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PHYSICAL OUTCOMES OF DAM REMOVAL

UNDISTURBED RIVERS are in a state of partial equilibrium wherein the discharge of water, discharge of sediment, channel geometry, and geomorphic conditions are all in balance. Leopold et al. (1964) referred to this condition as "pseudo equilibrium" because rivers have so many forces acting upon them that perfect equilibrium conditions are rare. The installation of a dam on a stream introduces a new controlling factor, bringing about a new set of equilibrium conditions. In run-of-river dams, the new conditions may be very similar to the original pre-dam arrangements, except in the impounded reach, whereas if there is substantial water and sediment storage behind the dam, the new conditions may be quite different from those existing before the dam. In any case, given enough time, the river and dam establish a new balance of forms and processes.

A dam removal immediately introduces upstream and downstream changes to the river system. These physical, chemical, and biological changes are in part reversals of the outcomes that resulted from the dam's installation, and they represent adjustments of the river as it seeks an equilibrium with the conditions without the dam. This chapter discusses the background concept of physical integrity for rivers and the physical changes that are likely to occur as the result of a dam removal; these changes include reestablishment of fluvial dynamics in the impounded reach across space and time, reconnection of the segmented channel system, changes in hydrology, sediment dynamics, geomorphologic adjustments, and water quality changes. For each of these topics, the chapter reviews the effects of dams, outcomes of dam removal, measurable indicators of change, and sources of information.

PHYSICAL INTEGRITY*

The Clean Water Act (33 U.S.C. §§1251–1387) outlines the general policy for the nation regarding river and water quality. Section 1251(a) of the Act states that "The objective of this chapter [of law] is the restoration and maintenance of chemical, physical, and biological integrity of the Nation's waters." The Act contains specific actions that the federal government and others are to take to achieve this end. Although the Act does not define integrity, subsequent practice in the fields of water chemistry, hydrology, and biology have established some meanings. If a stream lacks chemical integrity, it is clear that its waters and sediments have chemical characteristics that pose health risks to humans and other organisms. In practice, the idea of chemical integrity is expressed in the assessment of chemical pollution and determinations of whether or not the chemical conditions of the stream water attain a defined chemical quality for its designated use, such as swimming, boating, or water supply (Sittig, 1980). Although the state of scientific knowledge is evolving with respect to exposure limits for many chemicals, the monitoring of the chemical characteristics of rivers is a straightforward technical issue.

Hydrologists and geomorphologists have conducted considerable research into the behavior of streams, but their investigations of the response of rivers to human interventions have been a relatively late addition to the mix of science for rivers (Brookes and Shields, 1996). The physical characteristics of the river environment are critical to understanding the chemical and particularly the biological components because the physical system is the stage upon which the chemical and biological systems are played out. The restoration of biodiversity to provide for a wide range of socially desired species, for example, depends first of all on the restoration of geo- and hydrodiversity, and it is precisely these components of the river system that are affected most directly by dams and, presumably, the removal of dams.

Much of what can be said or written about physical integrity rests on the collective experience of hydrologists and geomorphologists, who have spent most of their time investigating issues other than physical integrity. The concept is therefore undergoing change. Some states, including California and Arizona, under the sponsorship of the U.S. Environmental

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* The ideas in this section are derived from research supported by a National Science Foundation grant to W. L. Graf.

Protection Agency, have formal statements regarding physical integrity that guide their river management decisions (e.g., Graf and Randall, 1998), and many state agencies are developing their own perspectives to fit their particular hydrologic, fluvial, and ecological conditions.

A broadly applicable statement defining physical integrity is the following:

> *Physical integrity* for rivers refers to a set of active fluvial processes and landforms wherein the channel, floodplains, sediments, and overall spatial configuration maintain a dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values. Rivers possess physical integrity when their processes and forms maintain active connections with each other in the present hydrologic regime (Graf, 2001b).

In this concept of fluvial integrity, active processes driven by the flows of water and sediment are the keys to change, including the change initiated by the removal of a dam. Changes in flows stimulate changes in the geomorphology of a river, particularly the channels, floodplains, sediments temporarily stored in the system, and geographical or geometric characteristics of the river. Change is a continuing part of a river with physical integrity, but the reality of most American rivers is that change is limited by what society is willing to accept. From an economic standpoint, completely uncontrolled rivers are unlikely because of the need to protect financial investments associated with them. The present regime of a river refers to hydrologic processes that exist now rather than under some conceived set of conditions that once existed before there were any human impacts on the system.

SPATIAL AND TEMPORAL CONTEXTS

Now, the majority of dam removals take place as "targets of opportunity" in the sense that owners of individual dams begin the decision-making process in response to financial or safety issues. In many cases, orphan dams become candidates for removal because of their deteriorating condition, and states or local governments take over their ownership. An assessment of the potential outcomes of these individual structures is best undertaken in a watershed context. In the future, if larger numbers of dams become candidates for removal, or water resource and ecological values drive more decisions, a watershed framework would become essential in prioritizing candidates for removal to maximize restoration benefits.

Rivers are long-lived components of the earth's landscape. Some rivers, like the deceptively named New River of the central Appalachian Mountains, have existed for tens of millions of years. Truly "new" rivers are those that occupy the areas of the world recently abandoned by continental glaciers, such as northern North America and northwest Europe. In these landscapes, the rivers seen today have been active for a few thousand years. Even these relative newcomers, however, have been around longer than the technological effects that humans have imposed on them through dam construction. In the United States, technologically effective dams are mostly the products of the past two centuries. Therefore, a decision to remove a dam needs to take into account two time scales: a short one of a few decades, during which the river might reasonably be expected to change back toward its previous, undammed conditions (within constraints imposed by other controls, particularly land use by humans); and a long time scale, during which the river slowly adjusts to geologic and climatologic controls. These larger-scale forces form the backdrop for more immediate processes initiated by human decisions.

SEGMENTATION

Dams divide rivers into segments. Even without dams, rivers are segmented to some degree by changes in their hydrologic or geologic setting. For example, those places where major tributaries join a main channel, or where the channel crosses geologic faults or other structures, or where surface materials change substantially, all exert enough control to cause changes in river behavior. Dams are similar to these other natural dividers but are much more important because they physically divide the system and prevent the passage of sediment, alter the flow of water, and restrict the movement of organisms through the system.

The natural and human-created dividers along the lengths of rivers create a fluvial system that, although it is connected to a certain degree by the flow of water, is fragmented. The various divisions of rivers span a range of scales (Graf, 2001a):

- A *river* is the entire length of a stream from its formative point to the place where it empties into a body of water or larger trunk stream.

- A *segment* is a length of river that has as its beginning and ending points significant hydrologic or geologic boundaries, such as major tributaries, fault lines, or geologic structural or material changes. Segments are usually several tens of miles in length.
- A *reach* is a length of river with similar hydrologic, geomorphic, and ecological conditions throughout its extent. Reaches are usually one to a few miles long.
- A *site* is a cross section of river channel.

Generally, small dams affect sites and reaches of rivers, whereas medium-sized and large dams may affect segments and entire rivers downstream (Williams and Wolman, 1984). Physical changes resulting from small structures with little storage are likely to be fewer than the more far-reaching changes resulting from larger structures with substantial storage that enables the manipulation of downstream discharge regimes. Fragmentation occurs along main trunk channels, but it is also a feature of streams with many dams on tributaries. In some river basins, changes in the main channel are the cumulative effect of the many smaller tributary streams that are regulated. The Connecticut River in New England is a primary example. The removal of dams reestablishes lost connections among river reaches and segments.

The most extreme form of stress on rivers, especially in the arid western United States, is the complete appropriation of water flowing in a channel, either by direct withdrawal or by pumping from the riparian zone. Only slightly less extreme is the conversion of reaches of free-flowing rivers into a series of lake-like impoundments by dams. The character of rivers also is drastically altered when the connections between the channels and riparian zone of floodplains are severed by channelization, levees, and regulation of the flood regime (see Plate I, on the inside front cover).

