Chapter 8

Dam Decommissioning and Sediment Management

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by

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8.1 Introduction

This chapter will briefly discuss the engineering considerations associated with dam removal and then present the basic types of sediment management alternatives. Next, the chapter will discuss the potential impacts associated with dam decommissioning, data collection, analyses of the potential impacts, and case studies.

Over 76,000 dams (that are at least 6 feet in height) exist in the United States today, and they serve many different purposes. These purposes include water supply for irrigation, municipal, industrial, and fire protection needs; flood control; navigation; recreation; hydroelectricity; water power; river diversion; sediment and debris control; and waste disposal (Heinz Center, 2002 and American Society of Civil Engineers (ASCE), 1997). While the great majority of these dams still provide a vital function to society, some of these dams may need to be decommissioned for various reasons including:

- Economics
- Dam safety and security
- Legal and financial liability
- Ecosystem restoration (including fish passage improvement)
- Site restoration
- Recreation

Some dams no longer serve the purpose for which they were constructed. When a dam has significantly deteriorated, the costs of repair may exceed the expected benefits, and dam removal may be a less expensive alternative. For example, if a hydroelectric plant is old, the present operation and maintenance costs may exceed the project benefits. Also, the plant modernization costs may exceed the expected benefits, and decommissioning the hydroelectric plant may be a less expensive alternative. If the spillway of a dam needs to be enlarged, the costs may exceed the project benefits and dam removal may be a less expensive alternative. If fish cannot adequately pass upstream of the dam and reservoir, the cost of adequate fish passage facilities might exceed the project benefits and dam removal may be a less expensive alternative. Some dams and reservoirs may inundate important cultural or historic properties, and dam removal may restore those properties. Along some rivers, the demand for white-water recreation might be a compelling reason to remove a dam.

Three recent publications provide information on the overall considerations related to dam decommissioning and removal. The American Society of Civil Engineers (ASCE, 1997) publication describes the decisionmaking process, available alternatives, and the important considerations related to dam decommissioning and removal. The publication by the H. John Heinz III Center for Science, Economics, and the Environment (Heinz Center, 2002) summarizes the state of scientific knowledge related to dam removal and provides recommendations for additional research. The Aspen Institute (2002) "recommends that the option of dam removal be included in policy and decision making that affects U.S. dams and rivers."

This chapter of the *Erosion and Sedimentation Manual* focuses on the sediment management aspects of dam removal and avoids the discussion of the legal and institutional issues. This chapter also briefly describes the linkages between sediment management, dam removal engineering, and the effects on the aquatic ecosystem.

8.2 Scope of Sediment Management Problems

Rainfall runoff, snowmelt, and river channel erosion provide a continuous supply of sediment that is hydraulically transported and deposited in reservoirs and lakes (see Chapter 2, "Erosion and Reservoir Sedimentation" and Chapter 6 "Sustainable Development and Use of Reservoirs"). Because of the very low velocities in reservoirs, they tend to be very efficient sediment traps. Reservoir sediment disposal (through mechanical methods) can be very costly for large volumes of sediment. Therefore, the management of reservoir sediment is often an important and controlling issue related to dam removal (ASCE, 1997). The sediment erosion, transport, and deposition are likely to be among the most important physical effects of dam removal (Heinz Center, 2002).

The sediment related impacts associated with dam decommissioning could occur in the reservoir and in the river channel, both upstream and downstream from the reservoir. Depending on the local conditions and the decommissioning alternative, the degree of impact can range from very small to very large. For example, the removal of a small diversion dam that had trapped only a small amount of sediment would not have much impact on the downstream river channel. If only the powerplant of a dam were decommissioned, then sediment-related impacts would be very small. The top portion of a dam might be removed in such a way that very little of the existing reservoir sediment would be released into the downstream river channel. In this case, the impacts to the downstream river channel might be related only to the future passage of sediment from the upstream river channel through the reservoir. If dam removal resulted in a large quantity of sediment being released into the downstream river channel, then the impacts to both the upstream and downstream channels could be significant.

The extent of the sediment management problem can be estimated from the following five indicators:

1. The reservoir storage capacity (at the normal pool elevation) relative to the mean annual volume of riverflow.

2. The purposes for which the dam was constructed and how the reservoir has been operated (e.g., normally full, frequently drawn down, or normally empty).

3. The reservoir sediment volume relative to the mean annual capacity of the river to transport sediment of the same particle sizes within the reservoir.

4. The maximum width of the reservoir relative to the active channel width of the upstream river channel in an alluvial reach of river.

5. The concentration of contaminants present within the reservoir sediments relative to the background concentrations.

The first two of these indicators help to describe how much sediment could potentially be stored within the reservoir. The next three indicators (3, 4 and 5) help to scale the amount of reservoir sediment, and its quality, to the river system on which the reservoir is located.

The relative size of the reservoir (ratio of the normal reservoir capacity to mean annual flow volume) can be used as an index to estimate the reservoir sediment trap efficiency. The greater the relative size of the reservoir, the greater the sediment trap efficiency and the amount of reservoir sedimentation. The sediment trap efficiency primarily depends on the sediment particle fall velocity and the rate of waterflow through the reservoir (Strand and Pemberton, 1982). For a given reservoir storage capacity, the sediment trap efficiency would tend to be greater for a deeper reservoir, especially if riverflows pass over the crest of the dam. Brune (1953) developed an empirical relationship for estimating the long-term reservoir trap efficiency, based on the correlation between the relative reservoir size and the trap efficiency observed in Tennessee Valley Authority reservoirs in the southeastern United States. Using this relationship, reservoirs with the capacity to store more than 10 percent of the average annual inflow would be expected to trap between 75 and 100 percent of the inflowing sediment. Reservoirs with the capacity to store 1 percent of the average annual inflow would be expected to trap between 30 and 55 percent of the inflowing sediment. When the reservoir storage capacity is less than 0.1 percent of the average annual inflow, the sediment trap efficiency would be nearly zero.

The purpose for which a dam was constructed, along with legal constraints and hydrology, determines how the reservoir pool is operated. The operation of the reservoir pool will influence the sediment trap efficiency and the spatial distribution and unit weight of sediments that deposit within the reservoir. The reservoir trap efficiency of a given reservoir will be greatest if substantial portions of the inflows are stored during floods when the sediment concentrations are highest. If the reservoir is normally kept full (run of the river operation), floodflows would be passed through the reservoir and trap efficiency would be less. Coarse sediments would deposit as a delta at the far upstream end of the reservoir. When reservoirs are frequently drawn down, a portion of the reservoir sediments will be eroded and transported father downstream. Any clay-sized sediment that is exposed above the reservoir level will compact as they dry out (Strand and Pemberton, 1982).

The ratio of reservoir-sediment volume to the annual capacity of the river to transport sediment is a key index. This index can be used to estimate the level of impact that sediment release from a dam removal would have on the downstream river channel. When the reservoir sediment volume is small, relative to the annual sediment transport capacity, then the impact on the downstream channel likely will be small. Reservoirs have a finite capacity to trap and store sediments. Once that capacity is filled with sediment, the entire sediment load supplied by the upstream river channel is passed through the remaining reservoir. For example, the pool behind a diversion dam is typically filled with sediment within the first year or two of operation. Therefore, the relative volume of reservoir sediment may not be large, even if the dam is considered old. When a reservoir has a multiyear, sediment storage volume, the dam removal plan should consider staging dam removal over multiple years to avoid excessive aggradation of the downstream riverbed. The dam removal investigation should determine how much of the reservoir sediment would actually erode from the reservoir.

The width of the reservoir, relative to the width of the active river channel (in an alluvial reach) upstream from the reservoir can indicate how much sediment would be released from the reservoir both during and after dam removal. When a reservoir is many times wider than the river channel, then the river may not be capable of eroding the entire reservoir sediment volume, even long after dam removal (Morris and Fan, 1997 and Randle et al., 1996).

The presence of contaminants in the reservoir sediments, at concentrations significantly higher than background levels, would likely require mechanical removal or stabilization of the reservoir sediments prior to dam removal. Even if contaminants are not present in the reservoir sediments, the turbidity created by sediment erosion during dam removal may impact the aquatic environment of the downstream river channel. Increased turbidity could also be a concern for downstream water users.

As an example, these five indicators were applied to three dams in the Pacific Northwest that are being considered for removal to improve fish passage:

- Gold Hill Dam near Gold Hill, Oregon (Bureau of Reclamation, 2001a)
- Savage Rapids Dam near Grants Pass, Oregon (Bureau of Reclamation, 2001b)
- Glines Canyon Dam near Port Angeles, Washington (Randle et al., 1996)

These three dams range in size from small to large, and their potential effects on sediment management range from negligible to major (see Table 8.1).

The major issues associated with sediment management, related to dam removal, may include cost, water quality, flooding, operation and maintenance of existing infrastructure, cultural resources, the health of fish and wildlife and their habitats (including wetlands), recreation, and restoration of the reservoir area. Sediment management plans are important to prevent the following impacts:

- If a large volume of coarse sediment were eroded too quickly from a reservoir, then the sediment could aggrade the downstream river channel, cause channel widening and bank erosion, increase flood stage, plug water intake structures, and disrupt aquatic habitats.
- If large concentrations of fine sediment were eroded from the reservoir, then turbidity would increase in the downstream river channel and may significantly degrade water quality for the aquatic environment and for water users.

- If the reservoir sediment contains significant concentrations of contaminants, then these contaminants could be potentially released into the aquatic environment and into municipal water treatment plants and wells.

- If the reservoir sediment has to be mechanically removed, disposal sites can be difficult to locate and the sediment removal cost can be the most expensive portion of the dam removal project.

- If a delta is eroded from the upstream end of the reservoir, the erosion of sediment deposits can continue to progress along the upstream river channel. Sediment deposited along the backwater of the reservoir pool will begin to erode once the reservoir pool is drawn down.

