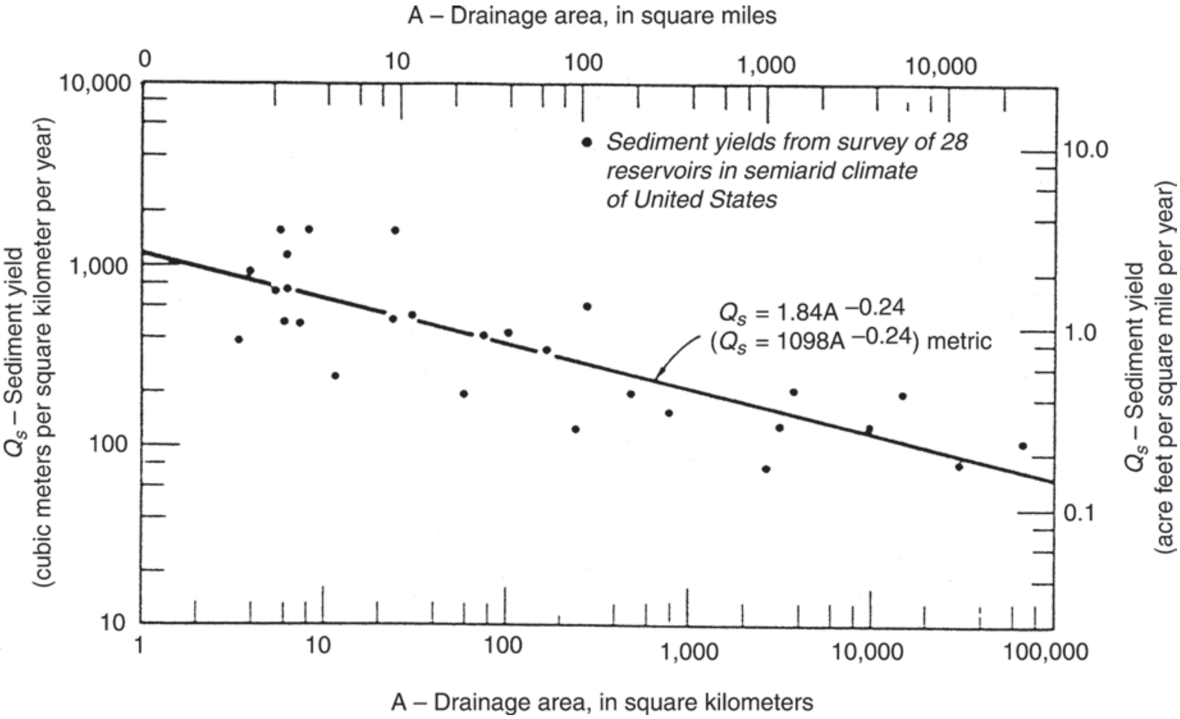

Fig. 12-6. Average annual sediment yield versus drainage area for semiarid areas of the United States (Strand and Pemberton 1987).

as in Fig. 12-7. This format gives a better idea of trends than a timewise plot since it helps compensate for runoff variability. Lacking site-specific data, long-term sediment yield can be estimated by data from similar watersheds within the ecoregion. Sediment yield data from various sources may be plotted on a log-log graph of yield versus drainage area for verification. Plotting yield data from several regional sources (Fig. 12-8) can help arrive at a better sediment yield estimate when site-specific data are sparse or are collected over a short time period (Burns and MacArthur, 1996).

In applying regional curves to a particular study site, take care to consider local features such as upstream reservoirs, a history of fire, and land use, topographic, or geological conditions that may depart from regional norms. Departures from average regional conditions by one or two orders of magnitude may be anticipated in heavily disturbed areas.

With long service lives, reservoirs will be affected by very long-term trends in sediment yield plus the years of lag time that may occur between changed erosion rates in the watershed and sediment delivery to the reservoir. As an example, consider the long-term changes in the erosion rates and sediment yield from the Piedmont area of the eastern United States from 1700 to 1970 documented by Trimble (1974, 1977). Deforestation for agricultural use began in the late 1700s, and the area was completely deforested by

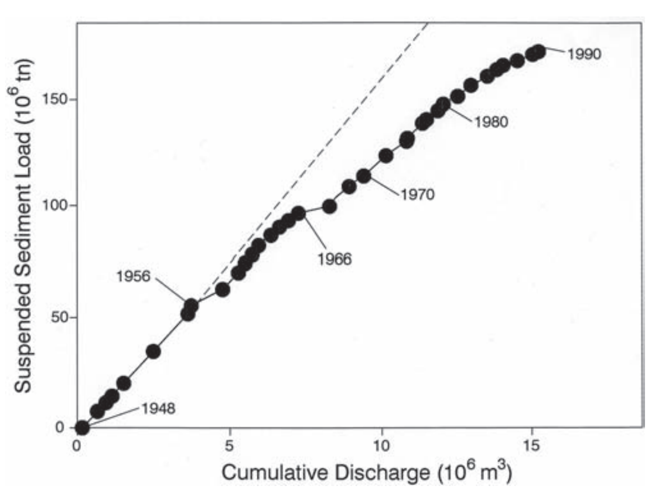

Fig. 12-7. Cumulative mass curve of water and sediment showing a long-term trend of declining sediment yield, Río Puerco, New Mexico (after Gellis 1991).

the mid-1800s, greatly accelerating erosion rates and sediment yield. Erosion rates declined after the 1920s as hillside farms were abandoned and revegetated naturally and soil conservation methods were developed and implemented on the remaining farms. Despite the erosion of 1 mm/year of soil over a 150-year period, export by rivers accounted for less than 0.053 mm/year (a sediment delivery ratio of

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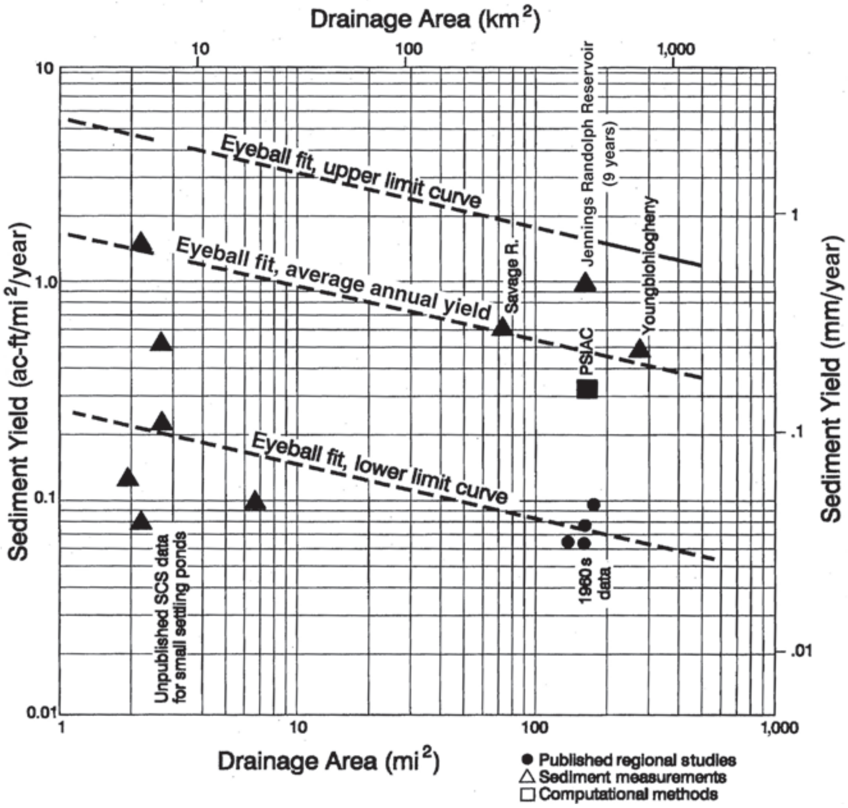

Fig. 12-8. Regional values of sediment yield versus drainage area, Jennings Randolph Reservoir (Burns and MacArthur 1996).

only 5.3%) because eroded sediment was redeposited further downslope in downstream channels and on floodplains. Debris filled streams and covered floodplains, and stream aggradation frequently swamped adjacent bottomlands, making them unfit for agriculture. Today, with low rates of erosion, the aggrading stream reaches are now incising.

Long-term sediment yield may also decline as the watershed degrades and the supply of readily erodible sediment is progressively exhausted (Sutherland and Bryan 1988; Rooseboom 1992). Long-term variations in sediment yield from rivers in the semiarid southwestern United States appear to be cyclic and attributable to a complex interaction of variables including climate (sequence of drought years and floods) and grazing pressure (Gellis et al. 1991). Sediment yield data from Río Puerco exhibits a long-term trend due to these effects (Fig. 12-7). Fire can cause a temporary increase in sediment yield. In areas subject to urban development, sediment yield is typically low in the predevelopment period, increases dramatically during development because of earth movement activity, and declines to lower levels after all soils in the catchment are stabilized with pavement and landscaping (Livesey 1975). Long-term yield can also be reduced by construction a large upstream reservoirs or by thousands of small stock watering ponds across the watershed (Chapter 17).

There has been a tendency to underestimate long-term sediment yield, particularly in developing areas where increasing population pressure results in the deforestation of sloping soils. In a comparison of predicted sedimentation rates with actual performance at 21 reservoirs in India, Tejwani (1984) found that sediment yield was less than predicted at one site, but from 40% to 2,166% higher than predicted at the other 20 sites. Lagwankar et al. (1995) found sediment delivery 1.5 to 3 times higher than predicted in 24 of 27 Indian reservoirs. Major factors contributing to underprediction of sediment inflows are watershed degradation and the lack of accurate long-term records.

12.6 QUANTIFYING SEDIMENT YIELD

12.6.1 Estimating Sediment Yield by Reservoir Survey

There are two basic strategies for measuring sediment yield: (1) by the volume of sediment deposited in reservoirs and (2) continuous monitoring of fluvial sediment discharge. Reservoir resurvey data are generally more accurate because reservoirs collect sediment from all events since their construction, eliminating problems of missed or underreported events at fluvial gauge stations. They also reveal patterns of sediment deposition critical to evaluating remedial actions.

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As a disadvantage, reservoir data do not reveal the spatial or temporal patterns of sediment delivery needed to analyze some sediment management alternatives.

12.6.1.1 Bathymetric Survey Bathymetric data from successive reservoir surveys are used to track volume depletion and revise elevation–capacity curves; to predict the type, magnitude, and time horizon for sedimentation problems; to calibrate mathematical models of sedimentation; and to help develop and monitor the effectiveness of sediment management practices. For modeling of sedimentation processes, bathymetric mapping should be complemented with borings to determine the grain size of the deposits and verify estimates of deposit bulk density determined by empirical methods. Mathematical models of sedimentation processes are considered in Chapters 14 and 15.

Reservoir may be generally performed at intervals of about 5 to 20 years, but this can vary substantially depending on budgetary constraints, rate of storage depletion, the type and importance of the uses threatened by sediment accumulation, and management requirements. In reservoirs with very low rates of sedimentation, the intersurvey period may be several decades. Unscheduled surveys may be called for after a major flood delivers a large volume of sediment to the reservoir, and partial surveys may address specific issues such as shoreline erosion, delta advancement, and flood studies in delta and backwater areas. Periodic cross-section surveys should also be made in areas below the dam where the riverbed is expected to adjust because of the reduced sediment supply and changed stream-flow regime.

If the goal is to identify long-term sediment accumulation trends, more than 20 years of survey record encompassing several surveys may be needed before a reliable trend can be established. During the first years of reservoir operation, the apparent rate of storage loss may be higher than the long-term rate because of incomplete sediment compaction. When the intersurvey sedimentation volume is small compared to the total reservoir volume, estimates of deposition rate can be significantly affected by use of different survey techniques or volume computation algorithms.

Reservoir volume computations are performed by either range-line or contour surveys. The original volume of reservoirs is generally computed using the contour method based on preimpoundment topographic mapping. The range-line method uses a system of ranges (cross sections) selected and surveyed after initial impounding. Each range line is tied to the initial elevation–capacity relationship of the reservoir reach corresponding to that range (as determined by preimpoundment contour survey) and provides the base against which all future surveys will be compared. The range lines are resurveyed at intervals, and the elevation–capacity relationship is recomputed for each reach on the basis of the change in the cross-sectional area of each range line. This method has been widely used, as it allows sediment accumulation to be tracked using minimum field data.