At present, there are no nationally available databases that specifically describe the segmented nature of river networks. Such a database might be constructed easily by combining two existing geospatial datasets, the National Stream Reach File and National Inventory of Dams (NID). The U.S. Environmental Protection Agency maintains the National Stream Reach File as a geographical information system product depicting stream courses with convenient dividing lines. The lines are often culturally related, such as roads, or are related to the junctions of tributaries joining the main streams. The purpose of the divisions is largely administrative and for accounting of the water quality in the streams. For the larger purpose of assessing the connectivity of river reaches, the file could be modified to establish divisions imposed by dams. The resulting segments of rivers then could be managed and assessed from an ecosystem perspective as separate geographical units of the stream system, and proposed dam removals could be assessed based on the degree of reconnection they might offer. The locations of existing dams could be added to the stream reach file from data in the NID, which includes the latitude and longitude of existing structures. Problems to be overcome in such an effort would include the large sizes of the files involved, the question of their compatibility, and the dubious reliability of much of the location data in the dam inventory (Graf, 1999).

In the absence of the dataset suggested in the previous paragraph, one measurable indicator of fragmentation is the total length of free-flowing streams without intervening dams in a watershed or river basin. Such measures can be made directly from topographic maps available from the U.S. Geological Survey. Paper maps can be ordered from the survey online (http://www.usgs.gov) and often are available for purchase in sporting goods, map, and outdoor recreation stores. Topographic maps are available in digital form online.* Other maps that are useful for investigating the connectivity of rivers and the distances between obstructing dams include published paper maps from the U.S. Forest Service and Bureau of Land Management. These maps cover portions of the nation where federally administered land is common. At a local scale, useful maps for distance measures along streams are available from almost all state departments of transportation. These transportation-oriented products are usually published at a county scale and show most significant watercourses.

HYDROLOGY

The removal of small, run-of-river dams is unlikely to alter the downstream hydrology of streams because such dams do not impound significant amounts of water. In dry land portions of the nation, however, small dams often serve as diversion works that guide the entire low flow of

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* One source is http://www.terraserver.microsoft.com, a site that also includes aerial photography for most parts of the nation. Another useful source is http://www.topozone.com, which provides digital topographic maps at a variety of scales.

streams into receiving canals. If these diversion works become obsolete or if their removal addresses some other priority social goal, their removal reestablishes a flow of water to downstream areas on a continuous basis. The discharge in such restored streams may be small in magnitude, but its continuous nature has important implications for the hydrologic underpinnings of the aquatic and riparian ecosystems connected with the stream (Malanson, 1993). Recharging of the groundwater supply near the downstream channel is nearly a certainty because of the direct connection between stream flow and groundwater (Dingman, 1994). Flows carry some sediment in many systems, so the restoration of water flow also means increased mobility for sediments.

Dams that have some storage capacity have measurable effects on downstream hydrology. In the most general sense, the extent of their effects is related to their storage capacity relative to the normal flow of the river and the engineering characteristics of their outlet works. The ratio of the total storage of the reservoir behind the dam divided by the average annual yield of the river (the total volume of water that flows past a site in one year) expresses the size of the structure as measured in hydrologic terms (Graf, 1999). This is a dimensionless measure of the size of the dam relative to the stream, a significant issue because a small dam may have far-reaching impacts on a small river, whereas a structure of the same size may have much less significant effects on a large stream (Petts, 1984). The ratio of storage over yield ranges from very small numbers to more than 10 for some very large dams (indicating that the dam can store a volume of water equal to 10 times the amount expected to arrive in a single average year). Dams that have storage capacities that approach one year's water yield of the stream are likely to have large upstream reservoirs and substantial effects on downstream hydrology. The removal of such dams, therefore, also is likely to have far-reaching outcomes.

In addition to the relative size of the storage pool, the engineering characteristics of the outlet works for medium-sized dams also affect the degree of influence the dam exerts on downstream hydrology. If the outlet works for the dam are small relative to the mean annual discharge of the stream, the dam is likely to effect major changes in the behavior of the river downstream. Flood control dams are often of this type, because their major function is to contain large volumes of water and release the water slowly to protect downstream areas. However, many flood control dams have been required to enlarge their emergency spillways to avoid overtopping; during major floods, these spillways will release large amounts of water, causing extensive downstream flooding and property damage. Water supply structures also may have small release systems. Because these dams have very limited capability to release large quantities of water over short periods, they tend to bring about substantial changes in the hydrologic regime of the river they control. Hydroelectric dams, on the other hand, may be equipped with a large outlet capacity so that they can generate large amounts of electricity on demand. Although water flows through the penstocks and turbines of these dams, from a hydrologic perspective they sometimes may operate like run-of-river structures. Glines Canyon and Elwha dams on the Elwha River of Washington State are of this type. Because of their operating rules and large outlets, they do not substantially change downstream flows over the short term (Pohl, 1999).

Dams with significant storage capacity and the capability to control releases have greater effects on downstream hydrology than do run-of-river dams. Some of these downstream effects may be partly reversible if a dam is removed; they also may be reduced by altered operating rules. The most common downstream hydrologic effects are reduced peak flows, altered low flows, reduced range of discharges, altered timing of flows, and changes in ramping rates.*

Dams reduce peak flows as a flood control measure by storing the high volumes of inflow to their reservoirs and then releasing the flow gradually. This arrangement is a significant change from natural conditions, because most river channels in dry land areas are adjusted to their flood discharges, and most floodplains in humid regions are defined by the periodic high flows of the nearby channels. When dams lower the peak flows, they decrease the physical integrity of the downstream river because the channel-forming discharge is reduced, and floodplains are not as extensively connected to the river. The dynamic connections among the various parts of the cross-sectional landscape of the river—its channel, islands, bars, beaches, and floodplains—no longer operate as an integrated system. The removal of the dam restores the peak flows (an objective achieved in some cases by changing the operating rules of the dam), and thus returns dynamic connections among the various parts of the river landscape downstream.

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* General information on the effects of dams on downstream hydrology, as well as references to detailed case studies, can be found in Collier et al. (1996), Dynesius and Nilsson (1994), Graf (1988, Chapter 7), Petts (1984, Chapter 2), and Williams and Wolman (1984).

Dams alter low flows, sometimes increasing them and in other cases decreasing them. Dams constructed primarily to store and supply water for irrigation purposes increase low flow, especially in the summer growing season, because the whole point is to deliver water during dry periods. Similar situations often develop for urban or industrial water supply structures. In these cases, a fairly uniform moderate discharge replaces highly variable and generally lower discharges that occurred under pre-dam conditions. These elevated flows form different channels and different aquatic habitats than existed before the dam, but the conditions are reversed if the dam is removed.

Dams also can reduce low flows, particularly during exceptional dry periods that do not coincide with downstream delivery contracts. In these cases, dam operators may close the outlet works temporarily to save water, resulting in the desiccation of downstream reaches and segments. As a result, physical integrity is compromised completely, and the river ceases almost all physical processes. As a physical basis for the ecosystem, it ceases to function as a river, but this condition may be completely reversible with the removal of the diversion dam.

Because dams alter both high and low flows, they alter the range of flows experienced in the river over the course of a typical year. The difference between the highest and lowest flow in a single year is important because it controls the extent of the active channel and floodplain system on the landscape. If the range between the highest and lowest flows is large, as is the case for many natural systems, a substantial width of the riverine landscape is activated each year. If the range is reduced by the placement of a dam, then the width of the active portion of the landscape is reduced, the channel shrinks, and the amount of active floodplain shrinks as well. The result is a fluvial system that is much smaller than the pre-dam system. Such shrinkage is especially common in systems west of the Appalachian Mountains. The Platte River of the middle Great Plains, for example, was miles wide before the construction of upstream dams, but its present channel and floodplain widths are so narrow that fish habitats and riparian forest areas have been damaged severely (Williams, 1978b).

The annual timing of peak and low flows is a characteristic of the operation of the physical system that has important consequences for reproduction in the biological components of the ecosystem. Fish in the channel and plants on the floodplain have evolved with internal annual clocks that maximize their reproductive success by timing certain activities to coincide with the annual flood, which usually occurs in spring.

Seed production among native tree species, for example, is usually at a maximum during the period when the annual peak flow occurs (Stromberg et al., 1991). When dams are installed, the schedule for the annual peak flow often changes, and, as a result, the production of new seedlings for native vegetation is reduced. Exotic vegetation with different reproductive mechanisms sometimes gains a competitive advantage as a result. The removal of the dam restores the natural timing of peak flows and is likely to favor native vegetation and native fishes.