Table 8.1. Sample application of reservoir sediment impact indicators to three dams in the Pacific Northwestern United States

Dam Properties	Gold Hill Dam near Gold Hill, Oregon	Savage Rapids Dam near Grants Pass, Oregon	Glines Canyon Dam near Port Angeles, Washington
River name and distance from mouth	Rogue River (river mile 121)	Rogue River (river mile 107.6)	Elwha River (river mile 13.5)
Active river channel width in alluvial reach	150 feet	150 feet	200 feet
Type of dam	Concrete gravity dam	Concrete gravity and multiple arch dam	Concrete arch dam
Hydraulic height	1 to 8 feet	30 to 41 feet	210 feet
Dam crest length	1,000 feet ("L" plan shape)	460 feet	150 feet
Reservoir Properties			
Reservoir length	1 mile	3,000 feet	2.3 miles
Reservoir width	150 to 350 feet	290 to 370 feet	1,000 to 2,000 feet
Reservoir capacity	100 acre-feet	290 acre-feet	40,500 acre-feet
Sediment Management Indicators			
Relative reservoir capacity	0.005 percent	0.01 percent	4.5 percent
Reservoir operations	Run-of-the-river	Reservoir pool raised 11 feet during the summer irrigation season	Run-of-the-river
Relative reservoir sediment volume	Negligible	1-to-2 year supply of sand and gravel	75-year supply of sand and gravel; 54-year supply of silt and clay
Relative reservoir width	2.3 (all sediment would be eroded from the reservoir)	2.5 (nearly all sediment would be eroded from the reservoir)	10 (about one-third of the sediment would be eroded from the reservoir)
Relative concentration of contaminants or metals	Less than background levels	Less than background levels	Only iron and manganese are above background levels
Sediment management problem	Negligible	Moderate	Major

The potential impacts from the erosion, transport, and deposition of reservoir sediment should be at least considered in all dam removal studies. If the impacts could be significant, then a sediment management plan should be developed. With an effective sediment management plan, potential impacts can be substantially reduced or avoided. In some cases, there may be benefits from the controlled release of reservoir sediments such as the introduction of gravel, woody debris, and nutrients for the restoration of downstream fish habitats.

8.3 Engineering Considerations of Dam Decommissioning

Dam decommissioning alternatives might include the discontinued use of a hydroelectric powerplant, partial removal of the dam, or complete removal of the dam and all associated structures (e.g., spillways, outlets, powerplants, switchyards, etc.). Partial removal of a dam could be planned in many different ways to achieve different purposes. For example, the portion of the dam that blocks the river channel and flood plains could be removed, while the abutments and other structures are left in place for historic preservation and to reduce removal costs. Any remaining structures would have to be left in a safe condition and may require periodic maintenance. In the case where a dam spans a valley width that is significantly wider than the river channel, a relatively narrow portion of the dam could be removed so that the remaining dam would help retain a significant portion of the reservoir sediments. A partial dam removal could also mean that the upper portion of the dam is removed, while the lower portion is left in place to retain reservoir sediments deposited below that elevation. This alternative might also help to reduce or eliminate any dam safety concerns by reducing the size of the reservoir, but fish passage facilities might still need to be provided.

The type of material used to construct a dam (concrete, masonry, rockfill, or earth) is important for determining how much of the dam to remove, the volume of material for disposal, and the removal process itself (ASCE, 1997). In addition, there are several other engineering considerations that influence the amount and rate of sediment erosion, transport, and deposition.

The rate of dam removal and reservoir drawdown has a strong influence on the rate that sediments are eroded and transported to the downstream river channel. The effects from releasing a large volume of reservoir sediment into the downstream channel can be reduced by slowing the rate of reservoir drawdown. This might be accomplished by progressively removing layers of the dam over a period of weeks, months, or years, depending on the size of the dam and the volume of the reservoir sediments. The rate of reservoir drawdown needs to be slow enough to avoid a flood wave of reservoir water spilling into the downstream river channel. Also, the rate needs to be slow enough to avoid inducing any potential landslides along the reservoir margins or a slide failure of any earthen dams.

The ability to drawdown the reservoir pool depends on how flows can be released through, over, or around the dam. If the dam has a low-level, high-capacity outlet works or diversion tunnel, the reservoir could be emptied at a prescribed rate and the dam could be removed under dry conditions. However, if the width of the outlet works is narrow relative to the reservoir sediment width, then a substantial portion of the sediments would remain in the reservoir until the dam is removed. A bypass channel could be constructed around the dam, but it would need the ability to at least partially drain the reservoir. For concrete dams, it may be acceptable to release flows over the dam or through notches cut into the dam (ASCE, 1997).

Dam removal and reservoir drawdown plans have to prepare for the possibility of floodflows occurring during dam removal. The occurrence of a flood may simply mean the temporary halt of dam removal and reservoir drawdown activities. However, an overtopping flood could cause a failure of the remaining structure and a downstream flood wave that would be many times larger than the reservoir inflow. If the remaining structure can withstand overtopping flows, then floods may help to erode and redistribute delta sediments throughout the reservoir. In a wide reservoir, a floodflow may help to leave the reservoir sediment in a more stable condition after dam removal.

8.4 Sediment Management Alternatives

The development of alternative sediment management plans for dam decommissioning requires concurrent consideration of engineering and environmental issues. Sediment management alternatives can be grouped into four general categories (ASCE, 1997):

> No action. Leave the existing reservoir sediments in place. If the reservoir-sediment storage capacity is not already full, then either allow future sedimentation to continue or reduce the sediment trap efficiency to enhance the life of the reservoir.
>
> River erosion. Allow the river to erode sediments from the reservoir through natural processes.
>
> Mechanical removal. Remove sediment from the reservoir by hydraulic or mechanical dredging or conventional excavation for long-term storage at an appropriate disposal site.
>
> Stabilization. Engineer a river channel through or around the reservoir sediments and provide erosion protection to stabilize the reservoir sediments over the long term.

A sediment management plan can also consist of a combination of these categories. For example, fine sediments could be mechanically removed from the downstream portion of the reservoir to reduce the impacts on water quality. At the same time, the river could be allowed to erode coarse sediments from the reservoir delta to resupply gravel for fish spawning in the downstream river channel.

8.4.1 Integration of Dam Decommissioning and Sediment Management Alternatives

The character of the sediment management alternative would depend on the dam decommissioning alternative. For example, the rate of river erosion is directly influenced by the rate of dam removal, and the amount of reservoir sediment eroded by riverflows would increase as more of the dam is removed. The cost of mechanically removing sediment from deep reservoirs (mean depth greater than 10 to 15 feet) would be less if the sediment can be removed as the reservoir is drawn down. The cost and scope of reservoir sediment stabilization would decrease as more of the dam is retained. The matrix of possible combinations of dam decommissioning alternatives and sediment management alternatives is shown in Table 8.2. There will be continual interplay between balancing the scope of the sediment management alternative, the requirements of dam decommissioning, acceptable environmental impacts, and cost. The steps to prepare a sediment management plan are shown in Table 8.3. Each sediment management alternative should include proper mitigation to make the alternative as feasible as possible.

Table 8.2. Relationship between dam decommissioning and sediment management alternatives (modified from ASCE, 1997)

Sediment management alternative	Dam decommissioning alternatives		
	Continued operation	Partial dam removal	Full dam removal
No action	• Reservoir sedimentation continues at existing rates, • Inflowing sediment loads are reduced through watershed conservation practices, or • Reservoir operations are modified to reduce sediment trap efficiency.	• Only applicable if most of the dam is left in place. • The reservoir sediment trap efficiency would be reduced. • Some sediment may be eroded from the reservoir.	• Not applicable.
River erosion	• Sluice gates are installed or modified to flush sediment from the reservoir. • Reservoir drawdown to help flush sediment.	• Partial erosion of sediment from the reservoir into the downstream river channel. • Potential erosion of the remaining sediment by sluicing and reservoir drawdown.	• Erosion of sediment from the reservoir into the downstream river channel. Erosion rates depend on the rate of dam removal and reservoir inflow. The amount of erosion depends on the ratio of reservoir width to river width.
Mechanical removal	• Sediment removed from shallow depths by dredging or by conventional excavation after reservoir drawdown.	• Sediment removed from shallow depths before reservoir drawdown. • Sediment removed from deeper depths during reservoir drawdown.	• Sediment removed from shallow depths before reservoir drawdown. • Sediment removed from deeper depths during reservoir drawdown.
Stabilization	• The sediments are already stable, due to the presence of the dam and reservoir.	• Retain the lower portion of the dam to prevent the release of coarse sediments or retain most of the dam's length across the valley to help stabilize sediments along the reservoir margins. • Construction of a river channel through or around the reservoir sediments.	• Construction of a river channel through or around the existing reservoir sediments. • Relocate a portion of the sediments to areas within the reservoir area that will not be subject to high-velocity riverflow .

Table 8.3. Steps to preparing alternative sediment management plans

1	Examine the possible range of dam decommissioning alternatives (continued operation, partial dam removal, and full dam removal).
2	Determine the reservoir sediment characteristics including volume, spatial distribution, particle-size distribution, unit weight, and chemical composition.
3	Investigate the existing and pre-dam geomorphology of the river channel upstream and downstream of the dam.
4	Inventory the existing infrastructure around the reservoir, along the downstream river channel, and along the upstream portion of the river channel influenced by the reservoir.
5	Determine the feasible range of sediment management alternatives and formulate specific alternatives.
6	Coordinate the details of each sediment management alternative with the other aspects of the dam decommissioning alternative.
7	Conduct an initial assessment of the risks, costs, and environmental impacts for each sediment management alternative.
8	Determine what mitigation measures may be necessary to make each alternative feasible and include these measures in the alternative.
9	Finalize the assessment of the costs, environmental impacts, and risks for each modified sediment management alternative.
10	Document the risks, costs, and environmental impacts of each alternative for consideration with the engineering and environmental components of the study. Provide technical support to the decisionmaking process.

8.4.2 No Action Alternative

Under this alternative, the dam, reservoir, and sediment would be left in place. For most diversion dams and other small structures, the sediment storage capacity of the reservoir pool is already full. In this case, floods, sluicing, and dredging can cause temporary changes in sediment storage, but the inflowing sediments are generally transported through the reservoir pool to the downstream river channel or into a canal. Under these conditions, a decision to leave the dam and reservoir in place will not change the existing impacts caused by the dam and its operation.

