HYDROLOGICAL AND ECOLOGICAL IMPLICATIONS ASSOCIATED WITH THE INTRODUCTION AND REMOVAL OF SMALL DAMS

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Abstract

Over the last two centuries, humans have constructed dams for numerous reasons. As dams reach the terminus of their design life, increased risk of strict liability demands increased maintenance. Not only does the need for extended maintenance impose excessive costs, but it also provides an opportunity for land managers to consider other alternatives. The growth of awareness toward maintaining self-sustaining natural resources has fueled advances in science and legislation that promote the value and policy supporting dam removal as a management priority. Now, more than ever, the consideration of removing a dam is more widely accepted by land managers, permitting agencies, funding entities, and the general public.

This paper provides the land manager with a general knowledge of the holistic problems associated with introduction of a small dam as well as the removal of a small dam. Very few individuals possess the diverse breadth and depth of academic training and skills to independently make a decision to remove a dam. However, regardless of background, it is equally important for all individuals involved in such an undertaking to realize the complexity of issues surrounding the decision to remove a small dam. This paper provides information about the hydrological and ecological implications associated with the introduction and removal of small dams in the context of natural resource management.

Background

Over the last two centuries, humans have constructed dams for numerous reasons. In response to variation in climate, private and public entities have utilized dams to manage surface water to ensure sufficient water supply during periods of drought and to provide safety and protection of property and infrastructure during periods of drought. Additionally, dams serve other human needs such as generation of power, creation of recreation opportunities, and support for commerce in the form of navigation. It has been estimated that over 76,000 dams (including only those greater than six feet in height) were developed to provide such services (Pohl 2002). The introduction of dams has distorted the natural river system of the United States into a fragmented sequence of anthropogenically modified segments.

Small dams: What are they, and how do they differ from other dams? Currently, forums hosting discussion on dam removal fail to maintain consistent language and frameworks for evaluating dam removal. This inconsistency includes a lack of convention regarding the data that is considered useful, the certainty with regard to environmental impacts, and a general limited base of knowledge of decommissioning and removal alternatives (Heinz Center 2002). The term “small dam” may invoke a number of perceptions of relative dam size with regard to height, length, area and volume of storage. Because the reservoir storage volume may be the single greatest indicator of geomorphic, hydrologic, and biologic influences of a dam upon the associated stream or river, the Heinz Center (2002) characterizes dams based on the respective storage volume ranges as follows: small (0-100 ac-ft), medium (100-10,000 ac-ft), large (10,000-1,000,000 ac-ft) or very large dams (> 1,000,000 ac-ft).

Information needs about dam decommissioning. Several important pieces of federal legislation were passed over the last three decades concerning environmental policy, including the Clean Water Act, Endangered Species Act, National Environmental Policy Act, Clean Drinking Water Act, Wild and Scenic Rivers Act. This legislation has promoted scientific research and inspired amendments to these acts to better accomplish their intent and expand applicability (Pohl 2002). Recent growth in scientific understanding of ecosystem response to the introduction and removal of dams has contributed to an increase in social value placed on the associated natural systems. The economic benefits gained from dams in the form of water supply, power production, and other resources do not account for the losses associated with deteriorated habitats, impacts to downstream water quality, and other intrinsic values assumed by a stable natural environment (The Aspen Institute 2002).

Small dams, unlike most large- to medium-size nonfederal hydropower dams, are not subject to relicensing requirements under the Federal Energy Regulatory Commission (FERC). Typically, small dams were constructed for small-scale power generation, irrigation, and water supply to support localized agricultural and manufacturing needs. Although, most small dams are privately or publicly owned, some small dams are abandoned and their jurisdiction has been assumed by state and local entities. For the most part, these “orphaned” dams that have been adopted in such a manner typically no longer continue to serve their intended function. These dams usually show signs of neglect invoking safety concerns resulting in inflated insurance costs, maintenance cost, and an overall high risk of ownership. The National Inventory of Dams (USACE 2005) has identified over 10,000 dams located in the United States as high hazard risk with the potential of loss of life if ever a single one of these dams fails.