Ramping rates are the rates of change from low to high flows and back to low flows again. In most river systems these changes are gradual, requiring a period of several days or weeks to go from low flow conditions to peak flows (Figures 4.1 and 4.2).* An exception to this generality is the small- to medium-scale, arid-region stream subject to flash flooding with a change from no flow to high flow in a period of an hour or so. The installation of dams with sufficient storage and outlet works can enable operators to alter the discharge quickly, with dramatic changes occurring within a short period, measured in minutes. These rapid ramping rates cause significant physical and ecological problems through accelerated erosion of banks, especially if the change is a rapid decrease in discharge. However, these rapid ramping rates are being increasingly moderated during relicensing to a closer approximation of natural ramping, thereby reducing fish stranding and erosion. Pore-water pressure in bank materials equalized at high flows suddenly is not supported by water in the channel, and bank collapse becomes common. Accelerated erosion of channel fringes from this process destroys islands, beaches, and floodplain edges with associated sediment loading in the channel. The removal of dams returns the system to a more natural arrangement with slow ramping rates and gradual change.

The most important data available for monitoring changes in stream flow are gaging records of daily discharge ("gaging" is the technical spelling of gauging, and installations that gauge stream flow are called stream gages). The U.S. Geological Survey (USGS) is the nation's custodian for water data based on the 6,600 stream gages that it operates. Since the first continuous gage was installed in 1885, more than 18,000 sites have been gaged for varying periods of time (Wahl et al., 1995). At

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* These two figures show the same trends, but the first uses discharge data whereas the second uses water depth. Both are provided here because planners and analysts prefer discharge data and the general public may want depth information.

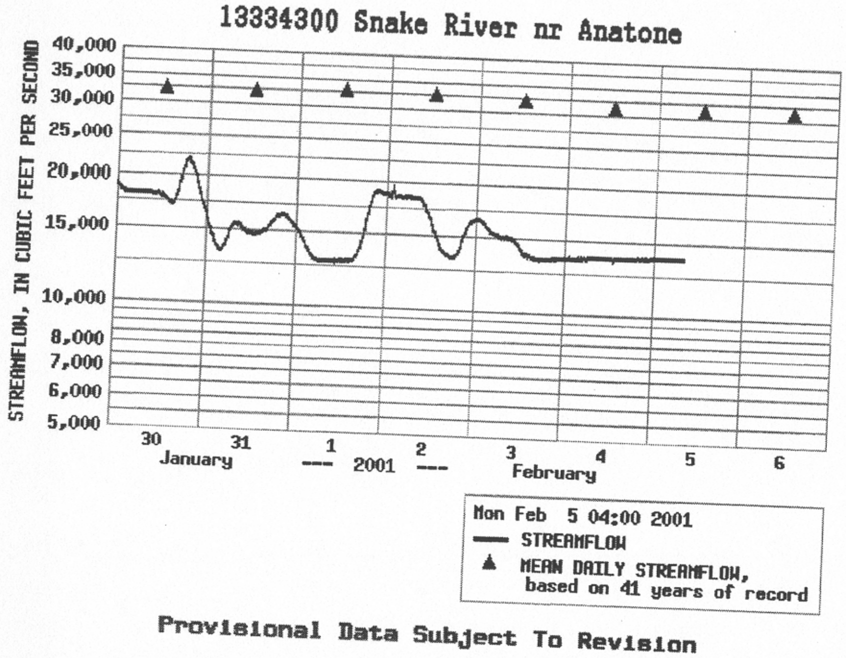

Figure 4.1 The operation of upstream hydroelectric dams creates steep ramping rates, as shown by this continuous stream flow record from the Snake River near Anatone, Idaho. See Figure 4.2 for a similar graph showing the changes in depth of flow that accompanied these discharge changes. *Source*: U.S. Geological Survey (http://www.usgs.gov/water).

present, about 7,000 sites are active. All of the data collected by the agency are available free of charge in digital form online (http://water.usgs.gov). The data are available for each day of record, as well as in an abbreviated form showing only annual peak flows. Information on each gaging station includes its dates of operation and a map showing its precise location. Users can retrieve the data either in tabular form for numerical analysis, or in easily read graphs (Figure 4.3). The data are the highest-quality information available about stream flow and often are used in engineering, scientific, planning, and legal studies.

The indicator measures of greatest importance for monitoring river hydrology to evaluate a possible dam removal include annual peak flow, annual low flow, annual mean flow, and real-time flow data. Annual peak flow is the highest discharge recorded in each year of record, and it provides a quantitative assessment of floods. The annual low flow is the lowest discharge recorded in each year of record. The annual mean flow is the average of all the daily flows for each year; it provides a measure of water yield. An examination of the tabular data for peak flows provides the date on which the highest flow occurred in each year and addresses the timing issue. Many gage sites produce real-time information transmitted to the main USGS facilities in Reston, Virginia, and these data can be examined to determine short-term ramping rates (Figures 4.1 and 4.2).

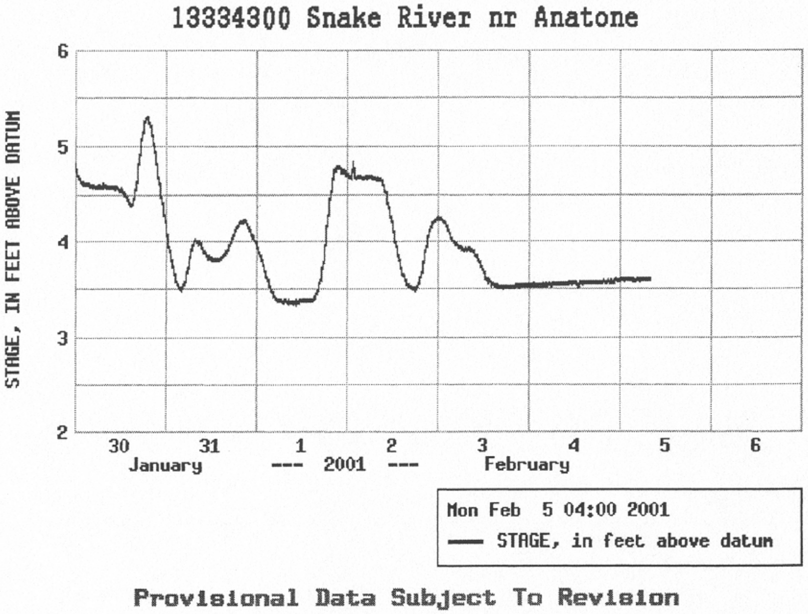

Figure 4.2 This graph shows an example of the changes in depth of flow that accompany rapid changes in discharge on the Snake River near Anatone, Idaho. See Figure 4.1 for a similar graph showing the changes in discharge. *Source*: U.S. Geological Survey (http://www.usgs.gov/water).

SEDIMENT

SEDIMENT QUANTITY

Rivers transport more than just water. Sediment transport and deposition occurs under entirely natural conditions. The construction and operation

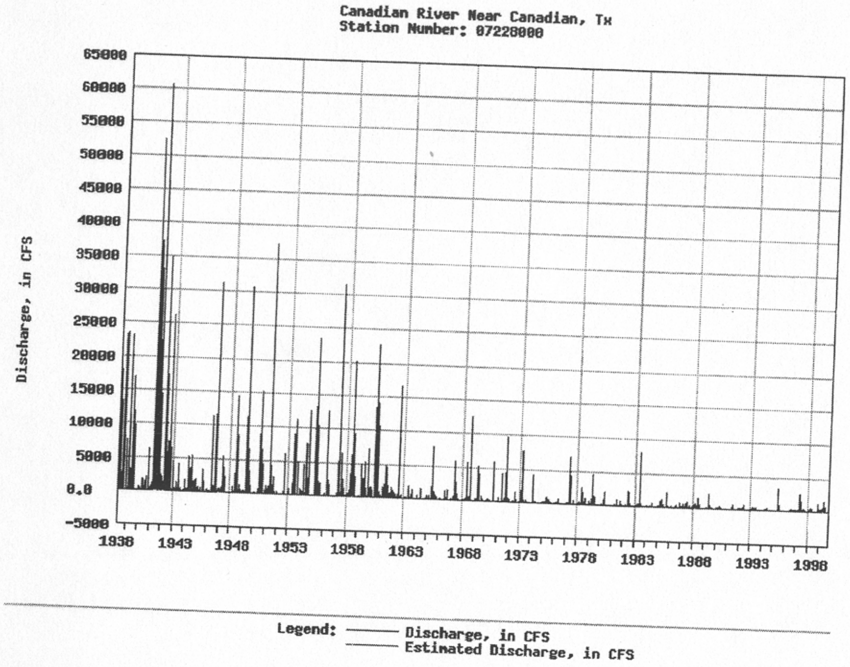

Figure 4.3 This graph is an example of historical (1938–1999) daily discharge data for the Canadian River near Canadian, Texas. Upstream storage reservoirs and diversions contribute to the decline in flows after the early 1960s. *Source*: U.S. Geological Survey (http://www.usgs.gov/water).