The contour method entails the complete survey of the reservoir and preparation of a bathymetric contour map. This method is more accurate than the range-line method and gives a more complete picture of the pattern of sediment deposition. Contour surveys are facilitated by modern GPS and bathymetric measurement equipment and are preferred today.

Every survey method incorporates different types of data collection errors and approximations in the algorithms for volume computation. The same types of field data and computational algorithm must be used for each survey if results are to be strictly comparable. Therefore, when updating from the range method to contour surveying, compute the reservoir volume using both methods to determine how much of the apparent intersurvey volume change is attributable to differences in methodology.

Bathymetric surveys are typically performed using GPS positioning system in combination with a depth sounder, both connected to a portable computer that records the resulting *x, y, z* coordinate data into a file that can be processed subsequently to draw a contour map. Survey systems can also incorporate navigational features that allow the planned tracks to be laid out prior to the survey, giving directional instructions and positional plots to the operator during the survey. An example of this method is provided by Odhiambo and Boss (2004).

Accurate contouring requires that the data be checked and contour lines adjusted during postprocessing to eliminate contouring errors introduced by automated mapping. Because error-correction effort declines as the density of data points increases, the distance between survey lines used for automated contouring should be shorter than the reservoir width, and a much higher data densities should be obtained if possible. The data density will ultimately be limited by data-collection budget since a typical surveying speed is about 2 m/second. An example of survey track lines for construction of a contour map is given in Fig. 12-9.

On large reservoirs, if the pool is drawn down or emptied regularly, the lake surface area can be photographed from aircraft or satellite at different reservoir stages to construct a contour map based on the area of the water surface at each stage.

When computing average specific sediment yield (tn/km^2/year) based on the sediment volume trapped in a reservoir, it is necessary to compensate for sediment trapping by upstream reservoirs constructed over the period covered by the data. The changing area of the watershed effectively contributing sediment can be expressed as *effective watershed-years* by the following expression:

$$\begin{pmatrix}\text{Effective}\\ \text{Watershed}\\ \text{Years}\end{pmatrix} = \left[\begin{pmatrix}\text{Unregulated}\\ \text{Area}\end{pmatrix} + \begin{pmatrix}\text{Regulated}\\ \text{Area}\end{pmatrix} * \begin{pmatrix}\text{Sediment}\\ \text{Release}\\ \text{Efficiency}\end{pmatrix}\right] * \text{Years}$$

where the sediment release efficiency = 1 – trap efficiency for upstream reservoirs. The time period in years should be

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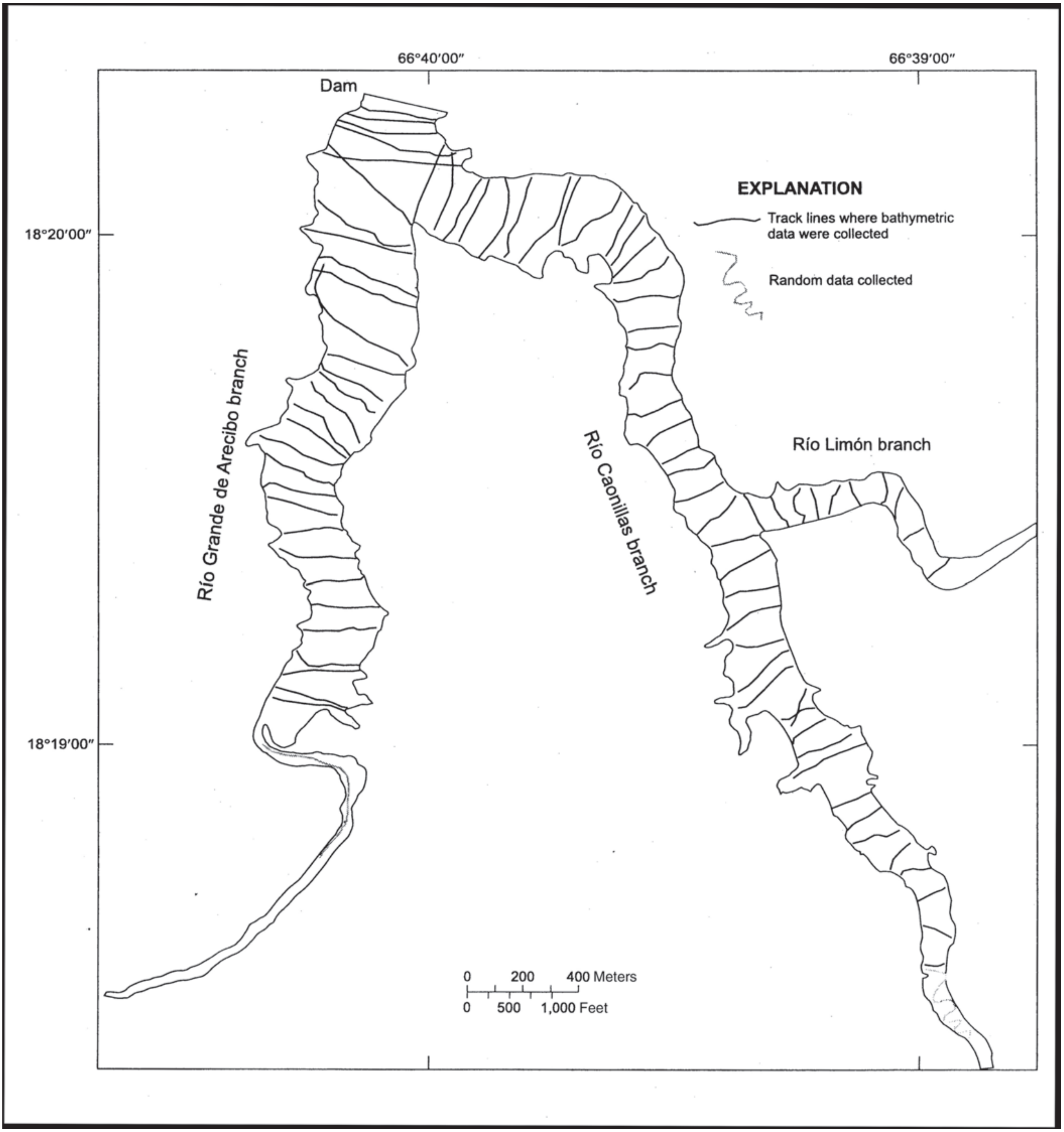

Fig. 12-9. Hydrographic track lines for contour surveying of a reservoir (Soler-López 2001).

computed for each interval of upstream reservoir construction and summed to obtain the effective sediment-contributing area as the basis for computing specific yield.

12.6.1.2 Deposit Thickness over Event Horizons Lacking reliable original bathymetric data, sediment thickness over a datable horizon can also be used to determine sedimentation rate. Cesium 137 is a man-made isotope produced only by the atmospheric testing of thermonuclear devices and dispersed globally. It was first produced in measurable amounts in 1954; its concentration peaked in 1964 and declined rapidly thereafter following signature of the international treaty to ban atmospheric testing. Cs^{137} is tightly sorbed onto clay particles and penetrates only a short distance into clayey soils. As these soils are washed into lakes and reservoirs, they mark

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radioactive horizons corresponding to the initiation of significant nuclear weapons testing and the peak weapons testing activity. This marker can be used to determine sedimentation depths overlying this event horizon both in reservoirs and in natural lakes. Cores are obtained, sectioned, and counted in a gamma-ray spectrometer. With a half-life of 30 years, Ce^{137} will be useful as a dating tool into the first decades of the twenty-first century (McHenry and Ritchie 1980). If the watershed has been impacted by a large fire, volcanic eruption, Chernobyl radioactivity, and so on, these events may also leave similar datable horizons within the sediments. An extensive bibliography of erosion and sedimentation studies based on Ce^{137} are located at http://hydrolab.arsusda.gov/cesium137bib.htm (accessed March 12, 2006).

Horizon-dating methods have several important limitations. When a reservoir is drawn down, sediments can be mobilized and reworked, making horizon-dating methods useful only in areas of continuous deposition. Also, the depth of sediment deposition in reservoirs is uneven, making it necessary to core and analyze samples from a number of locations to reliably map deposition thickness.

Sediment depth over the density horizon corresponding to the original bottom can also be determined by a subbottom profiler, which uses a higher-frequency sonar signal (200 MHz) for bathymetric mapping in combination with a lower-frequency signal (4–28 MHz). The lower-frequency signal penetrates finer sediment and is reflected from underlying denser layers corresponding to the original bottom, allowing the sediment thickness to be mapped. For example, a 28-MHz subbottom signal was used by Odhiambo and Boss (2004) in an Arkansas study that penetrated sediment deposits not more than about 1 m thick. Subbottom profiling is limited by several factors: thick sediments cannot be penetrated, coarse sediments that have prograded over previously deposited fines may register as a false preimpoundment bottom, and sonar signals are also strongly reflected by the gas–liquid interface generated by the anaerobic decomposition of organic sediment, which creates methane bubbles.

12.6.2 Sediment Yield Estimation from Fluvial Data

Fluvial sediment data are required to determine variations in sediment yield over time. Techniques and methods for sediment measurements are addressed in Chapter 5. However, the collection of accurate fluvial sediment data has potential sources for error that should be understood by users. For more information on procedures and potential sources of error, consult Guy and Norman (1970), Glysson (1987), Edwards and Glysson (1988), and Walling and Webb (1981, 1988). The USGS suspended sediment database is available at http://co.water.usgs.gov/sediment/.

12.6.2.1 Sediment Rating Curves Fluvial sediment load is determined by the product of stream-flow and discharge-weighted sediment concentration. See Appendix D on estimation of sediment discharge. Sediment load is usually computed from a long-term discharge record and a sediment rating curve that relates concentration to stream flow. The rating curve is constructed from instantaneous discharge–concentration data pairs, but the resulting relationship typically exhibits considerable scatter, and sediment concentration may vary over two log scales at a given discharge. Furthermore, the large floods or hurricane events responsible for much sediment transport may be represented by very few data points, if any at all.

Sediment load is the product of concentration and discharge, and when plotted as a function of discharge, it will exhibit less apparent scatter than a concentration–discharge plot using the same data because the discharge term occurs on both the ordinate and the abscissa. Both Ferguson (1986) and Glysson (1987) have cautioned against use of rating curves of load versus discharge because they can incorporate significant spurious correlation.

A sediment rating curve developed from several years of field data and that includes sampling of flood events can be applied to a longer-term discharge data set to estimate long-term sediment yield. In these computations, the time base for the rating curve must be representative of the discharge data set time base. For example, one would not apply a rating curve derived from instantaneous discharge–concentration data pairs to a hydrological record consisting of average daily flows in a flashy mountain stream, yet this same procedure may be acceptable in a river with a slowly rising and falling hydrograph. Published USGS data typically report total daily load versus average daily discharge.

Recommended procedures for the development of accurate rating curves have been summarized by Cohn (1995). Appendix D also provides guidance on methods currently used by the USGS. Regression techniques commonly used to develop rating curves incorporate a significant undercounting bias and will produce sediment loads significantly lower than observed even when applied to the data set from which the regression was derived. In some cases, this error can undercount sediment discharge by 50%. It is important to back test a rating relationship by applying it to the original stream-flow data set to ensure that it accurately computes the total load. Also, a multiple-slope relationship should be used as necessary to restrict maximum sediment concentration to realistic values at high discharges. Without this precaution, the resulting relationship will ascribe an inordinate amount of sediment yield to the highest discharges, thereby skewing the results of sediment management simulations.

The suspended sediment concentration in streams is determined primarily by watershed processes responsible for delivering fine sediment to channels, but bed material transport is controlled primarily by channel hydraulics. Whereas stream discharge is a consequence of rainfall, suspended-sediment concentration is also influenced by many watershed parameters not directly related to discharge, such as seasonal changes in land use and vegetative cover, variation in rainfall intensity and erodibility, exhaustion

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of erodible sediment supply by antecedent events, and variable arrival times of runoff from subbasins having large differences in sediment yield (Chapter 17).

If sediment concentration varies directly as a function of discharge, there will be a single-valued relationship between discharge and concentration (or load). However, sediment concentration and discharge often do not peak simultaneously, creating graphs of concentration versus discharge that are looped rather than single-value functions (Williams 1989). Error-free sampling over multiple events of this type will produce a sediment-rating curve of "average" conditions including both rising and falling limbs of the hydrographs. Additional scatter is produced by seasonal variations in rainfall intensity, rain versus snowmelt events, seasonal or long-term changes in vegetative cover, different antecedent conditions, and so on.

