CHAPTER 5

CHANNEL EVOLUTION UPSTREAM OF DAM REMOVAL SITES

James G. MacBroom

5.1 INTRODUCTION

The removal of obsolete, unsafe, and environmentally harmful dams has become increasingly frequent in the past decade due to their increasing age and deterioration, favorable economics for removal, and environmental impact. Among the key technical issues are the fate of impounded sediments, aquatic habitat, water quality, risk of downstream channel aggradation, and uncertainty about the formation of a channel upstream of the dam through the impoundment area.

It is important to establish specific goals for channels and sediments upstream of dam removal sites so there is a clear understanding of and consensus on the river management approach. The goals vary from site to site and could include providing fish passage, minimizing sediment erosion, achieving channel alignment stability, grade control, and improving recreation, water quality, and safety. Post-dam fish passage and habitat restoration requires that the channel through the breach and across the impounded area has flow depths, velocities, substrate, and features appropriate for the targeted fish species. Coordination with regulatory agencies and aquatic biologists is essential to identify the desired aquatic species and their habitat characteristics. Sediment management may include stabilization-in-place, allowing its natural erosion, on-site relocation, or off-site relocation via partial or full dredging. There is a popular but erroneous perception that dam removal will always release impounded sediments and create problems. While this has occurred at some sites, most notably the Hudson River's Fort Edwards Dam, sediment release is not a universal problem. A typical evaluation of upstream conditions includes the following procedural steps:

1. Assess pre-dam channel conditions, hydrology, and morphology.
2. Evaluate impounded sediment formations, gradation, cohesion, and density.
3. Sample and test sediments for contamination.
4. Study sediment stability and channel evolution.
5. Determine whether uncontrolled channel evolution is acceptable.
6. Develop a channel and sediment management strategy.

The ability to anticipate future channel response is summarized by Pizzuto (2002), who states "[G]eomorphologists remain unable to forecast stream channel changes caused by the removal of specific dams." The review of dam removal analogies, however, along with channel evolution models and increasing observations of dam removals helps to identify channel evolution trends.

The purpose of this chapter is to assess the wide variety of channel types that evolve after dam removal and to develop an empirical model to help predict post-dam channel evolution. This model is already being used to screen and prioritize potential dam removal projects.

5.2 BACKGROUND

5.2.1 Impounded Sediment Formations

Channels that form after dam removal are dependent upon the watershed hydrology, pool bathymetry, and the characteristics of sediments in the impoundment. These materials affect the channel's slope, width, depth, stability, substrate grain size, rate of erosion, and location. The classic deposition pattern in an impoundment has often been described as a three-part sequence. The heaviest particles entering the impoundment settle fastest and are found near to the inflow point, creating a delta. As material accumulates, particles are transported to the downstream end of previous deposits before settling, forming a foreset deposit with a steep face. Smaller particles that settle slowly are transported beyond the coarse deposits, gradually accumulating as bottomset deposits spread over the base of the impoundment, or are transported past the dam. The upper surface of the delta deposit may aggrade to the pool level and become a floodplain or island, receiving topset deposits from later flood flows.

Morris and Fan (1998) and White (2001) studied sedimentation processes in reservoirs and discuss potential deposition patterns. In addition to deltas, wedge-shaped deposits may fill deep-water areas behind the dam and become thinner in the upstream direction. This is attributed to high-density turbidity currents that carry sediments across the reservoir bottom, and also can occur in large reservoirs operated with low water

levels. Uniform bottom deposits may occur when sediment loads are comprised of fine materials or when water levels fluctuate over a broad vertical range.

Studies of sediments in temporary glacial lakes in New England have identified seven types of depositional patterns called morphosequences (Stone et al. 1998), with three types of deposits consisting of fluvial, deltaic, and lake bottom. The drained glacial lakes allow direct observation of these deposits, which is seldom possible in active impoundments.

5.2.2 Channel Initiation

Channel erosion into impounded sediments after dam removal may be initiated in several different locations, starting at the delta face, dam site, inflow source, or by general progressive degradation. Breaching or removing a dam at the downstream end of impounded sediment creates a steep hydraulic gradient with high velocities and often high turbulence. This creates opportunities for local scour and creation of headcuts that migrate upstream, removing sediment at the exposed face and at the sides of the scoured channel as the banks become higher and steeper, ultimately leading to collapse. The migratory direction of the headcut will be influenced by gradients, flow velocities, and sediment characteristics, with headcuts typically extending upgradient following the highest velocities.

Redeposition may occur within the pool area or downstream of the dam if sediment transport capacity is less than the rate at which sediment is supplied from upstream. Channels that are carved into shallow deposits may quickly reach tough pre-dam soils, bedrock, or old channel armor that limits incision (Morris and Fan 1998). These conditions promote earlier channel widening or even increased sinuosity.