of dams affect the dynamics of sediments in rivers to a substantial degree, and dam removal is highly likely to involve issues related to sediment. Of the many physical outcomes related to dam removal, sediment erosion, transport, and deposition are likely to be among the most important. Dams trap sediment that enters their reservoirs because the turbulent downstream flow of water is halted temporarily. Sediments that are relatively large, such as gravel and cobbles, are deposited in deltas at the upstream ends of reservoirs, whereas smaller sediment particles, such as silt and clay, are carried farther into the pool area before they drop out. Most dams and reservoirs (excluding run-of-river dams) trap 95 percent or more of the sediment that enters them from upstream. Water released from dams is therefore relatively free of sediment, and downstream reaches do not receive the input of material that occurred before dam installation. As a result, the clear water erodes available sediment from the channel below the dam, winnowing away the finer material and leaving behind an "armor" of coarse particles too large to be entrained. Bank erosion in such cases is also common. The removal of dams restores the throughput of sediment and reconnects the various river reaches together in a continuous sediment transport system.

Sedimentation is considered by dam operators to be a problem in 25 percent of all reservoirs associated with hydroelectric projects, according to the results of a 1996 survey (Dixon, 2000). Sediment problems occur across the complete range of dam sizes and reservoir capacities when sediments occupy reservoir volume intended for water supply. As sediment fills reservoirs, it reduces storage capacity and the useful life of dams for hydropower generation. Sediment adversely affects dam operations by clogging power intakes, outlet works, and spillways, while also limiting recreational use of the reservoir by filling in surface areas. Because many dams create habitat for fish and wildlife, sedimentation also adversely affects these features. Sedimentation in the reservoir, initiated by the maintenance of a pool that triggers deposition, extends the adverse effects. Finally, the sediments themselves may accentuate chemical pollution, as outlined below. Matilija Dam in California is an example of a case in which history and the dam removal decision are closely connected with sediment (Box 4.1).

Sedimentation in a reservoir follows a general pattern.* Coarse sediments drop from the stream flow that enters the reservoir headwaters or backwaters area, creating a delta accumulation. If the reservoir contains water that is layered according to temperature, sediment-rich water containing relatively fine material (silt) may create turbidity currents issuing from the entry point of the stream into deeper reservoir waters. The resulting deposits consist of silt layers on the floor of the middle portion of the reservoir. The finest sediment (clay) is in suspension in the water and slowly settles out throughout the reservoir, including areas at the upstream face of the dam.

Rivers transport sediment from eroding landscapes to ocean and lake basins, temporarily storing significant quantities of sediment in floodplains, alluvial fans, and deltas along the way. Rivers that are in slowly changing, nearly equilibrium conditions exhibit a delicate balance among

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* For more information, including researched examples, see Hakanson and Jansson (1983) and McManus and Duck (1993).

Box 4.1 Sediment Problems Associated with Matilija Dam in California

Matilija Dam exemplifies dams that are candidates for removal because of sediment problems. Since the dam was constructed in 1947 on Matilija Creek, a tributary of the Ventura River in Southern California, its reservoir has been filling slowly with sediment. Today, 6 to 7 million cubic yards of sediment lies trapped behind the structure, reducing the original storage capacity by over 90 percent. The reservoir is expected to be filled completely with sediment by 2010 (U.S. Bureau of Reclamation, 2000).

Because Matilija Dam traps the majority of coarse sediment normally transported during large floods, erosion problems have been severe16 miles downstream, along the famous surfing beaches of Ventura County. To preserve the beaches, protect coastal property, and maintain a coastal tourism industry that brought in an estimated $45 million to Ventura County in 1992 (State of California, 1997), costly measures such as beach nourishment, groins, revetments, and a seawall have been used. However, the beach structures are falling into disrepair, and multimillion-dollar projects are necessary to maintain them. Estimates show that up to 70 percent of the 50 years of sediment trapped behind Matilija Dam is suitable for placement on beaches, an amount sufficient to widen all south Ventura County beaches by 30 feet (Marx, 1996–97). Several studies examining the possible removal of Matilija Dam have been completed recently or are continuing.

Photo courtesy of Sarah Baish

To combat erosion, hard structures such as groins and seawalls have been constructed on Ventura County beaches, shown here in 2001.

discharge of water, discharge of sediment, and channel geometry (Leopold, 1994). Important human-induced changes to that balance include accelerated erosion in upland watersheds caused by agricultural practices, logging, recreational activities, and urban development; as well as changes to the river channel system, such as channelization and dam building. Dam removal is also likely to induce changes in the sediment transport and storage system.

Sediment is a pollutant because unwanted deposition fouls engineering works, and because artificially high turbidity (sediment suspended in flowing water) clouds otherwise clear water, degrading the quality of aquatic habitats for plants and aquatic animals, including fish. In 1998, sediment was the pollutant most often identified by states in their reporting of problems associated with the Clean Water Act (Federal Energy Regulatory Commission and Electric Power Research Institute, 1996). Sometimes, however, exceptionally clear water is also a problem, because native fishes in regions such as the interior Southwest have evolved in sediment-rich environments. Their populations decline in rivers dominated by the clear water released by dams (Minckley, 1991).

Dam removal involves potentially significant changes in the river's sediment system because the reservoir basin behind the dam is likely to contain quantities of sediments that would not be there if the dam had not been built. Dams form efficient sediment traps until their pool areas are completely filled with sediment. The amount of stored material depends on the size of the reservoir, rate of sediment supply from the upstream watershed, and length of time the structure has been in place. Many small, run-of-river dams and low diversion works have pool areas completely filled with sediment within a few years of their construction, whereas medium-sized and large dams typically have reservoirs only partly filled with sediments. In some cases, filling of the reservoir is so great that the water storage capacity is eliminated, as is the case for some dams slated for removal such as Rindge Dam (Box 3.1, p. 85) and Matilija Dam in Southern California (Box 4.1).

An important management question in decisions related to dam removal is the fate and quality of the sediments stored behind the dam. If the dam is removed, how much of the stored sediment will remain in place, and how much will be eroded by the flowthrough of water and be passed downstream? Are there any contaminants in the sediment that will pollute the river downstream if they are released? For most small, run-of-river dams, the majority of stored sediments are likely to be washed away by the river after the dam is removed, but for structures with large reservoirs designed for water storage, a problematical amount of sediment is likely to remain in place. Tim Randle and Gordon Grant, investigators attempting to predict the amount of sediment that will remain after the impending removal of dams on the Elwha River in Washington State, estimate that about half of the stored sediment is likely to remain in place. Mathematical models of the Snake River indicate that, if four major dams were removed there, 65 to 85 percent of the coarse sediment and about half of the fine sediment stored behind the dams would remain. In a potentially instructive case on the Gila River in Arizona, a breach of Gillespie Dam by a 1993 flood so far has resulted in the movement of large amounts of sediment stored behind the structure, but at least half the material remains in place. Although there is likely to be great variability from case to case, these and other instances show that much sediment is likely to remain in the old reservoir area after a dam is removed, and those sediments, whether contaminated or not, need to be taken into account in any successful management plan. They might be removed from the site or stabilized in place, but they cannot be ignored.

The existing sediment models were developed to predict the transport of extensive sediment deposits located in reservoir basins behind dams. Most sediment transport models are rather primitive from the standpoint of predicting downstream effects of reservoir evacuation; they do not handle the mixed grain sizes and staged export of materials very well. Models for sediment transport would need to be reviewed and modified to be useful in predicting potential sediment redistribution following a dam removal.

The sediments that are released by dam removal are carried downstream by the river flow, triggering a range of outcomes that may require management decisions. Fine sediments are likely to cause increased turbidity in waters downstream from the structure, and they eventually may be deposited as island, bar, or beach material along the stream below the dam site. If the river drains to coastal areas, these materials may be deposited in coastal wetland zones or transported by longshore currents to beach locations. Coarse sediments also may be eroded from the reservoir deposit, but they are likely to travel shorter distances in average flow conditions. They may be mobilized only during flood events, and when they are deposited, they may form bars of coarse material along the length of the channel or rapids across it. Deposits of fine and coarse materials downstream from sites of dam removals may create new ecological niches, which may be desirable from a river management standpoint or may supplant other, more desirable niches such as backwater areas and pools. The effective prediction of outcomes depends on reasonable estimations of the amount of material likely to be removed, understanding of the geomorphic and hydrologic behavior of the channel, and accurate hydraulic assessment of the post-removal river flows.