Within a highly scattered discharge–concentration data set may reside seasonal or within-event patterns that can be exploited to reduce reservoir sedimentation. A clockwise loop in the concentration versus discharge graph indicates that most sediment is discharged during the rising limb of the hydrograph, and water in the falling limb has a much lower sediment concentration. This may be caused by declining erosion rates in the latter part of the storm as rainfall intensity diminishes and the readily erodible sediment supply is exhausted. To the extent the sediment-laden portion of the hydrograph is made to bypass or pass through the storage pool, sedimentation will be reduced. Similarly, early-season flows may carry more sediment than subsequent flows because of the seasonal increase in vegetative cover and seasonal exhaustion of readily erodible sediment supply. Frequent sediment sampling is required to determine if the scatter typically inherent in sediment data conceal temporal patterns of sediment transport that may be used for sediment management.

12.6.2.2 Monitoring Sediment Yield by Turbidity Measurements If frequent sediment concentration data are available, sediment load can be computed directly as the product of discharge and concentration at short intervals (e.g., every 15 minutes) instead of relying on a sediment-rating curve (Chapter 5). With this level of detail, the temporal variation in sediment concentration and load will also be apparent, which can be helpful in detecting looped rating curves and in planning sediment-routing strategies.

In rivers with rapidly rising and falling hydrographs, sampling is required at short sampling intervals to accurately track sediment yield. However, short-interval sampling using an automatic pumping sampler produces many samples with high laboratory costs. Also, the sample bottles in an automatic sampler can be filled prior to the end of a prolonged or multiple-peak event, leaving part of the event unsampled. Resultant undercounting errors as high as 50% by conventional sampling and rating curve techniques are discussed by Walling and Webb (1981, 1988) and Olive and Rieger (1988).

The combination of pumped samplers and turbidity measurement has been shown to represent a viable strategy for improving the quality of sediment discharge data. There is no direct relationship between turbidity and suspended-sediment concentration, yet the discharge–sediment relationship is also a poor predictor of sediment loads as evidenced by the order-of-magnitude scatter typical of concentration–discharge graphs. However, turbidity can be recorded every few seconds, averaged, and logged to onboard memory, thereby eliminating the error due to the unreported periods that occur with manual and pumped sediment samplers.

Specific turbidity is the turbidity measured in formazin units divided by the mass particle concentration in mg/L. Because the optical properties of a suspension vary as a function of grain size and other factors, specific turbidity changes over the duration of an event as the grain size distribution varies. Fines have a much higher specific turbidity than sands. Specific turbidity can vary by an order of magnitude as a function of the suspended-sediment particle sizes (Foster et. al. 1992; Gippel 1995).

Time-stratified and flow-stratified turbidity sampling schemes have been compared by Thomas and Lewis (1993). A protocol for suspended-sediment sampling based on turbidity reported by Lewis (1996) uses pumped samples to periodically calibrate the turbidity–concentration relationship to overcome the problem of variations in specific turbidity. This protocol generates more accurate data than a pumped sampler working alone while simultaneously collecting fewer pumped samples for analysis. Because suspended-sediment concentration varies over a cross section, sediment concentration at the fixed sampling point used by automatic samplers or turbidity sensors must be correlated against depth-integrated samples.

12.6.3 Neural Network Models for Sediment Yield

Neural network models have been demonstrated useful for better definition of the relationship between hydrologic parameters and sediment concentration. The neural network model is essentially a nonlinear black box that correlates outputs to inputs by training its internal algorithms and their weighting scheme against a calibration data set. Applications of neural networks in hydrology have been reviewed by the ASCE Task Committee (2000a, 2000b). Unlike the single-parameter sediment rating curve, which relates concentration to discharge, a neural network model can incorporate multiple parameters including both current and antecedent values for stream flow, rainfall, temperature, and other parameters from one or more gauging stations in the watershed.

One approach is to use the neural network to develop rating relationships based on channel hydraulic characteristics. Jain (2001) and Sen et al. (2004) have used this approach to develop a model to predict suspended-sediment concentration in the Mississippi River based on time-series data including using both current and lagged values of discharge and suspended-sediment concentration. Nagy et al. (2002) developed a more generalized sediment transport model correlating suspended-sediment concentration to eight unlagged channel hydraulic characteristics.

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An alternative approach is to predict suspended-sediment concentration or discharge based on channel plus watershed hydrologic parameters or watershed parameters alone. For example, Cigizoglu and Alp (2003) accurately predicted suspended sediment in the Juniata River, Pennsylvania, on the basis of both current and lagged values of discharge and rainfall but found that Thiessen-averaged rainfall alone was not an adequate predictor in this 8,690-km^2 watershed. In a smaller 92-km^2 watershed in northeastern India, Raghuwanshi et al. (2006) predicted both runoff and sediment yield for both daily and weekly time steps from temperature and rainfall data alone.

12.6.4 Sediment Yield Estimation by Spatial Modeling

Computationally intensive techniques can significantly improve the ability to predict and manage sediment, particularly when baseline data and good calibration data sets are available (Chapter 17). There are many alternative approaches, but no generally accepted methodology has yet emerged. This is due in part to the wide diversity of questions that can be addressed by these models plus regional differences in data availability, engendering problem-specific model formulations.

Spatially distributed data may be analyzed in a GIS-type framework to compute the yield of both water and sediment from the watershed on the basis of soil, land use, and hydrologic input parameters, and the resulting runoff and its sediment load is then routed to the watershed exit. Empirical soil erosion models have been in use for many decades, and parameter values are widely available, but the sediment delivery process must be simulated by other means. An example of the coupling of empirical erosion prediction models with a sediment delivery module to simulate sediment yield is presented by Kothyari et al. (1996).

Alternatively, physically based models that simulate both sediment detachment and transport processes may be coupled with fluvial routing procedures to simulate sediment yield. An example of the latter is the continuous water and sediment modeling approach demonstrated on watershed scales ranging from 17.7 to 9,000 km^2 by Arnold et al. (1995). This model coupled continuous physically based erosion prediction models with a routing scheme based on reasonably available data and was successfully tested against both annual and monthly sediment discharge data at the largest watershed scale. As an advantage, spatial data can be used to simulate the impact of alternative land use scenarios and identify areas where erosion control would provide the highest benefit, taking into account both erosion rate and the sediment delivery process. Neural network models can also be incorporated into a GIS framework (Doris et al. 2004).

The GIS environment can also be used to organize, interpret, and manipulate massive amounts of spatial data. The ongoing development of a GIS-based sediment assessment and management model incorporating 250 sediment gauging stations and spatial sediment yield data across the 1×10^6-km^2 watershed tributary to the Three Gorges Project has been described by Lu et al. (1999).

12.7 SEDIMENT DEPOSITION IN RESERVOIRS

The understanding and prediction of deposition patterns is important for a variety of reasons. Delta deposition can cause a stream to aggrade upstream of a reservoir and affect flood levels, groundwater levels, bridge clearance, commercial and recreational navigation, and environmentally sensitive areas. The shape of the stage–storage curve will change because of sedimentation, affecting different beneficial pools within the reservoir. Deposition by turbidity currents can interfere with low-level intake at the dam, even with as little as 1% storage loss in the impoundment (Garcia 1999; De Cesare et al. 2001). Observations of deposition patterns can also be helpful in developing strategies for sediment management. Reservoir surveys are undertaken at intervals can document both the volume and the pattern of sediment deposition.

12.7.1 Trapping and Releasing Efficiency

Trap efficiency is the percentage of the total inflowing sediment load that is trapped within a reservoir over a stated period of time. *Release efficiency* is the amount of sediment exiting a reservoir, expressed as a percentage of the inflowing load, and is the complement of trap efficiency:

trap efficiency = sediment trapped/inflowing sediment
release efficiency = released sediment/inflowing sediment = (1 − trap efficiency)

From the standpoint of sediment management, sediment release efficiency is a more useful concept than trap efficiency because it can be used to express events in which sediment discharge exceeds sediment inflow, as occurs during flushing and some sediment-routing events. Sediment trapping or releasing efficiency is not constant but is influenced by factors including detention period, inflowing sediment characteristics, and reservoir operation.

For preliminary screening of sediment trapping or release, two methods have been widely used. Brune (1953) developed an empirical relationship between the *capacity: inflow* (C:I) ratio and long-term trap efficiency (Fig. 12-10). Trap efficiency declines as sedimentation reduces the capacity:inflow ratio. Temporarily lowering the reservoir pool during a flood (pass-through sediment routing) reduces both detention time and sediment trapping. This straightforward method is widely used to make preliminary estimates, as the data required are usually readily available. Another well-known method, that of Churchill (1948), requires information on reservoir capacity, reservoir length, and inflow during the study interval and is better oriented to the analysis of specific events. Strand and Pemberton (1987) recommend use of the Brune curve for large storage

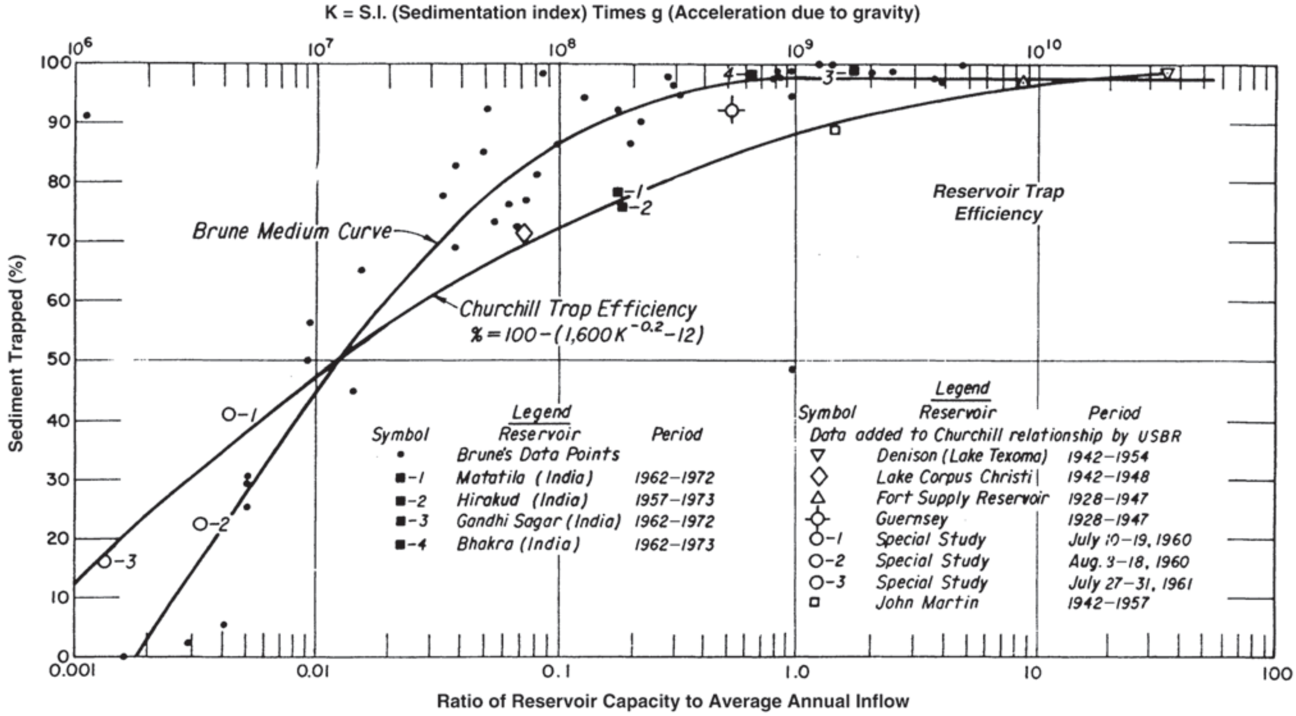

Fig. 12-10. Relationship between reservoir hydrologic size (capacity:inflow ratio) and sediment-trapping efficiency by Brune and the sedimentation index approach by Churchill (Strand and Pemberton 1987).

or normally ponded reservoirs and Churchill's method for settling basins, small reservoirs, and flood-retarding structures.

Churchill's (1948) relationship to predict sediment trapping is based on a reservoir sedimentation index, defined as the ratio of retention period to mean flow velocity through the reservoir. The Churchill curve has been converted to dimensionless form in Fig. 12-10 by multiplying the sedimentation index by the gravitational constant, g. Definitions of the terms required to compute Churchill's sedimentation index are as follows:

Capacity is the mean volume of the operating pool during the analysis period (m^3).