If the reservoir sediment storage capacity is not already full, future sedimentation could be allowed to continue or actions could be taken to reduce sedimentation rates and prolong the life of the reservoir. The life of the reservoir may be extended by reducing the upstream sediment loads, bypassing sediment through or around the reservoir, or removing the existing sediment (see Chapter 6 “Sustainable Development and Use of Reservoirs”). If the reservoir continues to trap sediment, the remaining reservoir capacity will eventually be filled with sediment, but this could take decades or centuries to occur, depending on the reservoir size and the upstream sediment loads.

Sediment deposited in the reservoir would have naturally been transported to the downstream river channel. Consequently, the clear-water releases from the reservoir tend to cause erosion of the downstream river channel (see Chapter 7 “River Processes and Restoration”). Continued long-term sedimentation of the reservoir would reduce the project benefits and perhaps even pose a threat to dam safety. Reservoir sedimentation can also cause deposition in the upstream river channel (especially for mild slope rivers) and increase river stage in the backwater reach upstream from the reservoir. Eventually, reservoir sedimentation will cause velocities through the reservoir to increase and subsequently decrease the sediment trap efficiency. Once the reservoir sediment storage capacity is full, the sediment load entering the reservoir would be transported through to the downstream river channel. Once coarse sediment (sand and gravel) passes through the reservoir, any erosion process of the downstream river channel would be reversed and sediment deposition would occur in the previously eroded river channel. Aggradation of the downstream riverbed may eventually increase water surface elevations to pre-dam levels (depending on the existing upstream sediment supply and downstream riverflows). New developments in the pre-dam flood plain may be flooded more frequently. Concentrations of fine sediment may also increase to pre-dam levels, which may affect downstream water users and the aquatic environment. In contrast, some reservoirs store and divert so much water that the downstream river channel aggrades. In this case, continued long-term sedimentation of the reservoir would tend to force more water into the downstream river channel and at least partially reverse the aggradation trend.

8.4.3 River Erosion Alternative

Sediment removal from the reservoir by river erosion can be applied to all dam decommissioning alternatives. River erosion is a frequently employed sediment management practice associated with dam removal of all sizes. In fact, this is the preferred alternative for the removal of the large Elwha and Glines Canyon Dams on the Elwha River in Washington (Olympic National Park, 1996). The reservoirs behind these two dams contain 18 million yd^3 of sediment (Gilbert and Link, 1995).

Allowing reservoir sediments to erode and discharge into the downstream river channel may be the least costly alternative if the downstream impacts can be accepted or mitigated. However, water quality considerations may make this alternative unacceptable if the reservoir sediments contain high concentrations of contaminants or metals. The advantage of the river erosion alternative is that the cost of physically handling the sediments is eliminated. However, these benefits must be weighed against the risks of unexpected riverbed aggradation or unanticipated increases in turbidity downstream.

8.4.3.1 River Erosion Description

In the case of continued dam operation, sluice gates with adequate discharge capacity can be used to initiate and maintain sediment transport through the reservoir. This is normally done in conjunction with reservoir drawdown to increase the flow velocities through the reservoir and increase the sediment transport (Morris and Fan, 1997). For partial dam removal, the amount of reservoir sediment eroded by riverflows would depend on how much of the dam is removed and how much of the reservoir pool is permanently and temporarily drawn down.

For small dams with relatively small reservoirs and sediment volumes (see Section 8.2), the rate of dam removal may not be critical. However, for dams that have relatively large reservoirs or sediment volumes, the rate of final reservoir drawdown (corresponding with dam removal) can be very important. Severe impacts to water quality and flooding can occur if the reservoir drawdown rate is too fast. However, the alternative would take too long to implement and perhaps cost too much if the reservoir drawdown rate were unnecessarily slow. The rate and timing of staged reservoir drawdown should meet the following general criteria:

- The reservoir discharge rate is slow enough that a downstream flood wave does not occur.
- The release of coarse sediment is slow enough so that severe riverbed aggradation does not cause flooding to people and property along the downstream river channel.
- The concentration of fine sediment released downstream is not too great, or its duration too long, so that it would not overwhelm downstream water users or cause unacceptable impacts to the aquatic environment.

These general criteria would need to be specifically defined for each local area. In order to reduce the downstream channel impacts, staged dam removal may need to be implemented over a period of months or years, depending on the size of the reservoir, height of the dam, and the volume of sediment. The structural and hydraulic stability of the partially removed dam must be analyzed at these various stages to ensure adequate safety and to prevent a large and sudden release of water or sediment. With the proper rate of reservoir drawdown, the magnitude of the downstream impacts can be reduced and spread out over time. In some cases, it may be more desirable to have the impacts occur over a shorter period of time, with higher magnitude, than over a longer period of time with lower magnitudes. For example, a shorter duration of high turbidity may affect only 1 or 2 year classes of fish, whereas a longer duration of impact with chronic levels of turbidity may affect multiple year classes of fish.

For reservoirs that are much wider than the upstream river channel, river erosion during dam removal may only result in a portion of the sediment being transported to the downstream river channel. This is because the river will tend to incise a relatively narrow channel through the reservoir sediments. This erosion channel would likely widen over time through channel migration, meandering, and flood plain development, but the entire erosion width may still be less than the initial reservoir sediment width. Also, riparian forests may naturally colonize the remaining sediment terraces and additionally prevent or slow their erosion. Vegetation could also be planted to speed up the natural process and prevent the establishment of non-native species.

Some reservoirs are many times wider than the river channel and have relatively thick delta deposits (more than 10 feet) at the upstream end of the reservoir. In this case, it may be desirable to induce lateral erosion of the delta sediments and redeposition across the receding reservoir. This would result in leaving the remaining delta sediments, as a series of low, stable terraces, rather than one high terrace that is potentially unstable. During a reservoir drawdown increment, the river would incise a relatively narrow channel through the exposed delta. As long as a reservoir pool continues to remain during dam removal, the eroded delta sediments would redeposit as a new delta across the upstream end of the lowered reservoir. As a new delta deposit forms across the receded lake, the erosion channel is forced to move laterally to meet deeper areas of the reservoir. Thus, the sediment erosion width is narrow at the upstream end, but it increases to the reservoir width where the channel enters the receded lake. This can be accomplished by holding the reservoir level at a constant elevation between drawdown increments. The duration of constant reservoir elevation between drawdown increments (a few days to a few weeks) corresponds to the length of time necessary for the river channel to redeposit the eroding reservoir sediments across the width of the receded reservoir (Randle et al., 1996).

After enough of the dam and reservoir have been removed, the eroding delta sediments will have reached the dam and the reservoir pool will be completely filled in with sediment (Randle et al., 1996). At this critical point in time, further dam removal will result in the downstream release of coarse sediments. Also, the horizontal position of river erosion channel would be relatively fixed where the river channel passes the dam site and subsequent erosion widths through the reservoir sediment would be a function of riverflow and the bed material load.

8.4.3.2 River Erosion Effects

The amount and timing of reservoir sediment release and any resulting downstream impacts to water quality and flooding can be estimated through computer modeling, but thorough knowledge and experience with the model are required. The optimum rate of dam removal, for sediment management purposes, can be determined by modeling a range of dam removal rates.

Any sediment released downstream would deposit somewhere, either because of decreasing river channel slopes downstream or because the river enters a lake, estuary, or ocean. Depositional effects and sediment concentrations in the downstream river channel, lake, estuary, or ocean must be carefully studied to determine if the impacts from the sediment management alternative are acceptable or can be mitigated. Monitoring is essential during reservoir drawdown to verify these predictions and, if necessary, slow the rate of dam removal and reservoir drawdown.

The amount and rate of reservoir sediment that is eroded and released to the downstream river channel affect both short- and long-term impacts, the risk of unintended impacts, and cost. The period of short-term impacts might be considered the period of dam removal plus an additional 3 to 5 years. Over the short term, the release of fine lakebed sediment (silt and clay-sized material) would affect water quality, including suspended sediment concentration and turbidity. The release of coarse sediment (sand, gravel, and cobble-sized sediment) could increase flood stage, the rate of river channel migration, and deposition in a downstream lake or estuary. The release of gravel might improve existing fish spawning habitat. Over the long term, the amount and timing of sediment supplied to the downstream river channel would return to predam conditions. The predam conditions may be close to natural conditions if there are no other dams upstream. However, the presence of upstream dams may still leave the river system in an altered condition.

Floodflows may have different effects on sediment releases, depending on whether they occur during or after dam removal. Dam removal operations may have to be discontinued during floodflows. The temporary halt to dam removal during floods would tend to prevent large increases in the amount of sediment eroded from the reservoir. However, floods that occur immediately after dam removal could erode substantial amounts of reservoir sediment. After the first floodflow, significant channel widening in the former reservoir area would only occur during subsequently higher floodflows. Sediment releases downstream would rapidly decrease over time because higher and higher floodflows would be required to cause additional erosion. The time required to reestablish the natural river channel within the former reservoir area depends on the rate of final reservoir drawdown and future floodflows. If a period of drought occurs just after final reservoir drawdown and dam removal, the last phase of sediment erosion in the reservoir would be delayed. Conversely, if a major flood occurs just after reservoir drawdown and dam removal, large amounts of sediment could be transported downstream over a short period of time.

The short-term impact of full dam removal may be to temporarily aggrade the downstream river channel and increase suspended sediment concentration and turbidity. The long-term impact is to fully restore the upstream sediment supply to the downstream river channel. This may approach predam conditions, depending on the level of development in the upstream watershed.

8.4.3.3 Monitoring and Adaptive Management

For projects where the reservoir sediment volume is significant, monitoring and adaptive management are critical components to the river erosion alternative. The effects of the river erosion alternative should be predicted ahead of time. Monitoring is needed to confirm those predictions. If necessary, corrective actions should be taken before impacts could exceed these predictions. For example, the rate of dam removal could be temporarily slowed or halted to mitigate for unanticipated consequences.