Because sediments released from the reservoir area of a dam that is removed migrate downstream, river managers may need to consider the consequences of these sediments eventually being stored behind the next dam downstream, if one exists. Most rivers have a series of dams on their channels, so the release of sediments in one part of the multi-dam system is likely to result in partial redistribution to other downstream dam sites. Assessments of likely outcomes of dam removal need to adopt a river-basin scale of analysis in estimating the potential issues associated with remobilized sediments.

In addition to the issue of sediment quantity, a further consideration in remobilized sediments is the effect on downstream particle sizes in the channel bed. Many salmonid fishes, for example, require a particular grain size for bed particles in their spawning areas, and if an upstream dam is removed, changes may occur in bed particle sizes. The covering of coarse bed particles by newly released fine material, for example, may decrease the usefulness of spawning areas. More research is needed on the effects of sediment releases of different volumes, grain sizes, and rates on downstream channels. This is the fundamental physical problem associated with dam removal and is linked to the biological response. On the other hand, the draining of reservoirs and evacuation of fine material may uncover previously drowned spawning beds by stripping away the fine sediment, with additional useful areas made accessible upstream by the elimination of the barrier to fish passage. Although it seems likely that fine materials will be flushed through the channel system downstream from most dam removal sites, the issue needs to be explored thoroughly during the decision-making process.

The quantity of sediment discharged past some gaging stations is available from the USGS as part of its stream gaging efforts, but the number of sites producing sediment data, about 1,600, is only a portion of the total gage system (Figure 4.4). The data, in a form similar to the water data, are available online (http://water.usgs.gov/owq.html).

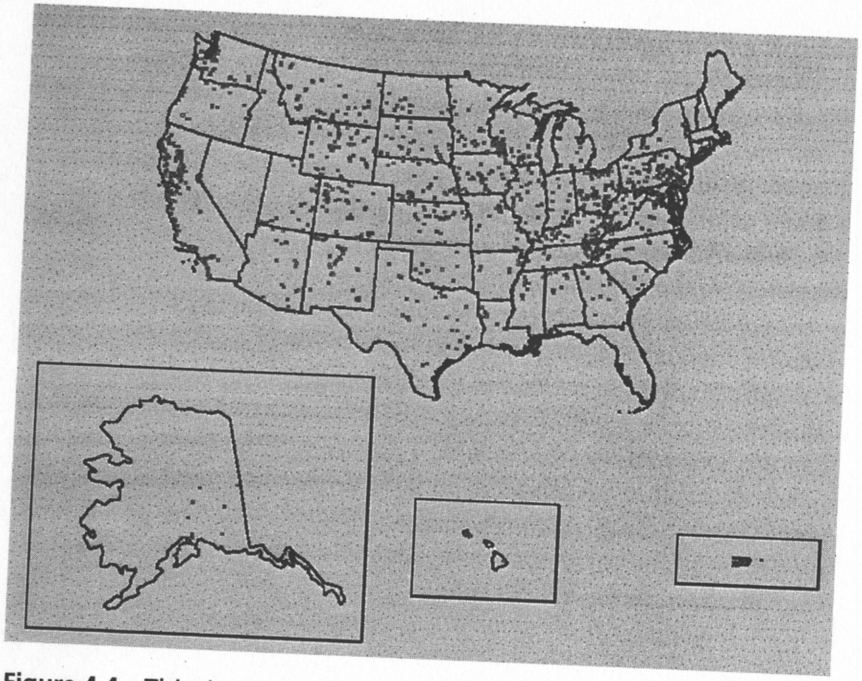

Figure 4.4 **This dot map shows the distribution of sites for which sediment discharge data are collected for rivers.** *Source*: U.S. Geological Survey (http://www.usgs.gov/water).

SEDIMENT QUALITY

The chemical quality of the stored sediment is an important issue. Contaminants such as heavy metals, radionuclides, herbicides, and pesticides often are dissolved in river water, but they precipitate out of solution and are adsorbed onto the outer surfaces of sedimentary materials. The concentrations of contaminants in sediment are, therefore, often many times higher than they are in the water. These precipitation and adsorption processes are common in reservoirs, such that the remobilization of the sediments during dam removal presents downstream environmental risks. A proposal to remove low dams along the Blackstone River of Massachusetts was abandoned in the early 1990s because the sediments behind the dams were contaminated with heavy metals derived from manufacturing. The release of these sediments might have polluted downstream river and coastal habitats (Graf, 1996).

Concentrations of individual contaminants are useful indicators of sediment quality, and standards are available for assessing risk (Solomons and Förstner, 1984). A chemical assessment of sediments before removing a dam can define potential pollution problems, but a measurement of concentrations of individual pollutants requires laboratory analysis. Existing data on sediment chemical quality are available but scarce, and many river reaches and reservoirs have not been assessed on this basis. Sources of sediment quality data include state game and fish departments, along with state environmental quality departments that monitor particular locations either as short-term projects or part of general environmental protection programs.

Specific sediment quality standards are not commonly applied in the United States, and there are no general policies regarding acceptable limits for the concentrations of many pollutants in sediments. Some general guidelines for allowable limits are available for many chemical compounds, including herbicides and pesticides (Sittig, 1980), and these limits can be used in the assessment of sediments in reservoirs behind dams that might be candidates for removal. Heavy metals are common in sediments behind small, run-of-river structures because these dams tend to be placed in areas that were once manufacturing centers. Metals are also of concern behind tailings dams in mining areas. For these reasons, proposed classifications for concentrations of metals may be useful to decision makers in dam removal cases (Table 4.1). These classifications have not been adopted as formal policy but are supported by scientific investigations focusing on the biotoxicity of metals. The USGS is conducting a major sediment evaluation at Engelbright Dam, with full recovery, datable sediment cores.

GEOMORPHOLOGY

The hydrology and sediment systems of rivers build and shape the landforms that make up the river landscape. The geomorphology of rivers refers to these physical forms and processes that underlie the biological system. In some areas, vegetation plays a major, interactive role in landform development in and along rivers. Vegetation adds adhesive properties to riverine soils and enables them to resist erosion, and stems and leaf structures add hydraulic roughness to channel margins and floodplains. The installation of dams alters hydrology and sediment processes so that

Table 4.1 Proposed Classification of Sediment Pollution[a]

Element	Unpolluted (ppm)	Moderately Polluted (ppm)	Heavily Polluted (ppm)
Mercury	<1	Not defined	>1
Lead	<90	90–200	>200
Zinc	<90	90–200	>200
Iron	<17,000	17,000–25,000	>25,000
Chromium	<25	25–75	>75
Copper	<25	25–50	>50
Arsenic	<3	38	>8
Cadmium	Not defined	Not defined	>6
Nickel	<20	20–50	>50
Manganese	<300	300–500	>500
Barium	<20	20–60	>60

Source: Adapted from Baudo et al. (1990) based on research by Gambrell et al. (1983).

[a] This classification has not been adopted in formal policy, but is supported by scientific investigations focused on biotoxicity of the metals.

the downstream system responds with associated adjustments. Generally, the greater the storage capacity of a dam, the more extensive are its downstream geomorphic impacts. The most important of these impacts include channel shrinkage, deactivation of floodplains, changes in channel pattern, and loss of complexity.

Channel shrinkage is common downstream from dams because the structures often reduce annual peak flows. These peak flows are the "channel forming discharge" in many systems. Channel forming discharges are those flood flows that are efficient at moving sediment and shaping the channel, occurring about once per year or every two years. If the channel forming discharge is made smaller by flood control measures in dam design, the channel responds by also becoming smaller. Sediment accumulates on the bed of the channel or is deposited laterally along the channel side, resulting in reduced overall channel size. The ecological implications of these changes include the loss of aquatic habitat for fishes. In many cases, the total amount of available space in a channel is greater before the installation of a dam than afterwards, as exemplified by the Green River in Utah (Grams and Schmidt, in press).