5.2.3 Sediment Control

Numerous methods are available to control the impounded sediments at dam removal sites. The intent of this approach is to retain the bulk of the sediment in place by controlling the channel's bed elevation; it is appropriate when the slope of the pool's sediment surface is suitable for an equilibrium regime channel and when the sediment thickness at the dam allows for a reasonable transition length between the downstream channel bed and the new upstream channel bed. Grade control methods include timber or steel sheeting, check dams, boulder sills, concrete drop structures, created riffles, and riprap channel sections. Their primary limitation, of course, is that vertical grade controls may block fish passage. Examples of grade control systems are the steep riprap channel installed at the Lake Switzerland Dam site in the Catskill Mountains of New York, and the cobble-lined channel at Zemko Dam in Eightmile River at Salem, Connecticut. In both cases, little sediment was released during and after dam removal.

Other sediment control measures at low dams include mass excavation, sediment relocation, preemptive channel excavation, partial dam removal, and bypass channels. During the 2006 removal of Ballou Dam from the Ballou Pond River in Berkshire County, Massachusetts, sand and gravel sediments were excavated to form a new step pool channel before they could erode. Cohesive contaminated sediments were excavated from Mill Pond Dam (Norwalk, Connecticut) during construction to prevent the release of mercury into downstream waters, and channel controls were used to prevent sediment releases from channel incision at the Billington Street Dam (Town Brook, Massachusetts) removal project. The Lowell (Johnson County, North Carolina) and South Batavia (Batavia, Illinois) Dams were only partially removed in order to retain asymmetric sediment deposits in place.

5.3 METHODS

5.3.1 Empirical Channel Evolution Forecasts

Several techniques are available to forecast future channel evolution upstream and downstream of dam removal projects. Empirical methods include the study of completed dam removal projects and review of similar phenomena. The writer has completed dam removal site investigations and feasibility studies at more than 60 sites and completed the removal of 15 low dams that are being informally monitored. Several analogies have also been considered to indirectly study the impact of dams and dam removals (Poff and Hart 2002). Natural analogs include debris dams, beaver dams, landslides, waterfalls, and lake outlets. The writer has considered four additional analogies (reservoir drawdowns, reservoir flushing, glacial dams and lake sites, and dam failures) to help define physical sediment deposits and channel evolution processes. Analytical methods are based upon hydraulic analysis of flow velocities, shear stress, and sediment transport with rigid or mobile boundaries. Analytical methods should be supplemented with empirical and historic data to help verify possible channel behavior.

5.3.2 Field Observations and Discussion

The initial factors affecting post-dam channels are whether the impoundment has sediment and the presence of a pre-existing channel or thalweg across its bed. At the Cuddebackville Dam on the Neversink River in New York, a low run-of-the-river dam site, there was no appreciable sediment and the post-removal flow simply reverted back to the pre-dam channel without new incision or widening of any kind. At the Chase Brass Dam on the Naugatuck River in Connecticut, there was a uniform veneer of thin bottom deposits across the impoundment that did not fill the old channel, and the post-dam flow simply reverted to the pre-dam channel with few geomorphic changes or sediment transport. Unconsolidated sediment in the pre-existing channel is likely to be rapidly removed with minimal channel migration.

Coarse, poorly graded sediments, often found at run-of-the-river dams or in steep watersheds with high bed loads, encourage wide, shallow channels that may form an armored bed. The Platts Mill (Spartansburg, Pennsylvania) and Anaconda (Tooele, Utah) dams fall into this category. Channels that form on fine sediments tend to initially degrade vertically, with periodic mass bank failures as the steep banks become too high for cohesive materials. The depth of incision will be limited by the channel's baselevel, equilibrium slope, or non-erodible materials. This condition was observed at Bunnells Pond Dam (Bridgeport, Connecticut) and Norwalk Mill Pond (Norwalk, Connecticut).

Another type of channel evolution occurs where a delta of coarse sediment extends part-way into an impoundment, creating a subaqueous mound that longitudinally bisects the impoundment. When water levels were drawn down at MacKenzie Reservoir (Connecticut) and at Red Cedar Lake (Lebanon, Connecticut) for dam repairs, the incoming flows split across the delta, much like an alluvial fan, resulting in an anabranched condition. This resembles braiding but is created by degradation rather than deposition. Another example of this scenario is the site of the former Jenkins Dam on the Neponset River in Boston. Following its removal (about 1960) in response to a flood, the river became anabranched around the delta with one channel following each bank, leaving the old pond sediments as islands, which still remain more than 50 years later.