Typically, the objectives of the sediment monitoring plan are to detect and avoid severe impacts related to flooding, erosion of infrastructure, and water quality. In addition, the monitoring program could assess project performance and provide scientific information applicable to other projects. A monitoring program could be designed to provide the following types of information:

- Real-time data on physical processes that would assist project management in decisions regarding the water treatment plant operations, bank erosion protection, flood protection, and the rate and timing of dam removal.

- Long-term data that would both identify and quantify physical processes associated with ecosystem restoration following dam removal.

Monitoring categories may include the following processes:

- Reservoir sediment erosion and redistribution
- Hillslope stability along the reservoir and downstream river channel

- Water quality (including suspended sediment concentration)
- Riverbed aggradation and flood stage along the downstream river channel
- Aquifer characteristics
- River channel planform and channel geometry
- Large woody debris
- Coastal processes including the delta bathymetry and turbidity plume

Not all of these processes may occur (or need to be monitored), and some processes may need detailed monitoring. The key is to determine if any of these processes could cause undesirable consequences and implement a monitoring program to provide early detection. In addition, a monitoring program could be used to assess project performance. The monitoring program could be divided into adaptive management and restoration monitoring categories. The adaptive management monitoring program could provide real-time information directly to project managers, verify or modify dam deconstruction scheduling, and trigger contingency actions required to protect downstream water quality, property, and infrastructure. The restoration monitoring program could provide a body of scientific knowledge applicable to understanding and interpreting natural river restoration processes. Such information could be used to guide management decisions over the long term and would be applicable to future dam removal projects in other locations.

The adaptive management responses could include the following actions:

- Modify monitoring techniques, locations, or frequencies
- Improve water treatment techniques
- Locally mitigate flooding and bank erosion
- Slow rate of dam removal
- Temporarily halt dam removal

The frequency and duration of monitoring activities depend on the local project conditions, including the relative volume of the reservoir sediment, rate of dam removal and time of year, hydrology, and budget. Measurement of initial conditions is necessary to establish a monitoring baseline for comparison. Monitoring should be conducted prior to dam removal, for a period long enough to test monitoring protocols and determine the range of variability in the data. As monitoring continues during dam removal, the results of certain parameters could be used to trigger the monitoring of additional parameters. For example, the monitoring of aggradation in the downstream river channel could be initiated after coarse sediment is transported past the dam site. Monitoring should continue after dam removal until either all of the reservoir sediments have eroded or stabilized in the reservoir and sediment has been flushed from the downstream river channel.

8.4.4 Mechanical Removal Alternative

Under this type of alternative, all or a portion of the reservoir sediment would be removed and transported to a long-term disposal site. This type of sediment management alternative can be used with any decommissioning scenario (continued operation, partial dam removal, or full dam removal). Sediment could be removed by conventional excavation, mechanical dredging, or hydraulic dredging. Transport to a disposal site could be through a slurry pipeline, by truck, or conveyor belt. Long-term disposal sites could include old gravel pits, landfills, or ocean disposal areas.

Mechanical removal would attempt to reduce the downstream concentration of sediment and turbidity by removing sediments from the reservoir before they could erode. This type of alternative is the most conservative and, potentially, the most costly. All costs are up-front construction costs, but the long-term risks would be relatively low (ASCE, 1997). Costs can be reduced by not removing all of the reservoir sediment. For example, only the sediments within the predam flood plain would need to be removed to prevent subsequent river erosion. The remaining portion could be allowed to stabilize within the reservoir. Coarse sediment (that may be present in a reservoir delta) could be allowed to erode downstream if it is considered to be a resource necessary to restore river gradient or spawning gravels for fish habitats. The coarse sediments, especially gravel, would likely be transported as bed load and would not increase turbidity as much as fine sediments (clay, silt, and fine sand). The three components of the mechanical removal alternative include: (1) sediment removal methods, (2) conveyance methods, and (3) long-term disposal methods.

8.4.4.1 Sediment Removal Methods

Several methods are available for removing the sediment. The main criteria for selecting a removal method are the size and quantity of sediments and whether the sediment would be removed under wet or dry conditions (ASCE, 1997). An overview of each method follows.

- Conventional excavation requires lowering of the reservoir or rerouting of the river so that sediment excavation and removal can be accomplished in dry conditions. After sediment has become dry enough to support conventional excavating equipment, the sediment can be excavated (by dozers and front-end loaders) and hauled (by truck) to an appropriate disposal site. The viability of this approach depends upon the facilities available, sediment volume, the amount of time required to dry the sediment, and the haul distance to the disposal site. If the sediment volume is small, and the sediments are not hazardous, this disposal process can be done economically. At a shallow 10-acre reservoir in northeastern Illinois, approximately 15,000 cubic yards of "special waste" sediment were removed and disposed of at a nearby landfill for total cost of $350,000 in 1989. The unit cost was about $25 per cubic yard.

- Mechanical dredging is performed using a clamshell or dragline, without dewatering the site, but it still requires that the excavated material be dewatered prior to truck transport to the disposal facility. Costs to dredge some 35,000 cubic yards of sediment from behind a low-head dam in northeastern Illinois were also estimated at $25 per cubic yard in 1987.

- Hydraulic dredging is often the preferred approach to removing large amounts of sediment, particularly if the sediments are fine-grained, because they are removed under water. The sediments are removed as a slurry of approximately 15 to 20 percent solids, by weight. Hydraulic dredging is normally conducted from a barge and can access most shallow areas of the reservoir. Dredging could begin in the shallow areas of the reservoir (5 to 30 feet) and continue to deeper areas as the reservoir is drawn down. If delta sediments are to be left to river erosion, dredges working from barges could pick up lakebed sediments immediately downstream from the eroding delta front. Submersible dredges could also be used to dredge deep areas of the reservoir before drawdown. Woody debris or tree stumps may prevent the removal of sediment from the lowest layer of the reservoir bottom. Design considerations would include volume and composition of material to be dredged, reservoir water depth, dredge capacity, and distance to and size of the disposal facility. For a 180-acre lake in central Illinois, 280,000 cubic yards were hydraulically dredged and disposed of at a facility constructed on the owner's adjacent property for a total cost of $900,000 in 1989, with a unit cost of approximately $3 per cubic yard.

8.4.4.2 Sediment Conveyance Methods

Some example methods of conveyance include transport through a sediment slurry pipeline, by truck, and by conveyor belt. A sediment slurry pipeline can be an efficient and cost-effective means of conveying sediment over long distances, especially under gravity-flow conditions. Conveyer belts may be efficient over short distances. Trucking is a conventional method that is often the most expensive because of the large quantities involved.

In the case of a sediment-slurry pipeline, the route and distance to the disposal site are an important design consideration. An alignment along the downstream river channel may allow for gravity flow and avoid pumping costs. However, construction in canyon reaches could be difficult and the pipeline would have to be protected from riverflows. The pipeline could be buried or secured above ground with lateral supports. These supports might consist of large concrete blocks or rock anchors. If gravity flow were not possible, then a pumping plant would be needed. Booster pumps also may be needed for slurry pipelines of long distance. The pipeline and any pumping stations could be removed after the sediments had been dredged from the reservoir.

A certain amount of water would be required to operate the slurry pipeline (80 to 85 percent water, by weight) and this amount would reduce downstream riverflows. If water is scarce, then the slurry pipeline operation may have to be temporarily curtailed or discontinued during low-flow periods to maintain minimum flows for the downstream water users and the aquatic environment.

Silt- and clay-sized sediments are expected to easily flow by gravity through the sediment slurry pipeline. However, sand-sized and larger sediment may abrade or clog the pipeline. Therefore, a settling basin or separator may be needed to prevent sand and coarser material from entering the slurry pipeline. The coarse sediment that is excluded could be discharged back into the reservoir or transported to the disposal site by conveyor belt or truck.

8.4.4.3 Long-Term Disposal

Disposal sites may include such places as old gravel pits, landfills, or ocean disposal areas. Distance from the reservoir is an important parameter in the selection of a disposal site, since conveyance costs increase with increasing distance to the disposal site. A land disposal site may have to be lined to prevent ground water contamination if the disposed sediments contained high concentrations of contaminants. In the case of a slurry pipeline, the sediment-water mixture is discharged into a settling basin at the disposal facility. The disposal facility should be sized to provide adequate settling times so that the return flow (effluent) meets regulatory criteria. Reservoir sediment volumes at the disposal site may be large (hundreds of thousands or millions of cubic yards) and require large land areas (tens or hundreds of acres). For example, disposal of the nearly 18 million cubic yards of sediment in two reservoirs on the Elwha River would require a 560-acre site if piled 20 feet high.

8.4.5 Stabilization Alternative

Under this type of alternative, sediment would be stabilized in the reservoir by constructing a river channel through or around the reservoir sediments. Stabilization of the reservoir sediments would prevent them from entering the downstream river channel. The cost for this alternative would typically be more expensive than river erosion, but less expensive than mechanical removal. This alternative may be desirable if the reservoir sediments are contaminated. One disadvantage of this alternative is that the reservoir topography would not be restored. If a river channel were constructed through the reservoir sediments (see Figure 8.1), then only some of the sediment would have to be moved and only short distances. Also, there would be a future risk that sediments could erode during floodflows and be transported into the downstream river channel. The challenge is to keep the reservoir sediments stable over the long term. A stable channel design should consider a range of river discharges and upstream sediment loads. The risk of erosion can be reduced if a flood plain is included in the design. If topographic conditions permit, the river channel and flood plains could be constructed around the reservoir sediments. Leaving the sediment in the reservoir may be an attractive alternative if restoring the reservoir topography is not an objective and the risk of erosion during floods is acceptable.

In the case of partial dam removal, the lower portion of the dam could be left in place to hold back the existing reservoir sediment. However, some fine sediment may be eroded downstream during drawdown of the upper reservoir. A portion of the dam could also be breached down to the predam riverbed, but the remaining length of the dam could be used to help retain sediment deposited on along the reservoir margins.

In the case of full dam removal, a stable channel to pass riverflows would have to be designed and constructed (either through or around the reservoir sediments). Mechanical or hydraulic dredging equipment can be used to excavate a new river channel through the reservoir sediments. The excavated sediments could be redeposited along the reservoir margins. The power of the river can also be used to excavate and transport sediment by controlling lake levels (similar to the river erosion alternative).