Inflow is the mean daily inflow during the analysis period (m/second).

Retention period is the capacity divided by the inflow (seconds).

Length is reservoir length (m) at the mean operating pool level during the analysis period.

Velocity is the mean velocity (m/second), computed as *inflow* divided by the mean cross-sectional area (m^2) of the pool. The cross-sectional area can be computed as *capacity* divided by *length*.

Sedimentation index is the retention period divided by the velocity.

For more than a preliminary analysis, mathematical modeling is required. Models of lake and reservoir sedimentation model are presented in Chapter 2.

12.7.2 Depositional Geometry

A highly generalized depiction of sedimentation processes was presented in Fig. 12-4. The coarse fraction of the inflowing load creates a delta deposit where the main river or side tributaries enter the reservoir. Depending on the inflowing load, delta deposits can range from silt to cobbles. The delta may be divided into the topslope and foreslope deposits, and the downstream limit of the delta is characterized by a rather abrupt reduction in grain size (Chapter 2). This change in grain size may occur even in reservoirs lacking an obvious delta (Fan and Morris 1992a). Although the delta can often have a slope about one-half of the original river streambed, there can be wide variations in delta topslope. Deltaic deposits not only extend into the reservoir, but they also extend upstream because of backwater effects (Chapter 2). This can be exacerbated by ice jams in reservoir headwater areas that retard flow and produce sedimentation further upstream than might otherwise be predicted. Mathematical modeling is the recommended method for predicting deltaic deposition patterns (U.S. Army Corps of Engineers 1989). The mechanics of deltaic sediment deposition is addressed in Chapter 2.

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The depositional sequence within a single cross section illustrated in Fig. 12-2 shows that sediments first fill the deepest part of each cross section and subsequently spread out across the submerged floodplain to create broad flat sediment deposits. However, depositional patterns can also be more complex. Previously deposited sediments can be reworked and moved further downstream during drawdown, and large floods can transport coarse sediment deeper into the pool, prograding over finer sediment and producing layered deposits. Multiple deltas can be formed, each corresponding to a different pool elevation, and side tributaries can discharge coarser materials into an area where only fine sediment would otherwise be encountered. During periods lacking significant flood events, sediment deposits may consist only of fines and organic material, and shallow sediment samples collected during that period may not reveal coarser materials transported and deposited during flood events. The cores presented by Evans et al. (2002) provide a good example of depositional horizons of coarse sediment corresponding to floods in a hydrologically small reservoir.

12.7.3 Turbid Density Currents

Turbid density currents or turbidity currents are sediment-laden density-driven currents that flow along the bottom of the reservoir (Garcia 1993, 1994). These currents are caused primarily by density differences between clear and sediment-laden water, but cold water flowing into a warmer pool can also form temperature-driven density currents carrying suspended solids along the bottom of the reservoir. When significant amounts of suspended solids are present, the density differences imparted by the solids are much more important than temperature-induced density differences.

Turbid density currents occur frequently and are important in explaining sediment deposition patterns. The mechanics of sediment transport and deposition by turbidity currents in lakes and reservoirs is considered in Chapter 2. These currents focus fine sediment transport along the deepest part of the cross section instead of mixing sediments uniformly across the cross section. These currents are the primary reason that sediments in reservoirs fill from the bottom up within each cross section (as in Fig. 12-2) instead of having a more uniform depth of sediment deposits across the cross section.

Under favorable conditions, the turbulence generated by turbidity current motion will maintain a significant amount of sediment in suspension, thereby maintaining the driving force that sustains the motion of the current until it reaches the dam. Prior to the construction of Glen Canyon Dam further upstream, turbid density currents were documented to travel 129 km along Lake Mead to Hoover Dam (Grover and Howard 1938), the longest documented travel distance of turbidity currents in any reservoir. Although turbid density currents commonly occur in reservoirs, they often fail to reach the dam because the suspended sediment settles out of the current. Sediment loss diminishes the gravitational density difference driving the current, causing it to slow down, which in turn allows it to drop more of its sediment load. This cycle continues until the current dissipates. Turbidity currents will also dissipate if the inflow of turbid water at the upstream end of the reservoir stops before the current reaches the dam (Fan and Morris 1992a; DeCesare et al. 2001).

Turbidity currents reaching a dam or other submerged obstruction will create a submerged lake of muddy water, and sedimentation from this muddy lake will leave horizontal deposits of fine sediment extending upstream from the dam, as illustrated in Fig. 12-4. Deposits of this nature indicate that turbidity currents are transporting a significant amount of sediment to the dam. The release of turbid water from low-level outlets while the reservoir surface water is clear also indicates a turbidity current that reaches the dam. Indicators of turbid density currents may also be observed where the turbid water enters the reservoir and plunges beneath the surface. The *plunge point* or *plunge line* is marked by a dramatic change in water color. The conditions for plunging of a muddy turbidity current are discussed in Chapter 2. The plunging flow tends to create a surface countercurrent that flows upstream, and floating debris becomes trapped near the plunge line by the two opposing currents.

Turbidity current movement may be best ascertained by monitoring, from which data required for numerical modeling may be obtained (De Cesare et al. 2001). Modeling of turbidity currents is also addressed in Chapter 2.

12.7.4 Bulk Density of Sediment Deposits

Typical values of bulk density for reservoir sediments are given in Table 12-5. A more accurate empirical method for estimating initial bulk density was developed by Lara and Pemberton (1963). To estimate initial specific weight, reservoir operation should be classified into one of the following categories: (1) sediment always submerged or nearly

Table 12-5 Typical Specific Weights for Reservoir Deposits, t/m^3 or g/cm^3 (Geiger 1963)

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

Table 12-6 Coefficient Values for Specific Weight Computation by Lara-Pemberton Method

Operational Condition	Initial Weight (kg/m^3 [lb/ft^3])		
	W_c	W_m	W_s
Continuously submerged	416 (26)	1,120 (70)	1,554 (97)
Periodic drawdown	561 (35)	1,140 (71)	1,554 (97)
Normally empty pool	641 (40)	1,150 (72)	1,554 (97)
Riverbed sediment	961 (60)	1,170 (73)	1,554 (97)

submerged, (2) normally moderate to considerable drawdown, (3) normally empty reservoir, and (4) riverbed sediments. The grain size of the deposit must also be apportioned into sand, silt, and clay fractions by weight percent. Specific weight may be computed from the values in Table 12-6 and the equation

$$W = W_c P_c + W_m P_m + W_s P_s$$

where

W = specific weight of the deposit (kg/m^3, lb/ft^3);
P_c, P_m, and P_s = weight percentages of clay, silt, and sand, respectively, for deposited sediment; and
W_c, W_m, and W_s = initial weights for deposits of clay, silt, and sand, respectively.

12.7.5 Sediment Consolidation over Time

Sandy sediments attain their ultimate bulk density virtually as soon as they are deposited, but fine sediments may compact and consolidate for decades. If a constant mass of fine sediment accumulates in a reservoir each year, the volumetric rate of sedimentation will be highest in the first year and will appear to decline in subsequent years because the volume occupied by the second year's sediment deposition is decreased by compaction of the first year's deposit. To compensate, all sediment volumes can be adjusted to account for 50 years of compaction, by which time sediments have typically approached their ultimate density.

Sediment compaction over time is described in the equation by Lane and Koelzer (1943):

$$W_t = W_1 + B \log t$$

where

W_t = specific weight of deposit at an age of t initial years,
W_1 = initial weight at the end of the first year of consolidation, and
B = parameter value given in Table 12-7.

Table 12-7 Coefficient Values for Computing Sediment Consolidation

Operational Condition	Value of Coefficient B (kg/m^3 [lb/ft^3])		
	Sand	Silt	Clay
Continuously submerged	0	91 (5.7)	256 (16)
Periodic drawdown	0	29 (1.8)	135 (8.4)
Normally empty reservoir	0	0	0

For sediment deposits containing mixed grain sizes, determine the value of B as the weighted average of the tabulated values, based on the weight percent of each gain size in the deposit.

12.7.6 Prediction of Sedimentation Patterns

The Bureau of Reclamation developed the empirical area reduction method for predicting the change in the stage–storage relationship due to sedimentation, based on observations at reservoirs in the United States. This method is described by Strand and Pemberton (1987) and by Morris and Fan (1998). In this method, the user determines the reservoir trap efficiency, places the reservoir into one of four geometric classes, and then follows a procedure to apportion the sediment deposition into different depth ranges on the basis of empirical relationships. This is the accepted method for predicting adjustments to the stage–storage curve in the absence of computer modeling. However, it is not suited for use in reservoirs where operating rules are modified to reduce sedimentation. More detailed information on depositional patterns requires computer modeling as described in Chapters 14 and 15.

12.8 SEDIMENT MANAGEMENT IN RESERVOIRS

12.8.1 Sediment Control Strategies

Sediment management strategies in reservoirs may be divided among five basic strategies:

1. *Sediment yield reduction*. Apply erosion-control techniques to reduce sediment yield from tributary watersheds. These techniques will typically focus primarily on soil stabilization and revegetation.
2. *Sediment storage*. Provide sediment storage volume adequate for the anticipated sediment yield over a "long" period of time either in the reservoir itself or in upstream impoundments or debris basins.

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3. *Sediment routing*. Pass sediments around or through the storage pool to minimize sediment trapping by employing techniques such as offstream storage, temporary reservoir drawdown for sediment pass-through, and release of turbid density currents.
4. *Sediment removal*. Remove deposited sediment by dredging or hydraulic flushing.
5. *Sediment focusing*. These techniques are designed to tactically rearrange sediments within the impoundment to solve localized problems such as impacts from delta deposition. Any washout of sediment from the reservoir that may occur is incidental to the primary objective.

In reviewing options, a full range of management alternatives should be analyzed. An example of this approach is described by Harrison et al. (2000) for Solano Lake, California. Optimal management may include two or more strategies applied simultaneously or at different points in the reservoir life. The applicability of different strategies varies at different stages of reservoir life, being a function of the reservoir's hydrologic size (capacity:inflow ratio), beneficial uses, and other factors, such as environmental regulations.

Techniques such as sediment routing require significant pool drawdown and use part of the natural inflow to transport sediment beyond the storage pool, making it impossible to capture and regulate 100% of the flow. Consequently, some types of routing techniques will not be feasible at hydrologically large reservoirs. However, sedimentation will eventually convert large reservoirs into small ones, and sediment-routing techniques may become feasible at a future date.

12.8.2 Sediment Yield Reduction

Erosion control to reduce sediment yield is widely recommended to prolong reservoir function but is most difficult to implement successfully. Many reservoirs, particularly in developing areas, have experienced accelerated erosion from intensified land use and deforestation, despite recommendations for erosion control. Even when land use changes to less erosive patterns, many years may be required before significant reduction in sediment yield occurs. For example, 20 years after transition to less erosive land use within the 1,150-km^2 Buffalo River basin in Wisconsin, Faulkner and McIntyre (1996) could not detect any reduction in sediment yield.

Accelerated soil erosion has many negative impacts in addition to reservoir sedimentation. Clark (1985) estimated that storage loss in reservoirs accounted for only 11% of total annual erosion costs of $6.1 billion (1980 dollars) in the United States, where the largest single cost was impairment of water quality for recreational use. Biological impacts were not estimated in that study. In less developed countries, the largest impacts of soil erosion may be borne by small hillside farmers who experience loss of soil fertility and reduced soil moisture–holding capacity and declining yields as topsoil is washed away.

Appropriate land use practices are well known and readily demonstrable on model farms or experimental watersheds. However, implementing and sustaining good land use practices by many thousands of land users across a watershed is highly problematic. A good overview of the socioeconomic barriers to the adoption of soil conservation measures by farmers of all income levels and on every continent is provided by Napier et al. (1994). Land users will not altruistically change their practices to reduce sedimentation of a downstream reservoir, especially if the reservoir benefits accrue to another community. Sustained improvements will not be achieved unless land users understand how they will directly benefit from these practices. For this reason, successful watershed management programs must be developed as a community-level effort with readily identifiable benefits to land users.