Concern has been expressed about channel degradation or headcutting upstream of dams that have been removed. In many cases, rivers in upland areas are naturally degrading and headcuts are quite common. Headcuts at dams will release previously stored sediments that will be transported downstream. This process is harmful where it causes excessive environmental damage such as burial of benthic species or spawning sites, or causes water quality problems such as high turbidity. Excess sediment can also aggrade channels, obstruct bridges or culverts, and raise flood water levels.

Upstream channel degradation has not been a major problem at low dam removal sites. It is either limited due to shallow sediments or intentionally controlled before it develops. Control methods include the construction of boulder ramps (Platts Mill Dam), created riffles, and vortex 'eirs (Billington Dam, Plymouth, Massachusetts). Shallow headcuts with ıinimal channel damage are being allowed to run out at the Anaconda nd Union City (Pennsylvania) dams. The 1979 failure of Community ake Dam on the Quinnipiac River in Wallingford, Connecticut initiated 3-ft-high knickpoint that migrated 1 mile upstream to the head of the riginal pool, where it had to be controlled by a concrete sill installed at sanitary sewer crossing that was in danger of being undermined.

.3.3 Sediment Presence

One should not assume that all dams have sediment. Many of the ation's dams are low run-of-the river structures with short retention mes, and some of these have limited sediment accumulation. The ›moval of the 6-ft-high, 220-ft-long Good Hope Mill Dam in Pennsylvaia exemplifies this class. Removed in 2001 for fish passage, only traces f sediment over a bedrock and gravel bottom were found, and no sigificant cross section changes occurred (Chaplin 2003). Subsequent inspecons by this writer found no mass bank erosion, little reduction in 'aterway width, and no downstream deposition. Similar conditions were resent at Freight Street Dam on the Naugatuck River in Connecticut, ›moved in 1999. The 158-ft-long low concrete dam had little upstream ›diment and no changes in morphology (Wildman and MacBroom 2000). even years after removal, the dam site is indistinguishable from upstream nd downstream river reaches.

Pre-removal studies of the 25-ft-high, 917-ft-long Edwards Dam in laine found little sediment in its 15-mile-long but narrow impoundment, ı part due to frequent flood flows and upstream dams (Dudley 1999). he through-flow velocity was sufficient to minimize settlement of finerain sediments, and coarse sediment was forecast to remain in place (Oak idge National Laboratory 1997). The post-dam river has rapidly returned) free-flow conditions, with documented fish returns to upstream areas. similar lack of sediment was found during dam removal studies at the eazie, Great Works, and Howland hydroelectric dams in the Penobscot iver basin in Maine (Milone & MacBroom 2003).

.3.4 Submerged Barriers

It is not unusual to find substantial objects that are submerged in dam npoundments or buried in sediment, which modify channel evolution fter dam removal. The water drawdown to inspect Sandy Hook)am (Connecticut) exposed an old, undocumented timber crib structure ›taining sediment upstream of the modern concrete dam, and our bathyıetric surveys of the Veazie and Great Works dams in Maine found artial remains of nineteenth-century submerged dams. The sediments at Carbonton Dam (North Carolina), removed in 2005, were held in place by a submerged log jam that had to be removed. Channel evolution at other sites has been affected by buried automobiles, boats, tires, trees, stumps, barrels, head races, and shopping push-carts.

5.3.4.1 Narrow Impoundments. Narrow impoundments occur where dams were built in confined valleys with significant cross-section side slopes, or at run-of-the-river dams whose pools are largely contained in the original banks. Dams constructed across previously incised channels, such as gorges, fall within this category. The post-dam channels across narrow impoundments have limited opportunity for lateral expansion or meandering and often revert to their original alignment.

Narrow impoundments with thin sediment deposits pose few problems due to limited volumes. The channel alignment has little flexibility due to the lateral constraints, and thin sediments do little to inhibit its return to the original thalweg. Sediment management could include no intervention (due to small sediment quantities), or sediment removal if there are contaminants or water quality concerns. With narrow impoundments and thin sediments, there is little need to preform the future channel's alignment, width, and depth. Narrow impoundments with high dams could have substantial sediment thicknesses. The post-dam channel will have a constrained alignment but could become incised, resulting in banks that could exceed critical heights for stability. The degree of incision will be influenced by the potential channel gradient, velocity, and substrate, while the channel width is influenced by the strength of the banks.

5.3.4.2 Wide Impoundments. Wide impoundments are defined here as those with a width (at the water surface) more than three times the width of the meander belt of the subsequent channel. The channel is not laterally constrained and is able to have lateral movement and a sinuous alignment. The relatively large width of wide impoundments also means that the subsequent self-formed channel may not revert to its pre-dam alignment, and may change alignment as it evolves.