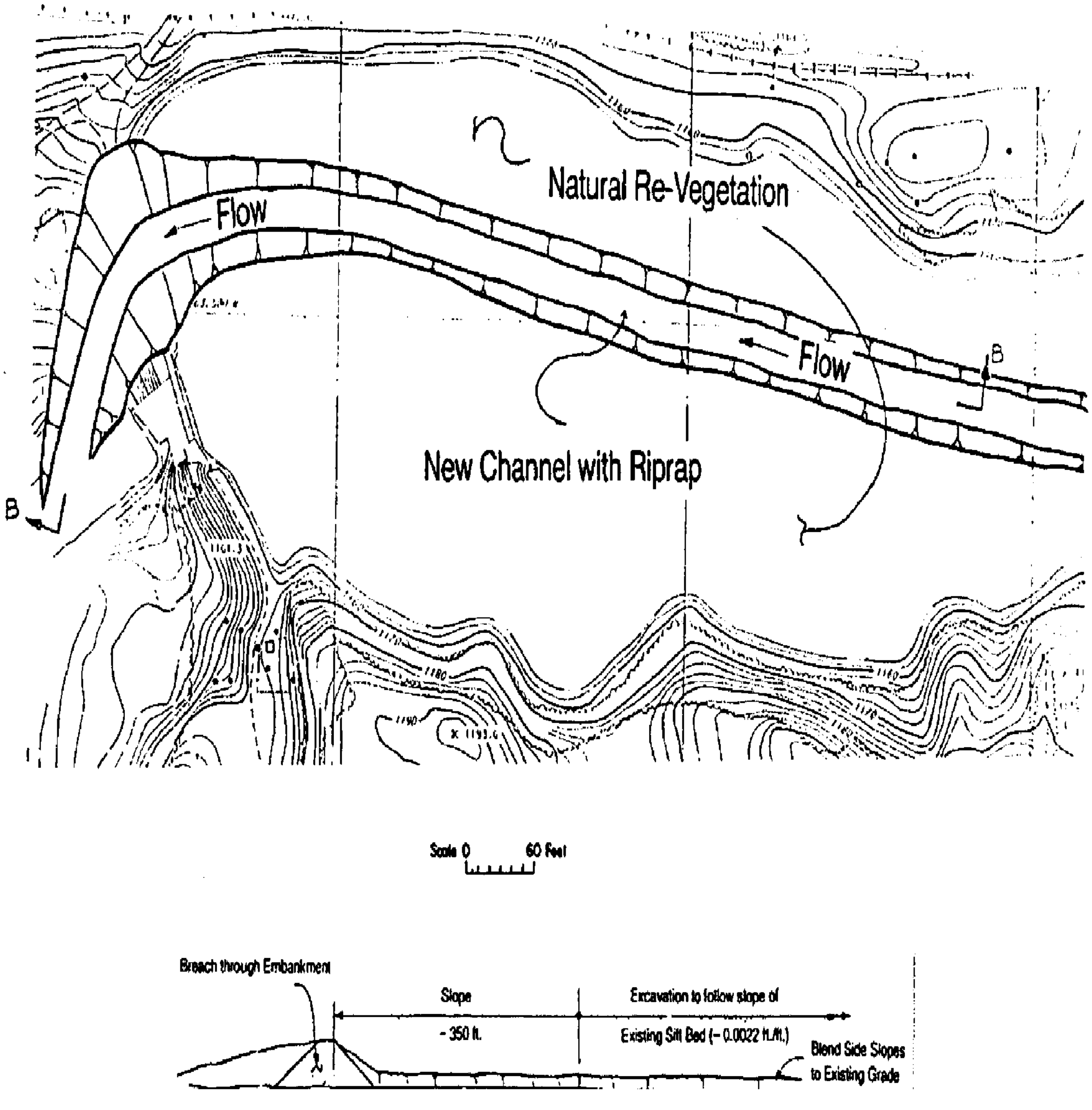

Figure 8.1. Example river channel constructed through the stabilized reservoir sediments (ASCE, 1997).

The size of the channel to be excavated is determined based on hydrologic, hydraulic, and sediment load characteristics of the river basin as well as an acceptable level of risk (e.g., the 100-year flood). Matching the alignment, slope, and cross section of a new river channel (excavated through the reservoir sediments) to that of the old predam river would help ensure a stable channel over the long term. A channel with relatively low velocity and slope would reduce the risk of bank erosion, but it may result in the deposition of the upstream sediment supply. A channel with relatively high velocity and slope would decrease the risk of sediment deposition, but it may result in erosion during floods. The width, depth, and slope for a stable channel can be computed for a given discharge, roughness, and upstream sediment supply. The procedure uses Manning's equation, the water conservation equation ($Q = VA$), a sediment transport equation, and the minimum unit stream power theory (VS = minimum) (see Chapter 7, "River Processes and Restoration").

Vegetation can be planted to help stabilize the remaining sediment from surface erosion. Bank protection structures may be required for the channel and the terrace banks at the edge of the flood plain. However, these bank protection structures would have to be maintained over the long term. If the bank protection failed during a flood, large quantities of sediment could be transported downstream. A diversion channel may be needed to route water around the work area while the channel and bank protection are constructed. This alternative can become quite costly if the channel to be excavated and protected extends a significant distance upstream of the existing dam.

The influences from tributary channels entering the reservoir area need to be considered in the stabilization alternative. Local storms may cause floods in these tributary channels, erode large amounts of the sediment, and damage the main channel protection. Channels may need to be excavated for these tributaries to prevent sediment erosion. To properly convey tributary inflow, the entire reservoir area must be mapped to identify these local inflow drainages, and erosion protection should be provided to contain the sediment on the flood plain.

A network of dikes could be constructed within the reservoir area to contain excavated sediment. A series of dikes could be constructed to contain the sediment so that, if one dike failed, only a portion of the stabilized sediment would be released downstream. If the dikes can be placed above the design flood stage, protection from riverflows would not be necessary. If the dikes are exposed to riverflows, stream bank protection is needed to prevent erosion. Stream bank protection structures could be constructed from natural materials such as rock, vegetation, or woody debris. For large volumes of sediment, the slope of the stabilized sediment or dikes is an important consideration. Although mild slopes are generally more stable than steep slopes, mild slopes would require a larger area of the reservoir to be occupied by the stabilized sediment.

8.4.6 Comparison of Alternatives

The best sediment management alternative will depend on the management objectives and design constraints, which depend on engineering, environmental, social, and economic considerations. Some of the basic advantages and disadvantages of the sediment management alternatives are listed in Table 8.4.

Table 8.4. Summary Comparison of Sediment Management Alternatives (ASCE, 1997)

Sediment management alternative	Advantages	Disadvantages
No action	• Low cost.	• Continued problems for fish and boat passage. • For storage reservoirs, continued reservoir sedimentation, loss of reservoir capacity, and reduced sediment supply to the downstream river channel.
River erosion	• Potentially low cost alternative. • Sediment supply restored to the downstream river channel.	• Generally, largest risk of unanticipated impacts. • Temporary degradation of downstream water quality. • Potential for river channel aggradation downstream from the reservoir.
Mechanical removal	• Generally low risk of reservoir sediment release. • Low impacts to downstream water quality. • Low potential for short-term aggradation of the downstream river channel.	• High cost. • Disposal site may be difficult to locate. • Contaminated sediments, if present, could impact ground water at the disposal site.
Stabilization	• Moderate cost. • Impacts avoided at other disposal sites. • Low to moderate impacts to downstream water quality. • Low potential for short-term aggradation of the downstream river channel.	• Long-term maintenance costs of the river channel through or around reservoir sediments. • Potential for failure of sediment stabilization measures. • Reservoir area not restored to natural conditions.

8.5 Analysis Methods for River Erosion Alternative

The river erosion alternative generally requires the most analysis from a sedimentation perspective. This section first describes methods appropriate to estimate the rate and volume of sediments eroded from the reservoir. It then describes the methods appropriate to estimate the downstream impacts.

In the river erosion alternative, the dam is removed either in several stages or all at once. As the reservoir is drawn down, the previously trapped sediment is now available for erosion. The rate at which the sediments are removed will be governed by the rate of reservoir drawdown, the flows, grain sizes, and the reservoir geometry. These sediments will be transported downstream eventually deposited in a downstream reach, reservoir, estuary, or ocean.

8.5.1 Reservoir Erosion

A general schematic of sediments within a reservoir is shown in Figure 8.2. The coarse sediments deposit in the upper reaches of the reservoir and form the delta, while the fine sediments are carried into the reservoir and deposited nearer the dam. In this figure, the reservoir still has a large portion of its original capacity. If, however, sediments have almost completely filled the reservoir, the delta deposits will have reached the dam and covered finer material below. Upon dam removal, the sediments will be eroded from the reservoir.