Because measures to reduce erosion typically benefit many parties in addition to dam owners, any dam owner attempting to reduce sediment yield from a watershed may have many potentially helpful alliances. For example, in the North Fork Feather River watershed in California, where the Rock Creek and Cresta hydropower dams were experiencing sedimentation problems, the dam owner, PG&E, catalyzed the implementation of a community-based coordinated resource management group to implement watershed management activities. The group eventually expanded to involve 17 different institutions and community groups, all having a vested interest in erosion control and sediment management. Participants included landowners desiring to control streambank erosion; state and federal forestry agencies desiring to stabilize eroding logging roads; federal, state, and local environmental resource agencies; fishermen and other recreational users; environmentalists; and tourist interests (Harrison and Lindquist 1995; Morris and Fan 1998).

The literature on watershed management is extensive; the reader is referred to the following sources for publications and contacts:

- Natural Resources Conservation Service (www.nrcs.usda.gov). This is the lead national agency for erosion control in rural areas, with local offices in communities throughout the nation.
- Environmental Protection Agency (www.epa.gov). Regulates water quality and sediment discharge from construction sites through the NPDES program and has numerous publications.
- Soil and Water Conservation Society (www.swcs.org). Focus on agricultural soil conservation in the United States and worldwide.
- Conservation Technology Information Center (www.ctic.purdue.edu). Focus on mechanized agriculture in the United States. Also contains electronic listing of

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watershed management programs and contacts throughout the United States.
- International Erosion Control Association (www.ieca.org). Trade publication focusing on manufacturers of erosion-control equipment and materials with a focus on urban areas.

12.8.3 Provision of Large Storage Volume

Sedimentation has traditionally been "controlled" by providing a storage volume large enough to postpone anticipated sedimentation problems for 50 to 100 years. The "sediment pool" assigned to reservoirs has typically consisted of the dead storage space below the lowest outlet, but sediment deposits are frequently not focused in that zone, and sedimentation problems may be caused by deposits in the delta or other areas prior to filling of the provided sediment storage pool.

An often-used strategy for increasing the storage volume in the face of sedimentation issues is to raise the dam. Garbrecht and Garbrecht (2004) offer an interesting historical example of successive raising of the Marib diversion dam in Yemen between 940 B.C. and its final destruction around A.D. 570 to accommodate both increased sediment upstream of the dam and an increase in land level as much as 15 m in the downstream irrigation area due to silt loads in the diverted irrigation water. Loehlein (1999) described the raising of pool elevations in a flood-control reservoir due to sediment accumulation.

A 500-year horizon should be considered for analysis of the geomorphic evolution of the impounded river reach and its sediment management alternatives. Against the argument that this is an unreasonably long time frame, consider that Schnitter (1994) has documented dams with operational lives exceeding 1,000 years. Among all types of engineered infrastructure, dams are unique in terms of their longevity and their interrelationship to the geomorphic processes along rivers. The time frame for their analysis should consider their potential operational life (including prolongation by sediment management) and the structure's long-term impact on the fluvial sediment balance.

The objective of long-term analysis is to define, on a preliminary basis, the probable time frames and types of sedimentation problems to be anticipated, the potential sediment management strategies potentially feasible as a function of reservoir age, and any long-term sediment management elements that can be incorporated into current design or operational practices. Sedimentation problems are both difficult and costly to cure, and the consideration of long-term consequences can help both the design and regulatory communities to identify effective long-term solutions. For example, it is often assumed that reservoirs will be dredged or alternative reservoir sites developed in the future. However, if the land area required for either of these two options is not acquired or otherwise protected by zoning restrictions, the planned-for alternative may no longer be feasible when it is needed. Similarly, if bank instability due to long-term channel incision below a dam is anticipated, it would be prudent to create no-development buffer zones along the riparian corridor where bank erosion is anticipated.

This long-term analysis is limited to geomorphic and sedimentation issues within and below the impounded reach and does not necessarily imply 500-year computer simulations, and it would not impact the time frame normally used for socioeconomic or similar evaluations. It seeks to extrapolate geomorphic processes along the impounded river reach to their logical conclusion and to identify any feasible present-day actions or design strategies that will help ameliorate long-term negative consequences.

12.8.4 Sediment-Routing Strategies

12.8.4.1 Offstream Reservoir for Sediment Bypass The ideal way to manage sediment is to prevent it from entering the reservoir. High volumes of sediment-laden floodwaters can be bypassed around a storage pool by placing the pool offstream and diverting only relatively clear water from moderate flows into storage (Fig. 12-11). The key feature of the offstream reservoir is an intake system that has a limited inflow capacity and will therefore exclude most flood flow and its associated sediment because the flood discharge will be much greater than the intake capacity. Additional sediment exclusion can be achieved by closing the intake during floods with high sediment concentration or in anticipation of hurricanes.

As compared to a conventional onstream reservoir, an offstream reservoir can generate many benefits in addition to a reduced rate of storage depletion:

- The dam does not pose a barrier to migratory aquatic species or to navigation.
- Instream water quality (e.g., temperature, dissolved oxygen) is not altered by the reservoir.
- Riparian wetlands and river corridor habitats are not submerged.

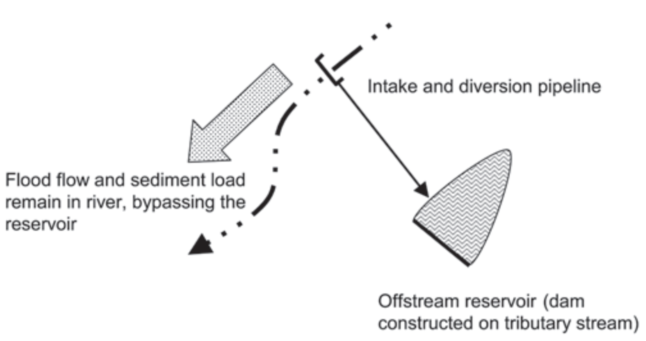

Fig. 12-11. Conceptual representation of sediment exclusion by an offstream reservoir.

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- The dam does not impact bed-load transport processes essential to maintain instream sediment transport, river morphology, and the ecological integrity of instream ecosystems.
- The large-capacity onstream spillway is eliminated.
- Low sediment loading and turbidity levels in the reservoir benefit users, such as water filtration plants, by reducing coagulant and sludge handling costs.
- The intake can be closed to exclude contaminants from hazardous waste spills, treatment plant malfunctions, or periodic water quality degradation by fertilizers or other nonpoint runoff.

These environmental advantages can favor offstream reservoirs over conventional structures, independent of sediment-loading considerations. However, offstream reservoirs may not develop the full yield potential of the stream because sediment-laden flood flow is not diverted to storage, especially in hydrologic environments with annual runoff concentrated in a short time period.

An example of this strategy is the offstream reservoir supplied from Río Fajardo, Puerto Rico, which began filling in 2006. Suspended sediment loads in Puerto Rico are high. To achieve a multicentury reservoir life, the impoundment volume for an onstream reservoir becomes controlled by the size of the sediment storage pool rather than the water conservation pool.

Río Fajardo is a flashy mountain stream in a moist tropical environment with a 38-km^2 watershed area. Behavior simulations using 33 years of daily data and a continuously open intake were used to develop the relationship between storage, yield, and sediment loading. At the selected design point, 37% of the long-term stream flow is diverted into the reservoir and thence to municipal use, but less than 10% of the suspended sediment load enters the reservoir and none of the bed load material. Firm yield for the offstream design is only 5% less than for a conventional onstream reservoir having the same conservation pool volume, but with the low sedimentation rate, there is no need to oversize the reservoir to provide a large sediment storage pool.

The half-life of Fajardo offstream reservoir is estimated to exceed 1,000 years, as compared to only 180 years for a larger-volume instream reservoir originally proposed on this same river. To sustain reservoir capacity indefinitely, dredging of volumes less than 0.5 Mm^3 per event are planned at intervals of about 200 years in this 4.5 Mm^3 reservoir. A spoil disposal site adjacent to the reservoir has been reserved for this purpose. Offstream reservoirs have also been used for sediment control at nine sites in Taiwan, two of which are described by Wu (1991).

12.8.4.2 Sediment Bypass of Onstream Reservoirs In some cases, it may be possible to construct a reservoir onstream yet bypass sediment. For the passage of large sediment-discharging events, this would be most readily accomplished by locating the reservoir at the terminus of a meander and diverting flood flows across the meander floodplain (Annandale 1987).

The trapping of bed material by dams is an important environmental issue, and at several sites, processes have been used to move gravels from the delta upstream of the reservoir and deposit it below the dam. Procedures may involve trucking or pipeline, or on a steep channel even a tunnel may be used. The Asahi hydropower dam in Japan is constructed in a narrow gorge on a steep gravel-bed river. A low-head concrete diversion dam constructed immediately upstream of the reservoir intermittently diverts flushing flows and entrained gravels into a tunnel that runs parallel to the reservoir and then discharges below the powerhouse. This costly alternative was implemented to help preserve a popular recreational fishery below the dam.

12.8.4.3 General Characteristics of Pass-Through by Drawdown Sediments are maintained in suspension by high-velocity flows; they become trapped in reservoirs as flow velocity diminishes and hydraulic retention time increases. By opening high-capacity gates to minimize reservoir level, drawing down the pool as much as possible to

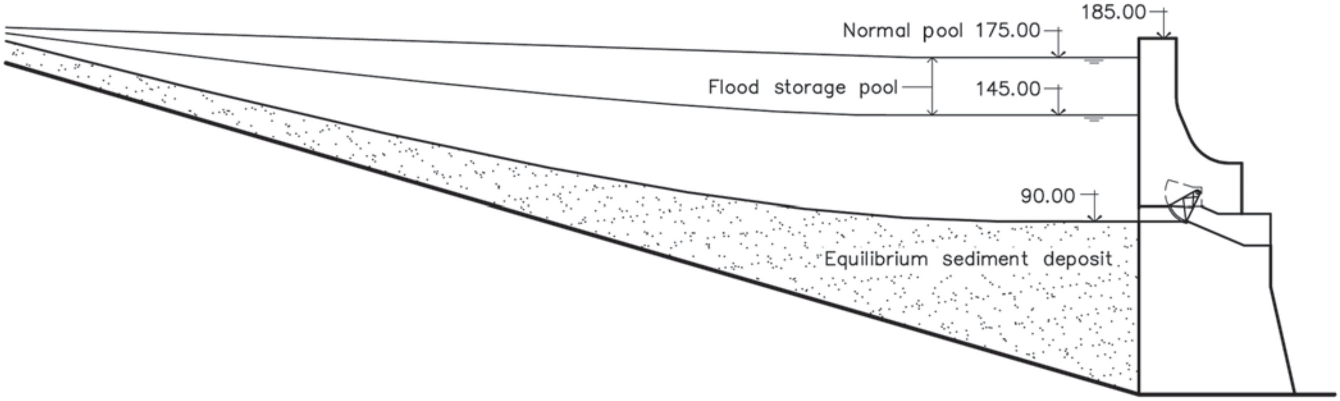

Fig. 12-12. Longitudinal profile of Three Gorges Reservoir, Yangtze River, China (modified from Lin et al. 1993).

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pass sediment-laden floods at the highest possible velocity, the opportunity for deposition is minimized. The reservoir pool is refilled at the end of the drawdown period.

Pass-through techniques are based on translating the inflowing flood hydrograph and accompanying sediment through the pool with the least possible attenuation. Although the high flow velocities generated by drawdown may scour some of the previously deposited sediment, the outflowing concentration will be similar to the inflowing concentration. Discharging sediment with a high flow eliminates excessive sediment concentrations and sediment redeposition in the channel below the dam, two serious problems that normally accompany sediment flushing.

Drawdown duration and operating rules will vary depending on hydrologic characteristics and reservoir size. Three distinct procedures are described. First, in large reservoirs such as the Three Gorges Project in China, drawdown is performed on a seasonal basis. Second, in smaller reservoirs, drawdown may be accomplished by the prediction of hydrographs for specific runoff events. Third, in very small reservoirs or diversions with limited storage, gate operation may be performed on the basis of a rule curve that does not require hydrograph prediction.

Techniques to optimize operating rules in multiple reservoirs to achieve specific sediment management objectives in river channels and pool areas has been demonstrated by Nicklow and Mays (2000) and Nicklow and Bringer (2001). These studies used data from the literature to formulate a three-reservoir network to demonstrate the interfacing of the HEC-6 sediment transport model with an optimization scheme. The HEC-6 model solves the hydraulic and sediment transport equations that govern the physical parameters of the system under the overall control of the optimization algorithm (Chapter 14). The control scheme operates within the systemwide constraints imposed by established operating parameters such as storage levels and release rates to optimize the specific sediment-management objectives.