In humid regions, a more appropriate measure is "bank-full discharge." Bank-full discharge is the level of discharge that is just sufficient

to fill the channel to the tops of its banks, where additional water would spill out of the channel and onto the floodplains. This bank-full level is the most efficient transporter of sediment, occurs about once every year or two (at a time often referred to as the annual flood), and is a direct connection between the hydrology and geomorphology of rivers (Leopold, 1964). Williams (1978a) found that the bank-full measure was less reliable as an interpretive tool in dry land streams than in humid areas. Nonetheless, bank-full is a measure often used to describe rivers (Rosgen, 1994). The strength of the connections among annual flood, bank-full discharge, and channel size is variable from place to place (Miller and Ritter, 1996), but it is a useful guideline for explaining the effects of dams and anticipating the likely outcome of dam removals. The shrinkage of channels that occurs with the installation of dams is likely to be reversed if dams are removed, all other factors being equal.

The most useful indicator of the size of the river geomorphic system is channel width. Channel width, along with depth, gradient, hydraulic roughness, flow velocity, water discharge, sediment discharge, and sediment size, is a primary determinant of channel processes (Leopold, 1964; Leopold et al., 1994). Of all these variables, width is the most responsive to changes in the hydrologic behavior of rivers, as indicated by its relationship to discharge as defined by hydraulic geometry, a set of equations that relate physical and hydrologic properties of the river to each other (Leopold et al., 1964). Width has the additional advantage of being relatively easily measured in the field. For small streams, direct tape measurement is possible, and for larger streams, infrared ranging devices enable one person to make accurate bank-to-bank measurements with little technical support. All streams except the smallest ones have widths easily measured from aerial photographs.

Aerial photography, which is useful for assessing all the geomorphologic indicators described here, is widely available. If purchased from the federal government, the cost is often $10 or less for a single image that shows an area of several square miles, including up to 5 miles of river length. The most extensive source of aerial photography is the USGS EROS Data Center in Sioux Falls, South Dakota, which is accessible online (http://edcwww.cr.usgs.gov) (Figure 4.5 provides an example). The data center houses a vast array of federally obtained aerial photography, including historical images from the military, Coast and Geodetic Survey, and all the mapping photography made as the Geological Survey carries out its major mission of creating topographic maps for the nation. The

Figure 4.5 This example of aerial photography available from the U.S. Geological Survey's EROS Data Center is the type of image that provides geomorphologic information, including channel width, sinuosity, and pattern, as well as floodplain dimensions. The image is of terrain in southern Minnesota. *Source:* EROS Data Center (http://edcwww.cr.usgs.gov).

center contains at least one image for every area of the United States and has numerous dates of coverage for most areas. Table 4.2 reviews additional typical sources of aerial photography. Channel width measurements taken from photographs, although not as accurate as ground-based sur-

Table 4.2 Typical Sources of Aerial Photography for River Analysis and Monitoring

Type of Source	Institution
Federal Agencies	Geological Survey, EROS Data Center: small-scale aerial National Aeronautics and Space Administration satellite imagery from a variety of sources of the entire United States
	National Park Service: areas that include national park lands
	Forest Service: areas that include national forest land and nearby areas
	Bureau of Land Management: areas that include BLM land and nearby areas
	Fish and Wildlife Service: areas in and near wildlife refuges
	Natural Resource Conservation Service, formerly the Soil Conservation Service: repetitive coverage of agriculture, usually once every few years
	Bureau of Reclamation: larger streams and rivers in the western United States
	Army Corps of Engineers: local coverage of flood control project areas
	Department of Energy: areas on and near DOE facilities
	National Archives: historical images, including Soil Conservation Service photography dating to the 1930s
	Department of Defense: areas on and near military bases
Tribal Governments	Native American tribal governments for areas on and near Indian reservations
State Agencies	Land Department
	Environmental Quality Department or Department of Natural Resources
	Department of Transportation, especially highway divisions
	Game and Fish Department
	Water Resource Department
	Parks Department
	State Lands Department
	Industrial Development Commissions

(continued)

Table 4.2 *(Continued)*

Type of Source	Institution
County Agencies	Planning Department
	Highway Department
	Parks Department
	County Tax Assessor's Office
Town and City Agencies	Planning Department
	Water and Sewer Department
	Engineering Department
	Streets Department
Other Public Entities	University and college libraries
	University departments of engineering, geography, geology, life sciences, ecology
	State, county, city, or local historical libraries
Private Businesses	Electrical power companies
	Television cable companies
	Water companies
	Telephone companies
	Aerial photography companies

veys, are nonetheless precise enough to monitor changes resulting from dam installation and removal.

Channel width also is easily determined from engineering or scientific cross sections surveyed for planning, construction, or research purposes. These cross-sectional surveys are sometimes difficult to find, but they exist in surprising abundance. Government agencies involved with bridge construction, for example, almost always survey cross sections of the streams spanned by the bridges, and resource management agencies often survey stream cross sections taken for water, species, or land management purposes. Federal, state, and local highway departments are often useful sources for survey data. The Federal Emergency Management Agency (FEMA) contracts with civil engineering firms to conduct detailed surveys of many streams and rivers to determine the extent of the active channels and 100-year floodplains. The resulting cross sections and highly detailed topographic maps are available from FEMA online (http://www. fema.gov/maps).

The area of active floodplain in a given reach of channel is

affected directly by the installation of dams, because most dams reduce the magnitude of flood discharges. As a result, the occasional floods are smaller than in pre-dam periods, and the area outside the channel that receives water, sediment, and nutrients in such events is less extensive. Thus, dams not only induce channel shrinkage, but also induce the shrinkage of active floodplains. Social and economic activities then encroach on the deactivated floodplain because people get the impression that they are safe from flooding. When rare, very large floods occur, they exceed the control capacity of some dams, resulting in the inundation of floodplain areas occupied by agriculture, industries, and residences. Additional protection for such properties in the form of levees further disrupts the once-active floodplain surface. The removal of dams is likely to result in higher occasional flood events and reactivation of floodplain surfaces (i.e., through periodic flood events large enough to flow over the floodplain, adding sediments and nutrients or eroding them away). Levees may restrict the out-of-channel flow of water temporarily, but sedimentation in the channel or breaches in the levees eventually result in inundation of the floodplain. For this reason, the reactivation of floodplains is incomplete, and additional measures dealing with the levees are sometimes required. For an example of the complex interactions among channels, floodplains, dams, and levees at a variety of scales, see Scientific Assessment and Strategy Team (1994). This assessment covered the midwestern United States, but the conclusions are broadly applicable.

In addition to changing feature sizes, the installation of dams simplifies rivers by reducing their geomorphic complexity. Although these effects are not yet well studied, the hydrologic and sediment adjustments caused by dams produces channels that have fewer complicated patchworks of different landforms than did the pre-dam arrangements. The loss of high ranges of flows and peak flows produces fewer islands, bars, beaches, and temporarily abandoned channels, so that there are fewer ecological niches. The removal of dams may reverse these changes, but there is no scientific research available to inform decisionmakers about this issue.

The frequency of islands, bars, beaches, and abandoned channels along a given length of channel provides a rough indicator of the complexity of the geomorphic system. If the numbers of such features are counted over time, the adjustments of the river can be traced to either installation or removal of control structures. The easiest way to determine the frequency of features along a channel is to assess aerial photographs, although for many systems, ground inspection or ground-based photography is also useful.

The installation of dams also affects downstream channels by changing their sinuosity and pattern. Sinuosity, in this case, refers to the degree of meandering of the low-flow channel. Because dams often reduce peak flows, and because the sinuosity of channels is controlled by peak discharges, channels respond to this hydrologic effect of dams. Generally, when flows are reduced and sediment loads decline, the channel becomes more sinuous, and the stream increases its winding characteristics. An additional adjustment observed in rivers in the Plains and western United States is a change in pattern from braided to single-thread geometry. A braided channel has many islands and bars with numerous sub-channels intertwined with each other (Figure 4.6). This geometry was common under unregulated conditions, with great ranges of discharge occurring over brief periods. In north Texas, for example, stream gage data show that unregulated rivers there have annual peak discharges that are 40 times the magnitude of the mean annual flow. Braided channels represent an accommodation to such radical variation. The imposition of dams, however, with the capability to smooth variations in discharge and eliminate very high flows, produces an entirely different hydrologic regime that often is conducive to maintenance of a single-thread channel. The removal of dams is likely to result in more braided conditions, especially if the bank materials have a low degree of cohesion (Schumm, 1977). A lack of woody debris and actively growing vegetation often causes braided conditions.