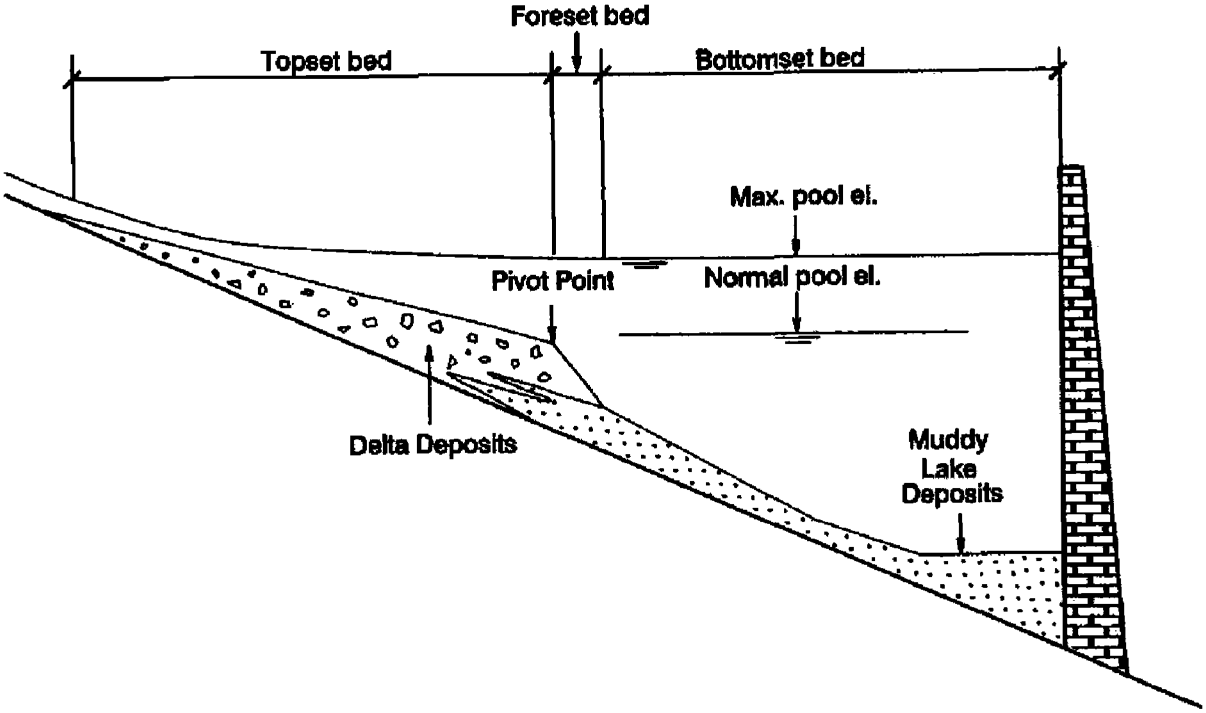

Figure 8.2. Generalized depositional zones in a reservoir (From Morris and Fan, 1998).

Doyle et al. (2003) used Figure 8.3 to describe the erosion of sediment from the reservoir. The geomorphic model was adapted from a headcut migration model of Shumm (1984). A summary of the model of Doyle et al. follows:

Stage A. This stage is the initial conditions before dam removal. Sediment has built up behind the dam.

Stage B. The dam is removed and/or the reservoir is drawn down.

Stage C. This stage is characterized by a rapid, primarily vertical erosion that begins at the downstream end and progresses upstream. Large amounts of sediment are released at this stage, and the downstream concentrations will be the highest of any stage. Depending upon the grain sizes present in the reservoir and the depth of the initial drawdown, this erosion may proceed as a headcut, or be primarily fluvial. The erosion is not expected to cut below the original bed elevation. The initial width of the channel formed by this erosion will be governed by the stability of the material in the reservoir.

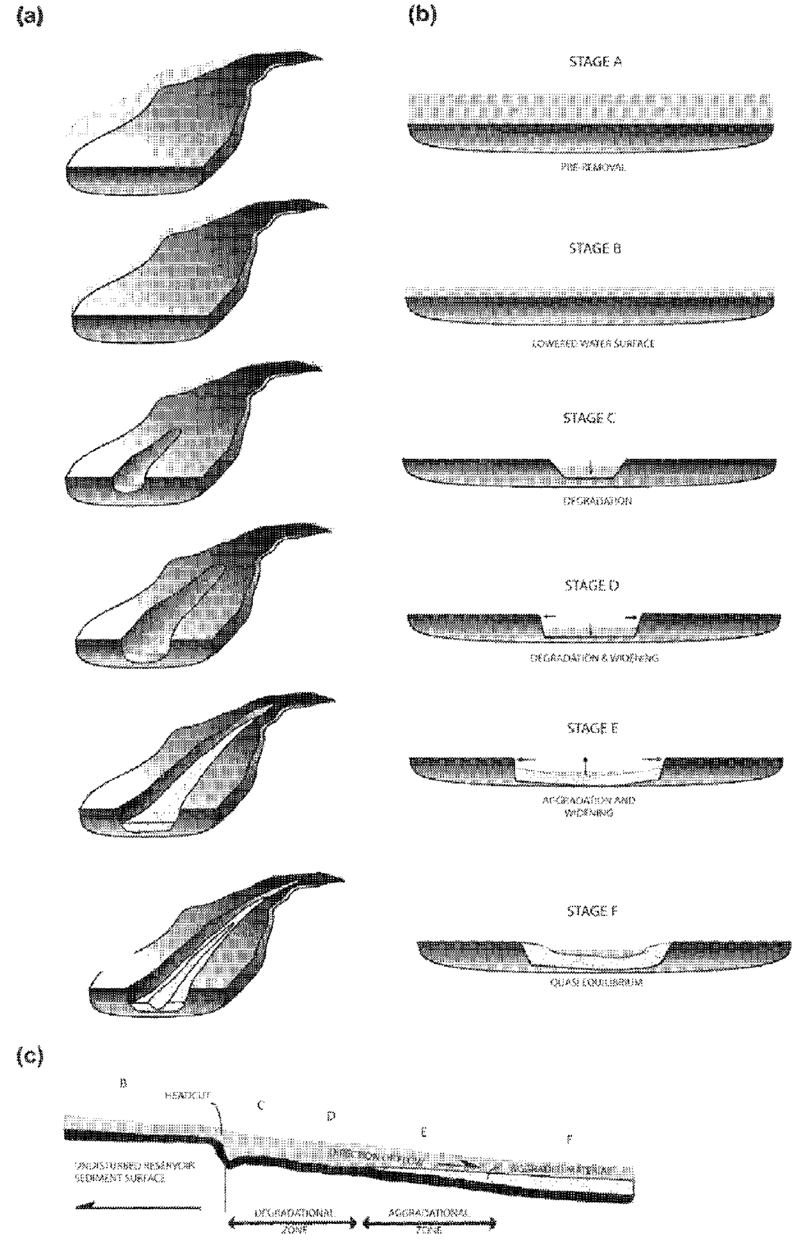

Figure 8.3. Schematic description of reservoir erosion process through delta deposits, from Doyle et al. (2003). (a) oblique view, (b) cross section view, (c) profile view.

Stage D. If the incision of Stage C produces banks that are too high or too steep to be stable, channel widening will occur by means of mass-wasting of banks.

Stage E. Sediment from the upstream reach starts to be supplied to the previously inundated reach. Some of this sediment is deposited in the reach, as the degradation and widening processes have reduced the energy slope within the reach. Some additional widening may occur during this stage, but at a reduced rate as compared to Stage D.

Stage F. This is the final stage and is the stage of dynamic equilibrium in which net sediment deposition and erosion in the reach are near zero.

It should be noted that most observations of dam removal have been for low head dams (i.e. less than 30 feet high) and correspondingly, the geomorphic model described above is most appropriate for smaller dams. The same processes will occur in larger dams, but the significance and magnitude of each stage may be much different. Also, the vertical and horizontal stratification of sediments may become more important. For example, if the dam shown in Figure 8.2 were removed in stages, the delta would progress as the dam is lowered and cover up finer sediments below. The delta would eventually reach the dam face, and sediment would begin to pass over the top of the dam. After the dam crest elevation is sufficiently lowered, the fine sediments would become exposed and quickly erode.

Another factor not considered in Figure 8.2 is the ability of the river to migrate laterally. Some rivers actively migrate laterally during storm events. Therefore, even though the initial channel formed through the reservoir may be small compared to the reservoir width, the river may eventually erode most of the reservoir sediments as it migrates across the valley floor. The lateral erosion process is expected to occur only during the larger storm events. These larger storm events usually carry large amounts of sediment under natural conditions, so the increase in sediment load due to the lateral erosion may not be significant.

8.5.1.1 Analytical Methods for Estimating Reservoir Erosion

Often, the best estimate for the final equilibrium profile of the river through the reservoir area is given by the pre-dam topography. However, predam surveys are not always available. If the necessary resources are available, drilling can identify the predam surface. For small dams, it is possible to estimate the stable bed from matching downstream and upstream slopes. An example of this is shown in Figure 8.4, where the equilibrium profile after dam removal is drawn through the stored reservoir sediments. A similar analysis was performed by Blodgett (1989), in which the downstream slope was projected through the reservoir region to determine the final channel bed thalweg profile after dam removal. For large dams, however, simply projecting the slope may introduce large errors. There may be hidden natural or manmade features that prevent a uniform slope. The resulting analyses and removal plans should take the possible uncertainty in the sediment volume and final profile into account.

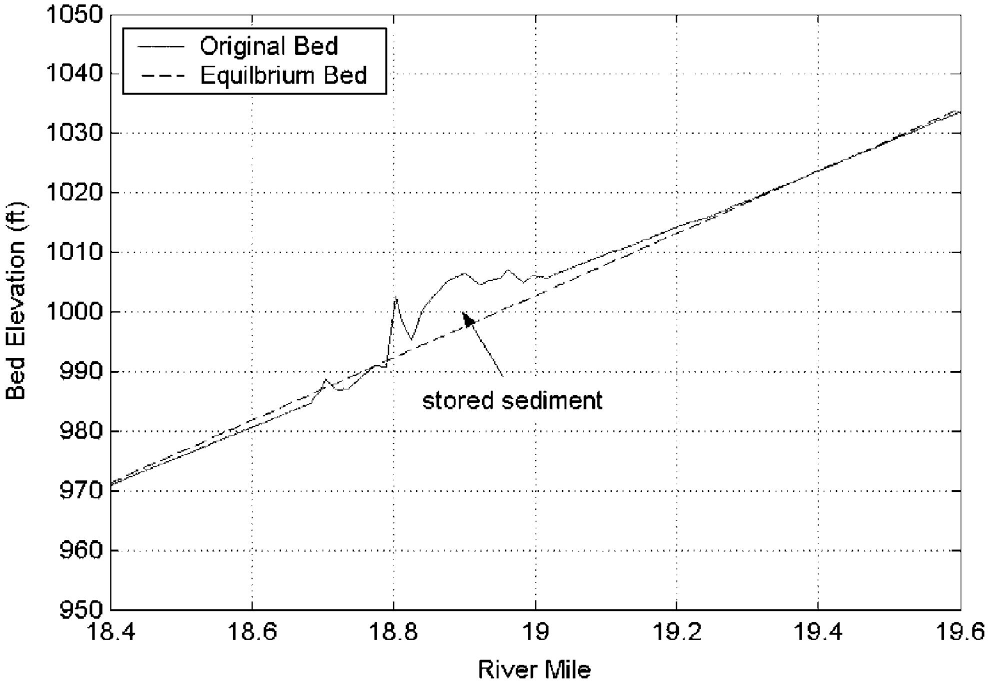

Figure 8.4. Example of estimating equilibrium profile after dam removal.