Pass-through will tend to establish and maintain the river channel, but in wide reservoirs the off-channel areas will continue to be depositional during impounding periods, and a channel–floodplain configuration can develop over a number of years, similar to the geometry associated with flushing as discussed in Section 12.8.6. Although routing can substantially reduce the rate of sediment accumulation, the ultimate reservoir volume that can be sustained by this method is limited by the channel dimension.

12.8.4.4 Pass-Through by Seasonal Drawdown Under seasonal drawdown, the pool is seasonally lowered or emptied to pass sediment-laden flows through the reservoir, which is refilled during the late part of the wet season. In areas with strong rainfall seasonality, runoff from initial wet-season rains may transport considerably more sediment than late-season runoff, when vegetation has regrown to protect the soil. Sediment pass-through techniques incorporated into the Three Gorges reservoir in China have been described by Lin et al. (1989, 1993), Chen (1994), and Morris and Fan (1998).

The 39-km^3 Three Gorges reservoir on the Yangtze River has been designed to achieve sediment balance across the impounded reach after approximately 100 years, allowing the project to operate indefinitely while passing 530×10^6 tn/year of sediment and 451 km^3 of water. This is achieved by designing a hydrologically small reservoir (C:I ratio 0.087) with adequate low-level outlet capacity to operate in seasonal drawdown mode. A conventional impounding reservoir of this same capacity on the Yangtze River would have a half-life of less than 100 years.

A conceptual profile of the Three Gorges reservoir is shown in Fig. 12-12. The reservoir is gradually drawn down during the dry season by making releases for hydropower and downstream navigation. Outlets and turbines will be operated during the initial part of the flood season to maintain the reservoir pool at a low level. This empties the flood storage pool and also generates high flow velocities along the reservoir, which is generally not more than 1 km wide along its 600-km length. These high velocities will transport most suspended sediment and sandy bed material through the reservoir and beyond the dam. Once equilibrium conditions have been reached, gravels will continue to be trapped and must be removed by dredging. About 2×10^6 m^3 of sand and silt is also expected to be dredged annually in the vicinity of the navigational locks at the dam.

12.8.4.5 Pass-Through by Hydrograph Prediction At hydrologically small reservoirs on rivers lacking prolonged and predictable periods of high flow, it may be possible to draw down the pool in anticipation of floods, pass the sediment-laden water through the reservoir with the shortest possible detention time, and refill the reservoir with the recession limb of the storm hydrograph. This strategy was analyzed at Puerto Rico's Loíza (Carraízo) reservoir (26.8×10^6 m^3 original volume, 538-km^2 tributary watershed), the primary water supply for San Juan (Morris and Hu 1992; Morris et al. 1992; Morris and Fan 1998).

The spillway crest equipped with high-capacity Tainter gates that control most of the usable storage pool. The reservoir has a capacity:inflow ratio of only about 0.06, and stream-gauge records show that over half of the inflowing sediment is delivered to the reservoir by large storms occurring on the average of only two days per year. This points to significant sediment reduction by passing large flows and their associated sediment through the reservoir.

The total volume of water upstream of the dam can be continuously computed during tropical depressions as the sum of two components: the water already in the reservoir and the water predicted to arrive on the basis of rainfall already received. Reporting rain gauges within the watershed, coupled with hydrologic software, can predict the volume of the recession hydrograph from received rainfall, and a

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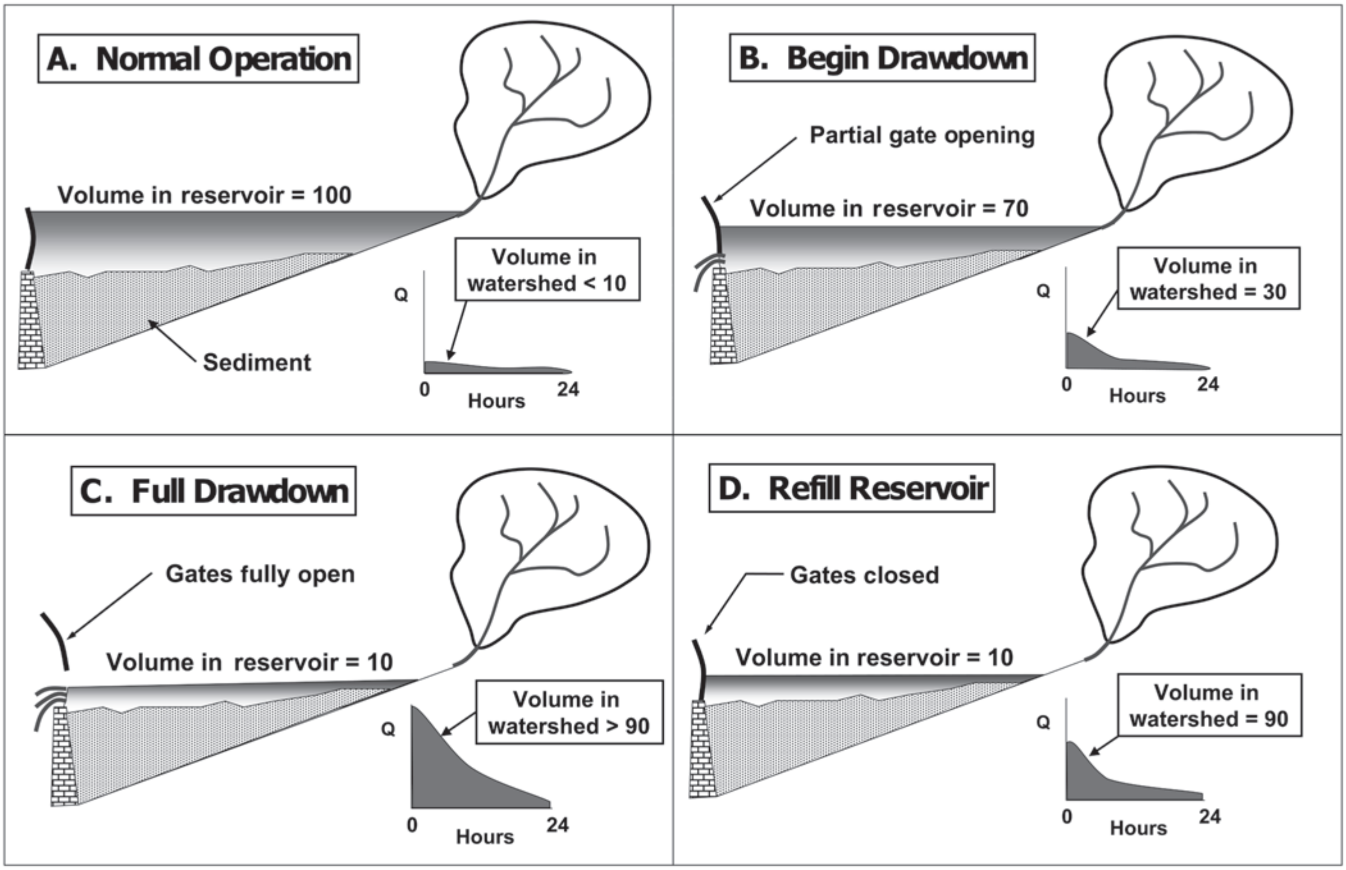

Fig. 12-13. Proposed operational sequence for sediment pass-through at Loíza reservoir, Puerto Rico. See text for description.

combination of stage gauges and hydraulic modeling can compute within-reservoir volume.

The proposed operational sequence is illustrated in Fig. 12-13. (A) When a storm begins, the reservoir's gates are opened to release a volume of water equal to the volume of runoff water accumulating in the watershed as predicted from the recession hydrograph computations but not yet delivered to the reservoir. (B) As the storm continues and more water accumulates in the watershed, gate openings are increased, and the reservoir is progressively lowered until all gates are fully open. (C) The gates remain fully open as long as the total water volume tributary to the dam exceeds the total volumetric capacity of the dam. (D) During the storm recession, the gates are closed as soon as the total tributary water volume drops to the full reservoir volume. Gate closure at this point allows the reservoir to refill completely with water during the next 24 hours (Morris and Hu 1992; Morris et al. 1992).

12.8.4.6 Drawdown by Rule Curve At very small reservoirs, pool drawdown for sediment pass-through during floods may be regulated by a rule curve based only on the rate of inflow. A rule curve of this type was implemented at the Cowlitz Falls dam in Washington State, which impounds a hydrologically small reservoir having a capacity:inflow ratio of only 0.3% (Locher and Wang 1995). This rule curve is shown in Fig. 12-14. A similar rule-curve operation has been studied at the Rock Creek and Cresta hydropower reservoirs on the North Fork Feather River, California (Chang 1996).

12.8.4.7 Routing of Turbid Density Currents Turbid water entering a reservoir typically plunges to the bottom and will flow along the original (but now submerged) riverbed. Under favorable conditions, the turbidity current will be transported to the dam where it can be released through a low-level outlet. Turbidity currents can carry fine sediment into the vicinity of the dam and obstruct low-level outlets even though there is little sediment accumulation elsewhere within the reservoir. When the reservoir profile is viewed longitudinally, the accumulation of a flat bed of sediment deposits extending upstream from the dam is an indication that turbid density currents reach the dam (Fig. 12-4).

Turbid density currents are inherently unsteady and are influenced by the variable discharge of the inflowing hydrograph, varying suspended sediment concentration, and variation in reservoir level over the duration of the event. The forward velocity of the density current is maintained by the continued inflow of turbid water, and when inflow ceases, the turbidity current will stall. In highly favorable situations

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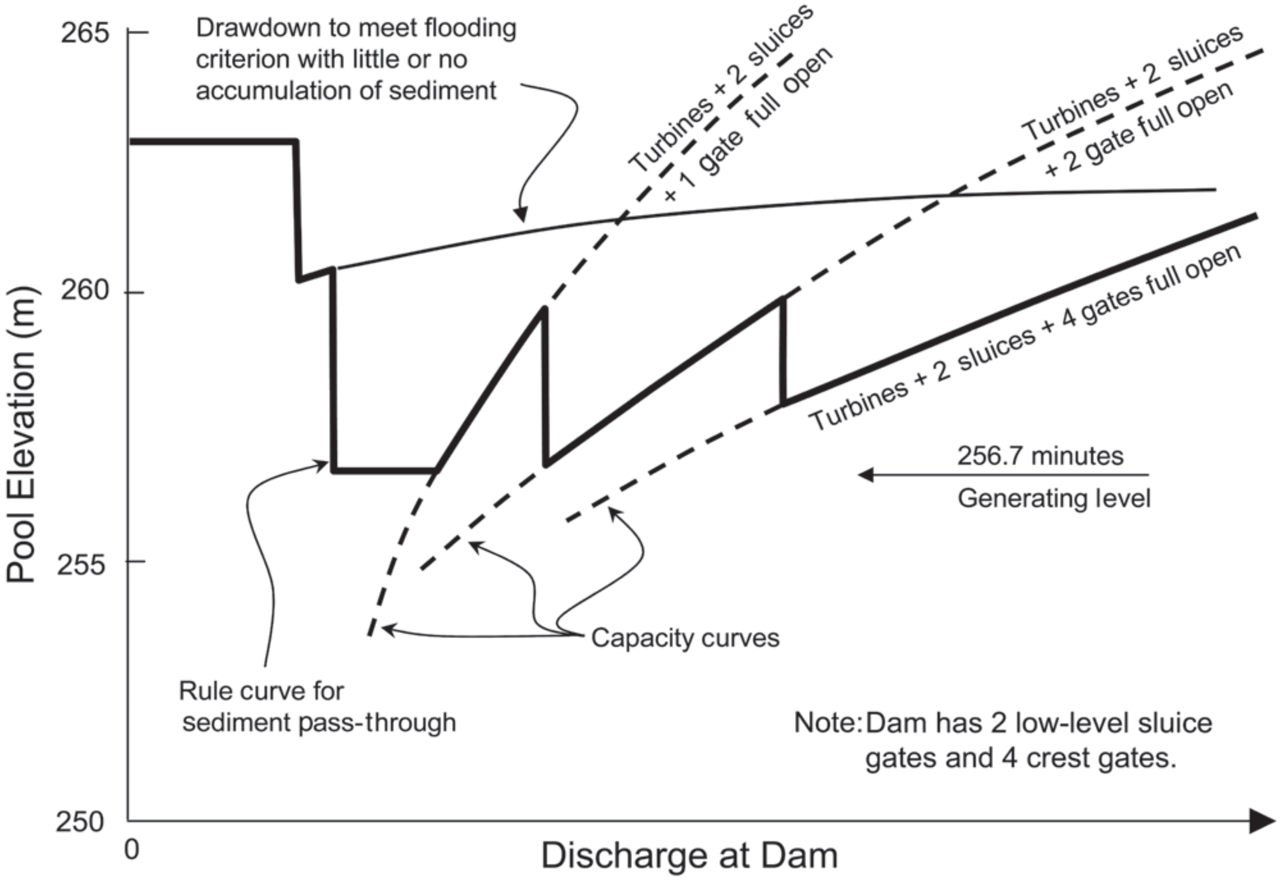

Fig. 12-14. Rule curve for sediment pass-through at Cowlitz Falls Dam, Washington (Locher and Wang 1995).

in China, it has been possible to release as much as 50% of the inflowing sediment as a turbid density current.