The behavior of the Poquannock River at Bunnells Pond Dam in Bridgeport, Connecticut is an example of channel realignment. During dam repairs in 2001 and 2002, the wide impoundment was drained, exposing a flat sediment plain. The initial channel was near the left (east) bank of the impoundment, formed by a combination of vertical incisions and headcuts. Following floods and temporary overbank flows, an alternate channel evolved closer to the right bank and captured all flow. Within 1 year, the latter channel quickly developed into a stable, straight equilibrium alluvial channel with an armored bed and no lateral meandering or subsequent degradation.

Observations indicate subsequent channels in wide impoundments with fine-grain sediments can degrade by either vertical incision or headcuts that migrate upstream. The incised channels retain relatively straight alignments until reaching vertical non-erodible controls that limit upstream gradients; then meandering begins. The Connecticut River at post-glacial Lake Hitchcock at Wethersfield, Connecticut and above Holyoke, Massachusetts behaved in this manner, as well as Six Mile Creek in Tomkins County, New York. The incision of subsequent channels at wide glacial lakes removed only a small part of the total available lakebed sediments.

5.3.5 Channel Pattern

Channel planform patterns are related to discharge, slope, and sediment size, with meandering rivers common on mild slopes found on depositional floodplains and less-sinuous channels common on steeper gradients. The initial bed gradient of a channel is based on the sediment's gradients. The initial bed gradient of a channel is based on the sediment's top slope, which may vary from very flat over bottomset deposits to steep on foreset delta deposits. Observations at sites where low dams have been removed indicate that channel degradation to an equilibrium bed slope occurs initially by rapid incision, and that the steep gradient creates a low-sinuosity channel. The reach downstream of the headcut then adjusts its pattern to fit its flow, sediment load, gradation, and slope. Straight channels developed after removing the Union City and Anaconda dams, both of which had fairly steep pre-dam channels.

Recent studies (Milone & MacBroom 2003) of Six Mile Creek near Ithaca, New York found that the channel incised into fine-grain glacial lake bed sediments until an equilibrium slope was reached, and then sinuosity increased with lateral movement into legacy sediments. The 25-ft-high Mad River Dam in Waterbury, Connecticut was notched in 1999 to draw down water levels. The spillway was subsequently removed and a new channel was dredged; it then immediately widened and increased sinuosity, but did not degrade. The meandering channel movement led to considerable sediment removal.

5.4 DAM REMOVAL ANALOGIES

5.4.1 Reservoir Drawdowns

Sediment deposits and channels that evolve after reservoir water levels are drawn down are similar to conditions that occur during dam removal, but over a long time scale. Direct observation of sediment deposits has been an invaluable aid in interpreting subaqueous deposits that are not visible. Water level reductions at the Lake Whitney and MacKenzie reservoirs in Connecticut both revealed coarse-grain sediment deltas where the inflowing rivers entered impoundments in broad, low-gradient valleys, with an impoundment far wider than the river channel. At both sites there was no evidence of pre-dam channels across the impoundment, as they were totally filled with sediment. During the drawdowns, the waters of the inflowing streams split around the sides of the deltas, creating bifurcated channels. This type of delta condition with split flow was a major factor in planning the Cuddebackville Dam removal project in New York, where a delta exposed by removing flashboards became a vegetated island. In contrast to the above deltas, drawdowns at the narrow Woodtick and Saugatuck reservoirs in Connecticut exposed fan-shaped deltas across the full width of the impoundments. The river inflow on the exposed full-width deltas rapidly incised single-stem, slightly sinuous channels.

Permanent reservoir drawdowns have occurred when dams are partially drained by removing gates or by lowering the spillway crest elevation for safety purposes. Spillway modifications at four aging dams along the Kalamazoo River in Michigan have exposed the impounded sediments, most of which have become revegetated. The river has carved a new channel through these materials and remains fairly stable with most original sediments still in place. However, the erosion of even minor sediment quantities affects water quality due to polychlorinated biphenyl (PCB) contaminants.

5.4.2 Reservoir Sediment Flushing

Impoundments with low velocities and long retention times trap a portion of their sediment inflow and gradually lose water storage capacity. Sediment deposits interfere with navigation, reduce pool area, and raise upstream water levels. It is increasingly common practice, particularly on water storage reservoirs, to manage impoundments for long-term sustainable use by flushing excess sediment.

Sediment flushing consists of periodically opening low-level gates to discharge water that erodes impounded sediment. Large-scale sediment flushing begins to create through-flow that temporarily approaches the impact of dam removal. A free-flowing channel beginning at the dam and extending across the sediments can be created by repeated flushing with full reservoir drawdown (Morris and Fan 1998). Rates of sediment flushing depend on discharge rates, water surface or bed slope, and channel width. In fine sediments, the flushing channel will tend to revert to pre-dam channel conditions; in coarse sediment, it may meander or braid. Empirical data on new flushing channel widths has been developed to estimate the volume of sediment eroded (White 2001). Large sediment