8.5.1.2 Numerical Models

There have been several applications of numerical models to the prediction of erosion following dam removal. These models can generally be divided into case-specific models and general application models.

Case-specific models are empirical in nature and generally need to be supported by field data. For example, a case-specific model was developed for Glines Canyon Dam. The model was based on physical reasoning and data from a drawdown experiment (Randle et al., 1996). The major components of the model were:

- Dam notching
- Assumption of stable slope, which can be calculated to be equal to the current delta slope
- Calculate new delta shape
- Calculate reservoir trap efficiency

- When delta meets the sill of the dam, start to move sediment out of the dam

- Continue until removal is complete

There are several general application sediment models that are able to simulate the transport of sediment in alluvial channels (see Chapter 5). Two basic categories of sediment models are one-dimensional (1-D) and two-dimensional (2-D) models. One-dimensional models generally solve steady-flow or unsteady equations of 1-D open channel flow. Unsteady flow effects are most likely not important to the erosion of the reservoir sediment and therefore steady flow models should be sufficient. The 1-D solution of the hydraulics is then coupled to tracking of the sediment movement and changes of the bed. One dimensional models have the general weakness that hydraulic properties are averaged over the cross section. In the river channel this is often a good assumption, but it tends to break down in wide reservoirs or meandering streams. The variation in velocity across the reservoir section may be large and cause the 1-D assumptions to not be valid. This can result in under prediction of erosion within the delta.

Two-dimensional hydraulic and sediment transport models have the ability to model the variation of hydraulic and sediment properties across the reservoir cross section. They could also model the failure of banks within the reservoir. At the present time, the author does not have a well-documented case of the application of a two-dimensional model to dam removal processes. Modeling the bank failure process in a two-dimensional model is a non-trivial exercise and would require advances to currently available models.

There are several other unique characteristics of erosion in reservoir deposits that may not be well represented with either one-dimensional or two-dimensional models. Some of the processes or features that are generally not well represented in sediment transport models are listed below:

- Headcut migration through cohesive material
- Bank erosion
- Large width changes
- Stratified bed sediment

Some more recently developed models have some ability to model these situations. Langendoen (2000) developed the CONCEPTS model to consider bank erosion by incorporating the fundamental physical processes responsible for bank retreat: fluvial erosion or entrainment of bank material particles by the flow and mass bank failure (for example, due to channel incision). It has not been applied to the case of dam removal, but has been applied to several rivers (Langendeon and Simon, 2000; Langendoen et al., 2002). The CONCEPTS model also accounts for stratified bed sediment.

MBH Software (2001) has made recent developments to the HEC-6T code to make it applicable to dam removal. In this model, the erosion width is determined by an empirical relationship between flow rate and channel width. Bank stability is modeled using a user input critical bank stability angle. If the bank becomes steeper than the input angle, the bank fails to that angle.

Stillwater Sciences has developed DREAM (Dam Removal Express Assessment Models), a model that is applicable to dam removal (Stillwater Sciences, 2002). The model assumes that the channel through the reservoir sediments has a simplified trapezoid shape. The user inputs the initial width and the model calculates the evolution of this channel based on transport capacity. The model ignores sediment that would travel as wash load (i.e., silts and clays).

The GSTARS-1D model (Yang et al., 2004, 2005) has been used to estimate the erosion of sediment from the reservoir. The channel formation is calculated based on the sediment transport capacity and bank slope stability criteria. In this way, it is similar to the DREAM model in the reservoir region.

More validation of these models with field data is required before their applicability and performance can be assessed.

8.5.2 Downstream Impacts

This section describes two basic methods for analyzing downstream impacts. The first is an analytical method that can be used to estimate deposition impacts of dam removal. The second method involves using more complicated numerical models to analyze a variety of impacts. The impacts include increase in suspended sediment concentrations and changes to the riverbed elevation.

8.5.2.1 Analytical Methods for Predicting Deposition Impacts

To predict the impacts associated with the movement of such accumulations, a model of the system needs to be constructed. The complexity of the model applied to the system should be consistent with the data and resources available. Most often, the prediction of the movement of these accumulations is accomplished by using a one- or two-dimensional hydraulic model coupled with a one- or two-dimensional sediment transport model (MBH Software, 2001; Stillwater Sciences, 2002; Reclamation, 2003). However, such models can be complex and require large amounts of input data. A simple method would be beneficial in providing initial estimates and for cases where complex models are not necessary.

Greimann et al. (2003) extended the analytical description of aggradation of Soni et al. (1980) to describe downstream aggradation following dam removal. A schematic of idealized representation of the movement of a sediment accumulation is shown in Figure 8.5. The sediment accumulation sits on top of the original bed material that is at a stable and uniform slope.

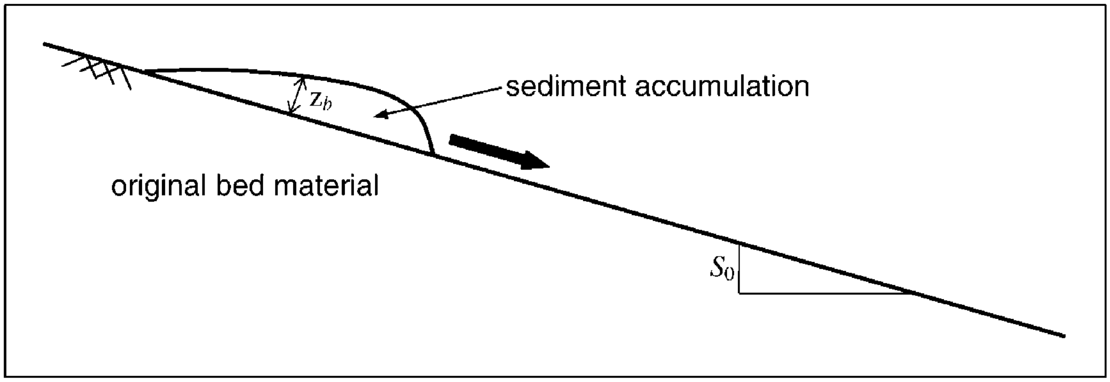

Figure 8.5. Schematic of idealized representation of the movement of a sediment accumulation.

The following equation was derived by Greimann et al. (2003):

$$\frac{\partial z_b}{\partial t} + u_d \frac{\partial z_b}{\partial x} = K_d \frac{\partial^2 z_b}{\partial x^2} \tag{8.1}$$

where

z_b = depth of the sediment originally trapped behind the dam, and
u_d, = velocity of sediment wave translation.

The variable u_d is defined as:

$$u_d = \frac{\left(G_d^* - G_0^*\right)}{h_d(1-\lambda)} \tag{8.2}$$

where

G_d^* = transport capacity in units of volume per unit width of the deposit material,
G_0^* = transport capacity of the original bed material,
h_d = maximum depth of the deposit, and
λ = sediment porosity.

The parameter, K_d, is the aggradation dispersion coefficient:

$$K_d = \frac{\left(b_d G_d^* + b_0 G_0^*\right)}{6S_0(1-\lambda)} \tag{8.3}$$

The transport rate of a particular sediment type is related to the flow velocity:

$$G_d = p_d G_d^* = p_d a_d U^{b_d}, \qquad G_0 = p_0 G_0^* = p_0 a_0 U^{b_0} \tag{8.4}$$

where

U = averaged flow velocity,

a_d , b_d = constants used to calculate the transport capacity of the deposit material, and
a_0, b_0 = constants used to calculate the transport capacity of the original bed material

The parameter b is generally bounded between 4 and 6 (Chien and Wan, 1999). Equation (8.1) can be solved analytically and can be applied to arbitrary initial deposits by dividing the stream into N segments,

$$z(x,t)=\sum_{i=1}^{N-1}\frac{\left(z_{1i}+z_{1i+1}\right)}{4}\left[\begin{array}{l}\operatorname{erf}\left(\dfrac{x-u_d t-x_i}{2\sqrt{K_d t}}\right)-\operatorname{erf}\left(\dfrac{x-u_d t-x_{i+1}}{2\sqrt{K_d t}}\right)- \\ \operatorname{erf}\left(\dfrac{x+u_d t+x_i}{2\sqrt{K_d t}}\right)+\operatorname{erf}\left(\dfrac{x+u_d t+x_{i+1}}{2\sqrt{K_d t}}\right)\end{array}\right] \tag{8.5}$$

where the function "erf" is the error function, and z_1 is the initial bed elevation.. There may have to be some trial and error in determining appropriate distances between stream segments. There should be enough segments so that the initial deposit and resulting bed profiles are adequately defined.

The error of this method is potentially great because of the simplifications made. A partial list follows:

- Assumes a prismatic channel
- Does not account for changes in channel geometry with distance along the channel
- Does not consider longitudinal slope breaks due to channel controls
- Assumes a steady flow rate
- Does not account for changes in roughness
- Is not applicable upstream of the sediment accumulation
- Assumes sediment accumulation is composed of single size fraction
- Assumes accumulation travels as bed load
- Ignores sediment sizes in the sediment accumulation that will travel as pure suspended load

Despite these shortcomings, this method holds promise as a simple assessment tool to determine impacts associated with aggradation. This method requires a minimal number of input parameters and can be completed in a fraction of the time required to complete a more complicated and time-consuming numerical model. The parameters that need to be estimated to use the model are listed in Table 8.5. All the parameters except for b_d are physical quantities that can be measured. The parameter b_d is the exponent in the sediment transport relation and based on results from several researches is generally bounded between 4 and 6 (Chien and Wan, 1999).