Gravity-driven density currents will run along the bottom of the reservoir seeking the lowest part of the cross section. In newly impounded reservoirs, this corresponds to the original river channel. In reservoirs where a channel is maintained by sediment routing or flushing, the turbidity current and its deposits will be focused along this channel, thereby facilitating the removal of turbidity current deposits during subsequent free-flow events. At the Cachí hydropower reservoir in Costa Rica, it was found that 18% of the total inflowing sediment load was accounted for by turbidity currents that ran along the flushing channel and passed through the turbines, and an additional 54% of the total inflowing load was deposited along the length of this channel prior to reaching the hydropower inlet and was removed by subsequent flushing events (Sundborg and Jansson 1992). However, if the submerged channel fills with sediments, the turbidity current will tend to spread across the flat bottom of the reservoir, reducing its velocity and sediment transport capacity, dropping its sediment load, and causing it to stall and dissipate.

De Cesare et al. (2001) undertook monitoring and numerical modeling of turbidity current processes at the Luzzone alpine hydropower reservoir in Switzerland with an average bed slope of about 4%. Turbidity current velocities up to about 0.4 m/second were observed for smaller inflow events. Turbidity currents caused sediment accumulation in front of the dam that required reconstruction of the intakes even though the reservoir had lost only 1% of its capacity to sedimentation. Turbidity currents had focused sediment accumulation beneath only 8% of the reservoir surface area.

Equations needed for the analysis of turbidity current phenomena in lakes and reservoirs are presented in Chapter 2.

12.8.5 Sediment Removal by Hydraulic Dredging

Dredging is any activity involving removal of sediment from underwater. Dredging in reservoirs is generally understood to have the objective of removing sediment to sustain or recover volumetric capacity. However, *tactical dredging* may be focused in a limited area to remove sediments from the vicinity of an intake or a navigation channel, and the dredged sediments are

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not necessarily removed from the pool. Information on dredging is presented by the U.S. Army Corps of Engineers (1987), Turner (1996), Herbich (1992), and Morris and Fan (1998).

Dredging is being used increasingly for the removal of sediment deposits from reservoirs. However, dredging can be considered a sustainable method for controlling sedimentation only if it can be repeated indefinitely. If a reservoir is to be dredged once, it will need to be dredged again. Assuming that the first dredging consumes the best available disposal site, sediment disposal for each subsequent dredging will become increasingly problematic and costly.

The two major impediments to large-scale dredging in reservoirs are high cost and limited availability of sediment disposal sites, and the cost of slurry transportation to distant disposal sites can dominate the cost of a dredging project. An example of a large reservoir-dredging job undertaken in the United States is the removal of 6×10^6 m^3 of sediment from the Loíza reservoir in Puerto Rico during 1997 at a cost of about \$10/m^3 including dredging cost, land acquisition and construction of three sediment-disposal sites, engineering, permitting, and environmental protection (Morris and Fan 1998).

Most reservoir dredging employs conventional hydraulic dredges having a cutter head, a submerged "ladder" pump near the cutter head to lift the slurry (if dredging to depths greater than about 10 m), a main pump on the dredge, and a pipeline to convey the slurry to the point of discharge. Booster pumps may also be required along the discharge pipeline. Because of the requirement for portability, dredges in reservoirs typically have discharge lines not larger than about 400 mm (16 in.) in diameter, although transportable dredging equipment up to 760 mm (30 in.) in diameter can be manufactured.

Dredged material is discharged to a diked containment area where it is allowed to settle, with supernatant return to the reservoir or other water body. Because of bulking of fine sediment, the containment area volume must be larger than the volume of sediment removed. The *bulking factor*, the ratio of sediment volume deposited in the containment area to the in situ sediment volume, may range from 1.0 for sands to about 1.5 for clays. The suspended sediment concentration in the supernatant will depend on the hydraulic loading rate in the spoil area plus the layout to prevent short-circuiting.

When dredging is completed and the disposal area dewatered, dredged sediments may be used beneficially. Sediments dredged from Lake Springfield, Illinois, were converted to agricultural use after 3 years. When dredging involves sands and gravels, the coarse material may be separated from the fines and used as construction aggregate.

Siphon dredges eliminate the dredge pump by discharging through the base of the dam and into the downstream channel, using the static head in the reservoir to discharge the dredged slurry. The typical arrangement involves a floating dredge, a submerged suction pipe that may be fitted with a mechanical cutter head, and a submerged line that discharges to the riverbed through the base of the dam. Intermittent reservoir spills scour and carry away the deposited sediment. This system has been used most notably in Algeria and China but has not been applied in the United States because of environmental regulations. The largest system to date is the 700-mm siphon dredge at the Valdesia hydropower dam in the Dominican Republic, no longer operational. Small-scale U.S. experiments with this type of system have been performed by Hotchkiss and Xi (1995). Because the maximum hydraulic head is limited by the available static head, siphon dredge systems typically do not extend more than about 2 km upstream of the dam.

In considering the feasibility of tactical dredging, it is important to consider that it may be simply creating a hole into which sediment inflows will be focused and quickly refill, and as such it may represent a costly and futile effort. For example, Loehlein (1999) noted that 66,000 m^3 of sediment were dredged from the Conemaugh River reservoir in Pennsylvania within 120 m of the dam, yet over a single winter, 38,000 m^3 of sediment had refilled into the dredged area. Plans for additional dredging were abandoned.

12.8.6 Sediment Removal by Hydraulic Flushing

Hydraulic flushing involves the opening of bottom outlets to completely empty the reservoir and allow stream flow to scour sediment deposits. Sediment flushing may be distinguished from pass-through because its principal objective is to scour and remove previously deposited sediment. The flushing flow will erode a "main channel" through the sediments, typically following the original river thalweg, but deposits on the normally submerged "floodplain" will be unaffected by scour (Fig. 12-15). Subsequent flushing events may deepen or widen the main channel to approximately the width of the preimpoundment stream channel, but sediments on the floodplain area will not be removed. The outflowing sediment concentration is typically one or two orders of magnitude higher than the inflowing concentration. Case studies on flushing are reported by Morris and Fan (1998) and White (2001). An overview of the method and empirical methods to evaluate flushing parameters are presented by Atkinson (1996) and White (2001).

For flushing to be effective, the reservoir must be emptied with free flow along its length and through the outlet. In contrast, operation of bottom outlets under partial drawdown, referred to as *pressure flushing*, will redistribute sediment primarily within the reservoir, eroding upstream deposits and redepositing this material closer to the dam where water remains impounded. Similar processes occur as a result of normal changes in the reservoir's operational level. Pressure flushing will develop and maintain a scour cone in sediment deposits upstream of the bottom outlet, but the scour effect does not extend a significant distance either upstream or laterally.

The reservoir volume at each cross section that can be sustained free of sediment by free-flow flushing is determined by the combination of channel width and angle of repose of

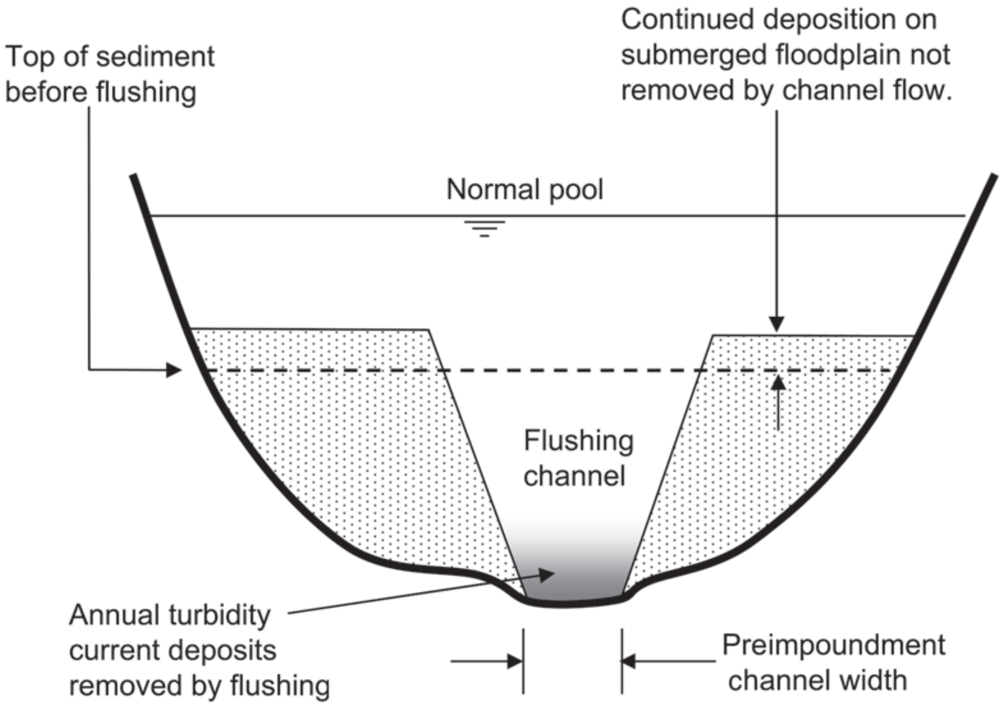

Fig. 12-15. Configuration of deposits in a reservoir subject to drawdown for sediment routing or flushing showing main channel with a stable thalweg profile along which turbidity currents will be focused. The floodplain submerged during normal impounding will continue to accumulate sediment, but the annual deposit thickness on the floodplain during each period will decline as the floodplain level rises. In narrow reaches, the main channel may extend across the entire width of the impoundment, and floodplains may be absent.

the sediment deposits (Fan and Morris, 1992b). On the basis of information reported in the literature, Atkinson (1996) presented an empirical equation to predict the self-formed flushing channel width:

$$W_f = 12.8\, Q_f^{0.5}$$

where Q_f = flushing flow (m^3/second) and W_f = flushing channel width (m). This equation provides a good fit with the available data sets and has the same form as the Lacey regime relation for irrigation canals, but Lacey's multiplier of 4.8 (in SI units) is lower. However, no reasonably reliable general purpose relationship could be found for predicting flushing channel side slopes.

Flushing removes previously deposited sediment using a small percent of the annual discharge water at flow rates low enough to pass through bottom outlets with minimal backwater upstream of the dam. However, the volume of water released by emptying the reservoir will typically exceed the flushing volume itself. This impact is lessened when the released water is used for hydropower production or the reservoir is normally drawn down by annual irrigation deliveries. Flushing durations of several days are typical at hydropower sites, whereas flushing periods of weeks to months durations have been used at larger reservoirs. There is little experience with hydraulic flushing in the United States due to downstream environmental impacts.

The transport of coarse material through a reservoir is the key to achieving long-term equilibrium by flushing. Low discharge rates through low-level outlets may not be adequate to mobilize and transport a significant fraction of the coarse material delivered to the reservoir by floods.

When a main channel is maintained by flushing, density currents during impounding periods will focus fine sediment deposition along the submerged channel to be removed during the next flushing event. Without flushing these sediments would first infill the channel and then spread across and deposit on the submerged floodplain. Well-documented annual flushing at the Cachí hydropower reservoir on Río Reventezón in Costa Rica (Jansson and Rodríguez 1992; Morris and Fan 1998) is illustrative of the procedure. At Cachí, the pool is drawn down at 1 m per day over a 30-day period by turbine operation, followed by a three-day period during which the bottom gate is opened and the river flows freely along the bottom of the reservoir. At the end of the flushing period, the bottom gate is closed, allowing the

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reservoir to refill and resume normal operation. Flushing is conducted during the wet season to provide a high flushing flow and allow rapid refilling of the pool.