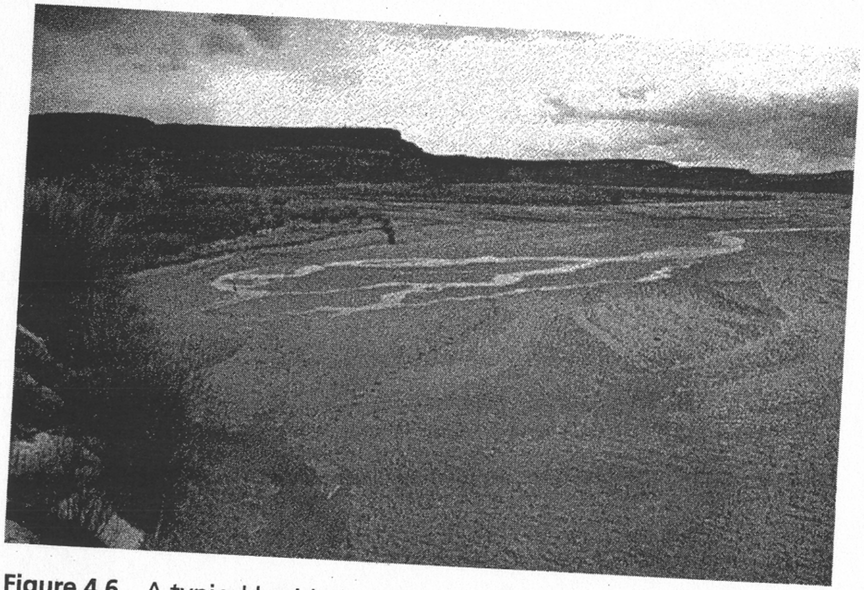

Figure 4.6 A typical braided stream channel, Canyon Largo in the San Juan River Basin of northwestern New Mexico. *Source*: U.S. Geological Survey, http://water.usgs.gov, Aug.14, 2001.

Sinuosity and braiding can be measured. The most common measure of the sinuosity of the low-flow channel is the ratio of the straight-line distance along the valley length between two points on the channel, to the along-channel distance between the two points (Leopold et al., 1964). A sinuosity ratio of 1.0 indicates a perfectly straight channel, whereas a ratio of 2.0 indicates a channel that is so sinuous that its length is twice as long as the straight-line distance between two reference points. Most river channels, including those in an unregulated condition as well as those subject to the influence of dams, have sinuosity ratios ranging between 1.1 and about 2.0. A useful measure of channel pattern is a braiding index proposed by Brice (1960). The braiding index is equal to the value of twice the total length of bars in a channel reach divided by the length of the reach itself. Investigators attempting to assess present conditions or historical changes in channels need to measure the landforms and calculate the sinuosity ratio and braiding index from aerial photography or maps, using the sources outlined above for the other geomorphic and hydrologic measures.

In summary, some of the most common, interrelated adjustments of the geomorphology of stream channels are controlled strongly by discharges of water, woody debris, and sediment. Knighton (1998) provides general descriptions of these associations, and Wohl (2000) offers insights into the processes and forms for mountain and canyon streams. Any changes to the discharges of water and sediment, such as those that occur with the installation or removal of dams, are likely to result in consequent adjustments in channel slope, particle size on the bed, channel depth, and channel width. The most likely general changes resulting from dam removal are increased water and sediment discharges resulting in decreased channel gradients, increased depths, and increased widths downstream. Initially, particle size may increase through the erosion of bed materials, but eventually bed materials may become finer as fine materials are released from behind the dam. These likely directions of change depend on a sequence of events that may be related to how a dam is removed, whether all at once, in stages, by progressive notching, or with staged drawdowns. The predications may vary from one case to another.

The state of geomorphic and sediment transport science for use by decision makers in dam removal cases, especially those involving small and medium-sized structures, is problematic. Extensive theory and model-based approaches are available for estimating the expected outcomes of dam removal. Hydraulic models and sediment transport models, for example, are widely available in the form of computer programs used by agencies and consulting firms (e.g., Simons and Sentürk 1992; Yalin 1992). Their application to situations involving dam removal has been limited, however, so this experience base needs to be weighed carefully. On the other hand, empirical research on the actual effects observed in dam removal cases is quite rare. Guidance on what to expect in terms of river channel change downstream from removed structures is, therefore, often lacking, and the decision maker is forced to rely on the judgment of a geomorphologist or hydrologist rather than on the more traditional scientific literature.

In 1997, as part of its efforts to improve the utility of federal environmental monitoring efforts, the White House Office of Science and Technology Policy asked The Heinz Center to identify a set of indicators for use in characterizing the state of the nation's ecosystems, using a nonpartisan, scientifically grounded process. The resulting report, to be issued in 2002, recommends improved collection of data on the extent of upstream effects of dams (i.e., inundation) and recognizes the need to quantify downstream effects as well. To help meet this need, the report recommends the development of quantitative tools and programs to monitor stream habitat quality. Such indicators and programs would measure changes in critical stream attributes resulting from a variety of causes, including the downstream effects of dams (The Heinz Center, in press).

WATER QUALITY

Dams have substantial effects on water quality because they alter the normal hydrologic behavior of rivers, which in turn changes the physical and hemical dynamics of the water. Among the most important potential hanges resulting from the imposition of dams are oxygen depletion, tem- erature modification, changes in acidity, supersaturation of gases, ele- ated nutrient loading, increased salinity, and changes in contaminant oncentrations in water and sediment. When nutrient-laden water enters

a reservoir, some of the nutrients precipitate out of solution and become part of the sediment on the floor of the reservoir. This also happens with herbicides, pesticides, and heavy metals. Thus, the reservoir is a cleanser for water users, because the water released from the reservoir is lower in contaminants than the water entering it from above. However, these contaminants wind up in reservoir sediment. If a dam is removed, the sediments are remobilized and can carry their contaminant load downstream, causing a general decline in water and sediment quality (Petts, 1984).

Oxygen depletion occurs in reservoir waters because vegetation is inundated and decomposes in newly formed lakes, processes that use large amounts of dissolved oxygen from the water (McCully, 1996). Eventually, a new equilibrium is achieved, but usually the amount of dissolved oxygen in water released from reservoirs is less than that found in free-flowing rivers, which continually inject oxygen through turbulence. In reservoirs with substantial depth, stratification can create oxygen-poor conditions that may produce anaerobic water in the deeper areas, and if these waters are released to downstream areas, the water flowing below the dams is severely lacking in oxygen.

Dam installation may lead to decreases or increases in the water temperature of rivers downstream. The significance of this observation is that these changes may be reversed if dams are removed, with the expected changes resulting from either installation or removal depending on the characteristics of the reservoir and the withdrawal structures that take water from the lake. Reductions in release water temperature are common if the intake of the water is from lower levels of the reservoir, because cold water sinks to the bottom of lakes and is not circulated to warmer areas high in the water column. Strongly developed stratification preserves this cold water, and if it is released to downstream areas through bypass tubes, penstocks, and turbines, it substantially affects the downstream temperature regime (Petts, 1984). The effects depend on residence time of water in a reservoir. Because of their relatively small volume at any one time, unregulated rivers have large temperature ranges that respond to seasonal, synoptic weather, and diurnal changes (Walling and Webb, 1996). In warm climates, the river water is also warm most of the year. Releases from dams replace these changeable conditions with cold water characterized by only minor fluctuations in temperature, conditions very unlike the original pre-dam conditions. Some dams release warm water in winter. Rivers with dams impounding reservoirs experience fish habitat changes connected with temperature adjustments that are often unfavorable to native fishes accustomed to warmer waters (Stanford and Ward, 1991), but favorable to non-native or introduced gamefish (e.g., trout).

Temperatures increase in release water either when the reservoir is shallow or when the withdrawal structure is close to the surface of the lake. In shallow reservoirs, seasonal warming heats the slow-moving waters to temperatures that are higher than those experienced in free-flowing streams, a situation very different from the stratification and isolation of cold, deep water in deep reservoirs. Withdrawal structures that are situated near the surface of a reservoir behind a dam also may supply warm water to downstream areas, because the warmest water is usually found near the lake surface. In any event, these temperature changes represent adjustments from previously unregulated flows, and the removal of a dam is likely to bring about readjustments in temperature for downstream reaches.