Table 8.5. Description of parameters necessary to use proposed model

Parameter	Range of values or method of obtaining value
S_0	Average natural stream slope. Measured from topographic maps.
G_d^* (L^2/T)	Transport capacity of sediment accumulation in units of volume per unit width
G_0^* (L^2/T)	Transport capacity of bed material in units of volume per unit width
λ	Sediment porosity, usually between 0.3 and 0.5
b_d	Exponent in sediment transport relation, usually between 4 and 6
h_d (L)	Maximum depth of sediment accumulation. Estimated from field surveys

A hypothetical case is considered to show how one would apply this methodology to the field. This hypothetical dam (No Name Dam) is approximately 4.5 m high and has approximately 120,000 m^3 of sediment deposited behind it. The average downstream river has an approximate bed slope of 0.005 and an average width of 30 m. The surface bed material downstream of the dam is mostly gravel with less than 20% sand. The trapped sediment in the reservoir consists of approximately 12,000 m^3 of silt, 42,000 m^3 of sand, and 66,000 m^3 ^{of} gravel and cobbles. The transport rates were taken from sediment transport calculations using the bed material. It was determined that the silt, clay, and fine sand would travel as suspended load, and the volume of those size fractions was subtracted from the total volume. After subtracting the fine sediments, the sediment wedge was determined to be approximately 3 m high near the dam and 0 m high approximately 1,200 m upstream of the dam.

Table 8.6 Problem parameters for simulations of hypothetical dam, No Name Dam

Parameter	Value for No Name Dam
S_0	0.005
G_d^* (m^2/s)	0.008
G_0^* (m^2/s)	0.0001
λ	0.4
b_d	5
h_d	3

The deposition along the downstream reach at various times is shown in Figure 8.6. For this problem, we have assumed the dam is suddenly and completely removed. The deposition decreases markedly in the downstream direction, and 2 km downstream deposition is less than 0.5 m.

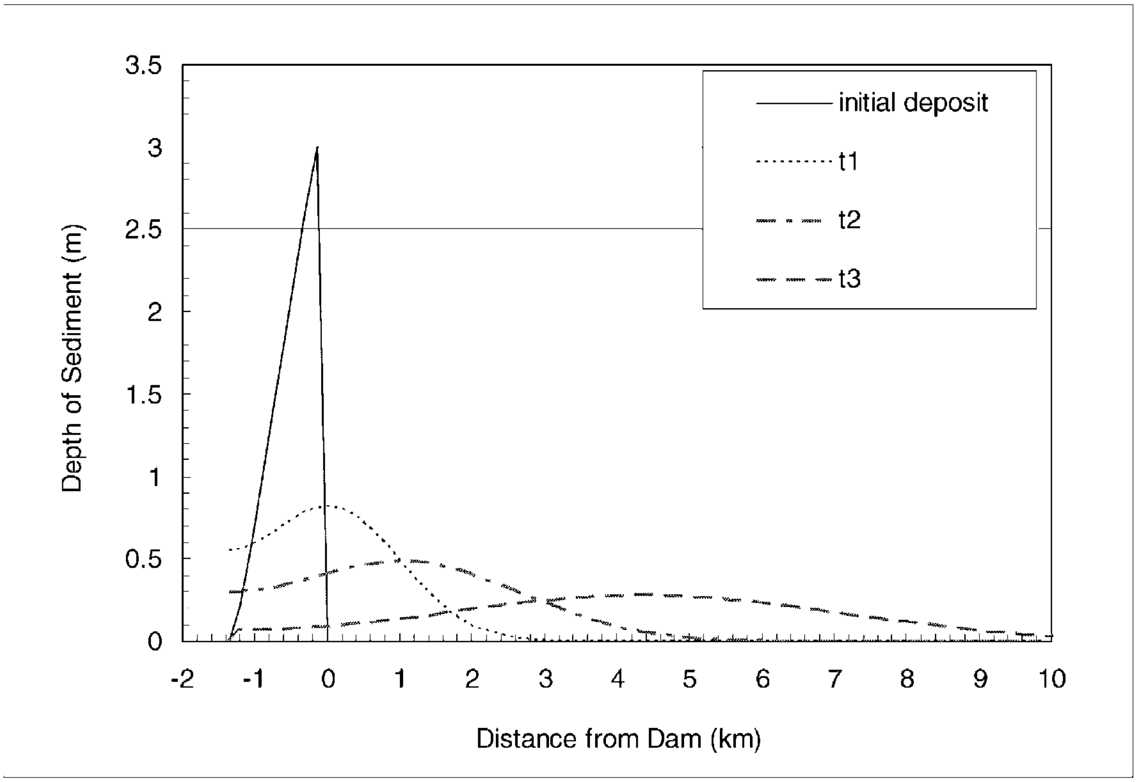

Figure 8.6. Predicted deposition downstream of No Name Dam using Equation (5). The deposition at different times is shown, $0 < t1 < t2 < t3$.

8.5.2.2 Numerical Modeling of Sediment Impacts

Numerical sediment models can be used to provide quantitative estimates of downstream impacts. However, dam decommissioning presents unique problems that some convention sediment transport models may not handle properly. First, the erosion in the reservoir must be estimated correctly. The previous section discusses issues involved in estimating the erosion in the reservoir. Two major considerations in modeling the downstream impacts include estimating the transport of sediment through pool-riffle systems and predicting the transport of fine sediment over a coarse bed.

Predicting the transport of sediment through pool-riffle river geometries is a general weakness of sediment transport models. Because the flow field in pool-riffle geometries has a three-dimensional structure, 2-D and 1-D models do not represent the transport of material well in these geometries. As a result, sediment transport models will generally overpredict the amount of material that is deposited in pool sections. Overprediction of pool filling is a serious problem when a goal of dam removal is to increase the amount of fish habitat in the downstream reaches.

Further work is necessary to develop better modeling techniques to better predict the transport of sediment through pool-riffle river geometries. Currently, the ad-hoc solution to predicting the transport through pool-riffle systems is to run a stabilization period before the dam removal is simulated. For example, the river is simulated with the dam in place until the entire river comes to equilibrium. During this stabilization period, the model would predict that many of the pools would fill with sediment. After the stabilization period, the dam removal is simulated and the additional deposition that occurs is assumed to be that caused by the dam removal. The incremental deposition is then superimposed upon the current bed to determine sediment elevations. Bountry and Randle (2001) used this method to predict downstream deposition. The DREAM model basically performs a similar computation by running what it calls a "zero process" before the dam is removed. This "zero process" will eliminate pool and riffles structures before the dam removal is simulated.

Another potential pitfall in simulating dam removal is predicting the transport of fine material over a coarse bed. Because most numerical sediment transport models are built upon an active layer concept, the transport capacity is proportional to the amount of sediment present in the bed. Therefore, the model will deposit fine sediment into the bed and mix the fine sediment with the coarse sediment. In reality, the fine sediment may just pass over the top of the coarse sediment, and very little may deposit. If the fine sediment does deposit, it may not mix with the coarser sediment of the original riverbed. To prevent this problem from becoming excessive, it may be necessary to have very small active layer thicknesses to limit the amount of mixing of fines with coarser bed sediment. Another option is to define the initial riverbed material as a very thin layer with a size gradation equal to the reservoir sediment gradation. The model is not allowed to erode material below the original bed elevations.

Hydraulic roughness also changes when a large amount of fine sediment is deposited on a coarse bed. When fines fill in the spaces between cobbles, the hydraulic roughness will decrease, and thereby, the transport capacity of the flow will increase. There are some empirical methods to account for this (Brownlie, 1982; Stillwater Sciences, 2002), but there has been little or no field verification of these models for large releases of fine sediment over coarse sediment.

8.6 Summary

While the great majority of dams still provide a vital function to society, some of these dams may need to be removed for various reasons such as economics, dam safety and security, legal and financial liability, ecosystem restoration (including fish passage improvement), site restoration, and recreation use.

The sediment effects related to dam removal may be significant if any of the following conditions apply:

- The reservoir storage, below the normal operating pool, is at least 1 percent of the average annual inflow.

- The reservoir sediment volume is equivalent to a multi-year sediment supply from the upstream river channel, or several years would be required to transport the reservoir sediment volume through the downstream river channel.

- The reservoir sediments are contaminated at concentrations significantly above background levels.

Portions of the dam can be left in place for historic preservation, to reduce dam removal costs, and to help stabilize reservoir sediments. The rate of reservoir sediment erosion and release to the downstream river channel is primarily controlled by the rate of dam removal and reservoir drawdown and by the upstream hydrology. Although headcuts may erode the reservoir sediments during periods of low flow, sufficient flow is necessary to provide transport capacity of reservoir sediments. The rate of reservoir drawdown needs to be slow enough to avoid a flood wave of reservoir water spilling into the downstream river channel. Also, the rate needs to be slow enough to avoid inducing any potential landslides along the reservoir margins or a slide failure of any earthen dams. The ability to draw down the reservoir pool depends on how flows can be released through, over, or around the dam. If the dam has a low-level, high-capacity outlet works or diversion tunnel, then the reservoir could be emptied at a prescribed rate and the dam could be removed under dry conditions. Otherwise, a diversion channel may have to be constructed around the dam or an outlet may have to be constructed through the dam.

The basic types of sediment management alternatives associated with dam removal include no action, river erosion, mechanical removal, and stabilization. River erosion is typically the least expensive and most commonly employed alternative. However, mechanical removal or stabilization may be required if the reservoir sediments are contaminated. If the reservoir is many times wider than the upstream river channel, then a significant portion of the reservoir sediments will remain stable in the reservoir over the long term, even without stabilization techniques.

The rate and extent of reservoir sediment erosion, and the possible redistribution and storage within the reservoir, need to be predicted before sediment transport can be predicted through the downstream river channel. The primary predictive tools include both numerical and physical modes. Physical models can provide accurate predictions if the model scales are properly selected and they can be used to calibrate numerical models. The numerical models tend to be more easily adaptable to simulate multiple management or hydrology scenarios. Most numerical sediment transport models are one dimensional and can simulate river conditions over many miles and over a time period of many decades. Two-dimensional models are also available, but their focus is normally limited to relatively short river lengths over periods of days or maybe weeks. A thorough understanding of the numerical model equations and limitations is necessary for proper application of the model to a dam removal problem. In addition, thorough understanding of the geomorphic, hydraulic, and sediment transport processes of the river is necessary for proper model application and interpretation of the results.

8.7 References

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