At the Cachí reservoir, this flushing procedure releases 73% of the inflowing load, as compared to only 18% of the inflowing load when the reservoir was operated at a continuously high water level. Because of the presence of turbid density currents that flow along the flushing channel, most fine sediments are deposited in the main channel and can be flushed out every year. The principal material that continues to be trapped at Cachí is the coarse bed-material load, which is advancing into the reservoir as a delta and is not effectively mobilized by hydraulic flushing.

The generalized sequence of sediment release during flushing events is shown in Fig. 12-16. The release of the greater part of the annual sediment inflow over a period of only a few days and at flow rates limited by bottom outlet capacity produces extremely high peak sediment concentrations. Experience at sites in Costa Rica, Iran, Switzerland, France, and China indicates that peak suspended sediment concentrations exceeding 200,000 mg/L should be expected during flushing. These concentrations will smother or suffocate aquatic organisms in addition to impacts by the release of potentially anoxic bottom water from the reservoir, the oxygen demand exerted by organic sediment, and elevated ammonia concentrations (toxic to fish). Fine sediment released by flushing can also clog coarse-bed river channels, infill natural pools and navigation channels, affect aquifer recharge from stream flow, clog spawning gravels, obstruct intakes and irrigation channels, make the water unfit for municipal or industrial use, and so forth. The releases needed to move flushed sediment through the downstream system will typically exceed the volume required to remove the material from the reservoir. To date there has been little systematic investigation of means of modifying flushing schemes to reduce environmental impacts to more acceptable levels.

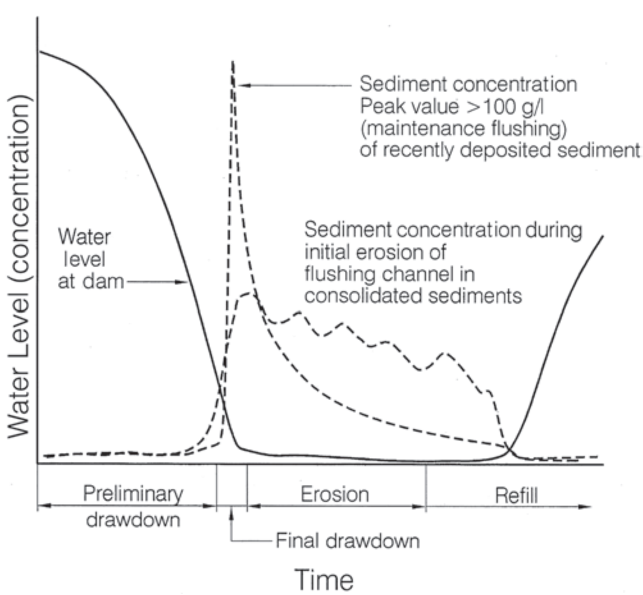

Fig. 12-16. Variation in sediment concentration and other parameters immediately downstream of a dam during reservoir flushing (Morris and Fan 1998).

Liu and Tominaga (2003) have reported on an "environmentally friendly" flushing scheme involving the simultaneous flushing of two reservoirs sequentially located along the Kurobe River in Japan, using high flows to minimize suspended sediment concentration. Environmental impacts were further mitigated by the construction of fish refuges along the downstream channel. However, this site has limited fines and oxygen-depleting organics, and during 10 flushing events over a 9-year period, minimum dissolved oxygen levels never fell below 5.8 mg/L (59% saturation) despite suspended sediment concentrations as high as 161,000 mg/L.

12.8.7 Sediment Focusing

Sediment focusing encompasses hydraulic techniques designed to redistribute sediment within the reservoir. Sediment deposition is naturally focused in deeper parts of the reservoir by turbidity currents, as described in previous sections, and the construction and maintenance of channels or other in-reservoir features can in some cases be used to hydraulically focus sediment deposition in areas where they lessen adverse impacts. Dredging may be used as part of this strategy, principally as a means to alter flow patterns and thereby influence sediment transport and deposition processes. An example is the study of delta deposition processes in Lake Sharpe on the Missouri River (Teal and Remus 2001). Options evaluated were a reduced pool level to move sediment deposits into deeper portions of the reservoir and the construction of dikes.

12.9 DAM REMOVAL

There is an increasing focus on the decommissioning and removal of older dams made obsolete by sedimentation or safety considerations or in the interest of environmental enhancement. To date, most dam removal projects have been limited to smaller structures with limited amounts of sediment accumulation. An ASCE (1997) guideline on the retirement of dams is available. Chapter 23 deals specifically with the numerical modeling of sediment transport following the removal of a dam.

Dam removal is in many ways similar to flushing; riverine flow is re-established along the length of the reservoir, and sediments are released, but following dam removal sediment deposits will continue to be scoured until a new stable geometry has been reached along the formerly impounded

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reach. Depending on the volume of sediments and stream flow, this process may occur in a period of weeks to decades. Similar to flushing, the highest concentration of sediment release can be anticipated immediately after free-flowing river conditions are established across the deposits. In the case of staged removal, a new peak in sediment concentration may be anticipated as each successive removal stage exposes a new layer of sediments to scour (Chapter 23).

The release of high sediment concentrations and loads can produce a wide range of environmental and socioeconomic impacts: closure of intakes and requirement to provide alternative water supplies; bed aggradation, which increases flood hazard and groundwater levels; navigation impairment; and conflict with recreation, sport fisheries, and tourism. Environmental impacts can potentially include massive mortality through the entire aquatic food chain. As a mitigating circumstance, these impacts will gradually lessen as the sediment is washed downstream and out of the system.

MacBroom (2005) has characterized the geomorphic process of channel evolution associated with dam removal and noted that sediment release will not necessarily create adverse impacts in the removal of small dams. Several points are important in planning for dam removal. (1) All potentially involved parties should be represented in project planning. (2) It is essential to have a complete inventory of potential impacts, and, to the extent possible, these impacts should be quantified. (3) The goals of impact mitigation should be clearly defined and prioritized, identifying critical species or economic activities for mitigation. (4) Alternatives should be understood, as should the inevitable trade-offs. For example, partial dam removal may reduce downstream sediment loading and environmental impact, but it will not restore the aquatic migration corridor. (5) The planning process should lead to a clear understanding and consensus of the river management approach and procedures to be used during the removal process.

Several strategies may be employed reduce the impact of sediment releases. Dam removal can be performed by lowering the crest in stages to release sediments at a lower and more controlled rate. Alternatively, it may be determined more feasible to simple remove (or notch) the entire structure at once, pushing the sediments through the downstream system as rapidly as possible and then allowing the stream and riparian ecosystems to recover. Dam removal and sediment release may be timed on a seasonal basis to minimize impacts to downstream species of critical concern.

Sediments may be partially or completely removed prior to dam removal. In this case it is important to define the stable geometry of the postdam deposits and focus removal on those areas where the sediments could be expected to be removed by fluvial action as opposed to areas that will remain as terraces following dam removal. In reservoirs where submerged sediment deposits will remain as terrace deposits after dam removal, dredging of the postdam channel and deposition on these terrace areas may be an option for minimizing sediment release to the downstream channel.

If the regime of stream flow and sediment load entering the impounded reach is similar to preimpoundment conditions, the channel scoured through the deposits can be anticipated to resemble the geometry of the original preimpoundment channel. Quantification of this channel width and its progression over time is necessary to compute sediment loads below the dam. A dam removal express assessment model (DREAM) for estimating sediment release has been advanced by Cui et al. (2006a, 2006b). More information about the components of this model can also be found in Chapter 23.

Chang (2005) used the FLUVIAL-12 sediment transport model to analyze the proposed removal of Matilija dam in California on the Ventura River, illustrating the application of an erodible boundary model that adjusts channel dimensions throughout the simulation, as opposed to an erodible bed model in which the bed width must be input as a parameter value. The simulated enlargement of a cross section in the delta portion of the reservoir over a period of years as simulated by modeling is presented as Fig. 12-17.

Definition of channel side slopes is a critical element in determining the amount of sediment that will be released. Rather than to allow channel slopes to naturally come to their stable angle of repose, it may be desirable to cut them back to create a more natural channel and floodplain configuration and a more stable channel reach. This would also eliminate the potential for future slope failures that could deliver large new sediment volumes to the river after it had experienced recovery from the initial perturbation.

Sediment deposits may contain contaminants that constrain removal options. Rathbun et al. (2005) described a general screening framework for possible contaminants, and Bennett et al. (2002) described a detailed sediment assessment program at two reservoirs in Oklahoma. Chapters 21 and 22 address contaminant processes in sediments as well as sediment oxygen demand in lakes and reservoirs, respectively.

12.10 CONCLUDING REMARKS

Sustainable sediment management represents a relatively new area of focus within the engineering community, and attainment of this goal is not impossible. However, it must be recognized that the "sedimentation problem" is ultimately neither about sediment nor about water itself but about the services provided by water. At most sites it will not be economically feasible to indefinitely maintain levels of water utilization corresponding to the original sediment-free reservoir, and work beyond sedimentation engineering will be required. Themes such as water conservation, more efficient irrigation, and alternative energy sources will all eventually come into play to address sedimentation impacts. Legal sedimentation aspects, addressed in Chapter 20, might also play an important role. These broader themes should also be considered as essential components of the sustainability equation.

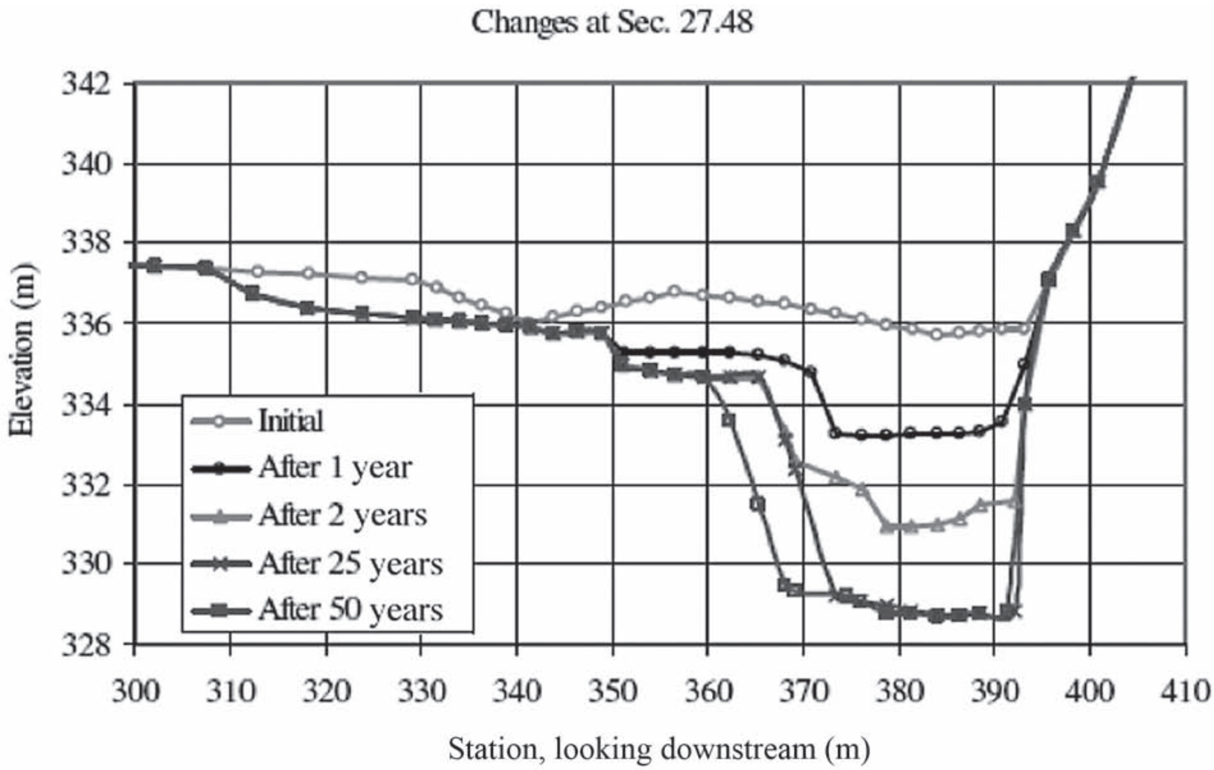

Fig. 12-17. Anticipated morphological changes in the channel as it incises through delta deposits of Matilija dam, California, following proposed dam removal (Chang 2005).

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