Changes in acidity occur in reservoir waters because of evaporation from the surfaces of artificial lakes. The waters entering reservoirs contain a certain amount of dissolved solids, but evaporation removes some of the water, leaving behind increased concentrations of dissolved solids, which in turn increase the alkalinity, or pH, of the remaining water. The most common dissolved solid in these cases is salt. The reservoir waters released through dams to downstream areas bring the increased salinity to aquatic plants and animals as well as riparian vegetation tuned to pre-dam low salinity conditions. The maintenance of native species is, therefore, more difficult with dams and storage reservoirs in place. River flow characteristics have a strong influence on dissolved solid concentrations in any case (Webb and Walling, 1996), and the alterations of river hydrology brought about by dams causes downstream changes in pH even if there are no increases in salinity in their reservoirs.

The supersaturation of reservoir waters with atmospheric gases such as nitrogen occurs because water is "buried" in reservoirs, where the increased hydrostatic pressures at the bottom of the reservoir force these gases into solution. If dam operations draw water from these lower levels for release, the supersaturated waters enter downstream reaches and strongly affect fish (Baumann et al., 1986). The release of water through turbines and penstocks contributes to this supersaturation (Petts, 1984), a circumstance that is hazardous for fish because they absorb the gases into their blood during respiration. As the gases come out of solution in a fish's bloodstream, the fish experiences a condition similar to the "bends" experienced by divers who surface too rapidly. The supersaturated gases cause

the blood to bubble, a debilitating and sometimes deadly condition (National Research Council, 1996).

Dam installation may improve water quality downstream from a dam site, and removal of the structure may reduce water and sediment quality downstream. This process is the result of a complicated series of physical and chemical processes that affect nutrients, herbicides, pesticides, and heavy metals. When these contaminants enter a reservoir area dissolved in water, they often precipitate out and become associated with the sediment on the floor of the reservoir. As a result, water released from the reservoir may be of higher quality than that entering from above. However, if the dam is removed, the contaminant-enriched sediments are released and remobilized, potentially creating pollution problems downstream.

A reservoir is a sink for nutrients when a dam is in place and a source for nutrients when the dam is removed. Nutrient loading occurs in reservoirs in agricultural and urban areas because of runoff contributions. The application of fertilizers to agricultural lands at a large scale and to suburban lawns at smaller scales produces an abundance of nutrients in many watersheds that does not occur under natural conditions (Baumann et al., 1986). Runoff from these fertilized areas contributes large amounts of nitrogen, phosphorus, potassium, and other chemicals to the water flowing into reservoirs. The evaporation of reservoir water in dry land settings concentrates contaminants, especially metals and salts, in the remaining waters (Salomons and Forstner, 1984). These elevated concentrations of metals enhance the transfer of contaminants to sediments in the reservoir, so that water released from the dam has reduced concentrations of these materials. Salt, on the other hand, may remain in solution, and the increased salinity is passed through the dam to downstream areas.

Contaminant concentration in sediments increases in reservoirs because of the exchanges between water and sediment (Baudo et al., 1990; Horowitz, 1991). The concentrations of contaminants, especially heavy metals, are often two or three orders of magnitude greater in sediment than in the overlying water (Glover, 1964; Salomons and Forstner, 1984). Herbicides, pesticides, heavy metals, and radionuclides are transported into the reservoir system by flowing water, but once in the lake they begin to be adsorbed onto the surfaces of sediments suspended in the water and resting on the bottom. Thus, as stated earlier, the presence of a dam and its reservoir may serve to protect downstream areas from contaminated sediments, but the removal of the dam may serve to remobilize stored contaminated material. Such material needs to be removed and disposed of before dam removal if contaminants are at issue.

The effects of dams and reservoirs on dissolved oxygen, temperature, pH, supersaturation of gases, and nutrient loading are all reversed with the removal of the dams. However, in the case of nutrient loading, dam removal does not return river reaches to entirely natural conditions. An important outcome of dam removal is the release of sediments that contain contaminants in exceptional concentrations because of adsorption onto sedimentary particles. Even the sediments stored behind small, run-of-river structures need to be examined to determine their quality. For example, the removal of Waterworks Dam on the Baraboo River in Wisconsin entailed the physical removal and disposal of its stored sediments to avoid downstream dispersion of contaminants.

The indicators for water quality are direct measurements of temperature and pH, along with laboratory analysis of water samples to assess concentrations of chemicals such as organic chlorines (indicators of herbicides and pesticides), heavy metals, and radionuclides. Laboratories using chemical methods stipulated by the U.S. Environmental Protection Agency and Environment Canada best conduct these analyses. The use of approved methods ensures compatibility with previously collected and published measurements. A readily accessible database for water quality in rivers of the United States is the National Water Quality Assessment Program (U.S. Geological Survey, 2000). Near real-time and historical data for many of the nation's rivers are available online (http://water.usgs.gov/owq/data.html). The data can be downloaded in the form of tables for much, but not all, of the country (Figure 4.7).

CONCLUSIONS AND RECOMMENDATIONS

Removing dams can restore some of the most important aspects of physical integrity to rivers downstream. In addition to the effects of their reservoirs, which inundate terrain and ecosystems, dams affect physical integrity by fragmenting the lengths of downstream rivers, changing their hydrologic characteristics (particularly peak flows), and altering their sediment regimes by trapping most of the sediment entering their reservoirs. These effects translate into major changes in the downstream geomorphology of the river landscape, most critically through channel shrinkage and deactivation of floodplains. Water quality changes also alter the ecosystem downstream. The removal of dams has the effect of reversing most of the undesirable changes, but it is unlikely to restore completely natural conditions because of other dams on the river and the multitude of other human-induced effects on streams, such as channel control and land use in watersheds upstream. The most important positive outcome of dam removal is the reconnection of river reaches so that they can operate as an integrated system, which is the basis of a river with physical integrity. Productive, useful ecosystems can result from dam removal, but outcomes may include many interrelated changes in the physical and biological

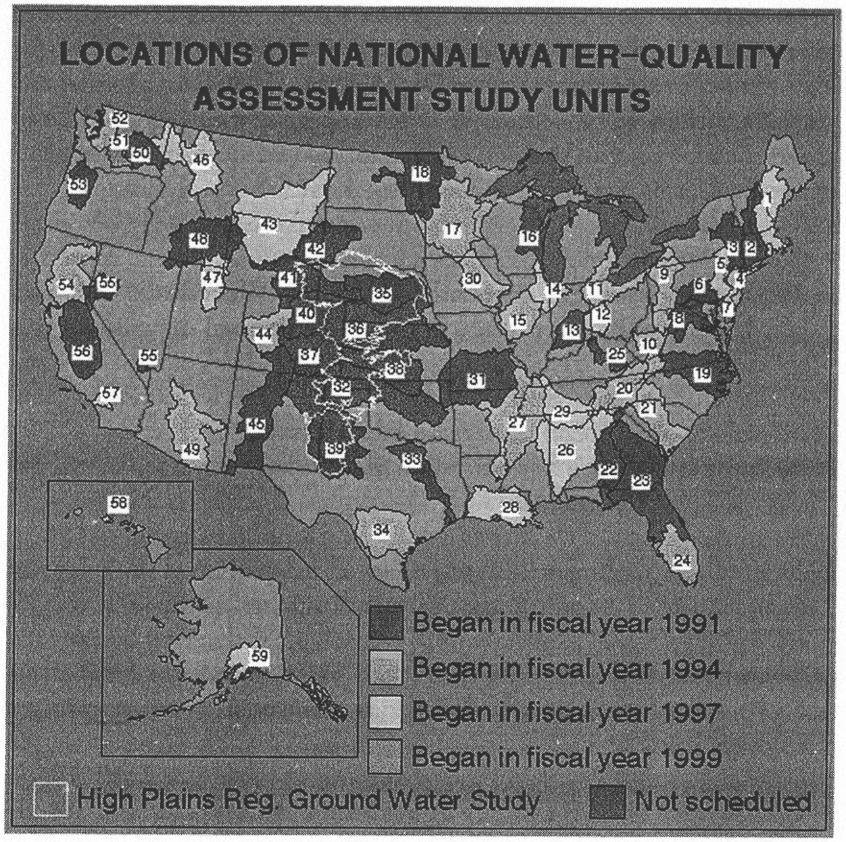

Figure 4.7 This map shows the distribution of basins for which highly detailed water quality information is available through the National Water Quality Assessment Program. *Source*: U.S. Geological Survey (http://www.usgs.gov/water).