However, like all dams regardless of size, small dams also must comply with safety requirements of the Dam Safety and Security Act. This Act defines a dam as any artificial barrier that has the ability to impound water, for the purpose of storage or control of water, that is 25 feet or more in height or has an impounding capacity for maximum storage elevation of 50 acre-feet or more, but does not include a levee or a barrier 6 feet or less in height regardless of storage capacity; or has a storage capacity at the maximum water storage elevation that is 15 acre-feet or less regardless of height. For the purpose of protecting human life and property, this act warrants the inspection of all dams, with the exception of dams, which have been constructed pursuant to licenses issued under the authority of the Federal Power Act. Currently, the United States Army Corps of Engineers, Association of State Dam Safety Officials (ASDSO), FEMA, and other state and federal agencies update and publish the National Inventory of Dams database of over 77,000 structures throughout the United States.

Because of economic cost, environmental value, and legal obligations, the option to remove or decommission problematic dams has grown in popularity as a remediation alternative. The terms “dam removal” and “dam decommissioning” are sometimes used interchangeably. Decommissioning suggests an alternative to complete removal wherein a part or all of the structure may remain but not in the impoundment capacity originally intended. Decommissioning alternatives range from a partial breach, such as notching of the spillway or removal of spillway gates of the existing structure (American Rivers and Trout Unlimited 2002), to partial or complete relocation of the primary flow path to circumvent the abandoned structure. Although less conventional than complete removal, decommissioning alternatives may accommodate financial or physical constraints associated with the problematic dam in question. For the purposes of this paper, “decommissioning” will be inferred by the use of the term “removal”.

Objective

Although informed decision making about dam decommissioning should take into consideration administrative, socio-economic, and political factors, the principal hurdle in such decisions is identifying environmental implications (costs and benefits) associated with ultimate management decisions. This paper introduces basic science principles and literature important for use as a “starting point” reference to assist the land manager in addressing environmental questions such as:

- Will removal/retrofit of the existing dam aid or inhibit: a) the recovery of threatened or endangered species, or b) the management of native, exotic or invasive species?

- What is the risk of dam alternations to the dependent and/or associated natural and manmade systems such as wetlands and the downstream riverine environment?

- What are the effects of dam alternations to: a) watershed water budget (timing and quantity) and quality of surface and ground waters, and b) downstream or other hydrologically connected users?

I address these questions from the standpoint of existing conditions, proposed disturbance, and the resultant conditions (subsequent to introduction of a disturbance). When the existing condition is a continuous stream and the introduction of a dam is the proposed disturbance, impacts may be more clearly identified when the resultant system upstream and downstream of the disturbance are considered independently. Similarly, when the existing condition is a stream divided by a dam and dam removal is the proposed disturbance, impacts may be more clearly identified when the resultant reconnected system is considered in its entirety.

Upstream impacts following introduction of small dams

When an impoundment is introduced to a free-flowing river or stream, noticeable changes occur immediately to the upstream physical environment. As time progresses, these changes to the upstream physical environment promote changes to the ecological environment as well. Such changes to the physical environment may be divided into hydraulic, geomorphic, and water quality changes.

Changes to hydraulics. Anthropomorphic development of the upstream watershed often occur concurrent with the introduction of a small dam, and both contribute to hydraulic changes. Over the long term, it may be difficult to identify the source of such changes. Because of this difficulty, I will focus on only those hydraulic changes associated with the initial impoundment of water, beginning with the introduction of the dam. Initial impoundment allows for storage of water and forces the stream to function hydraulically like an oversized pool. As water enters the pool from the mainstem and any other adjacent tributaries, the velocity may be reduced by orders of magnitude from a free-flowing scenario to nearly zero. This reduced velocity imposes a backwater condition further upstream to a distance that varies with the flow regime of the contributing tributaries. A more thorough understanding of the degree and extent may be predicted using conventional hydrologic and hydraulic models. Modeling the quantity and timing surface and subsurface watershed contributions and stream flow through the proposed reservoir may be accomplished using programs developed by the Hydrologic Engineering Center (Vicksburg, MS), or similar mathematical tools depending on required accuracy. Such models can aid in determining accurate zones of hydraulic impact associated with introduction of a small dam, or series of small dams.

Changes to geomorphology. Directly related to stream flow is the availability and movement of sediment. Together, discharge and supply determine the quantity and characteristics of sediment that is transported through streams. As mentioned previously, the hydraulic condition of the stream transforms into that of an oversized pool following impoundment. In response to this modified hydraulic condition, the upstream end of a reservoir begins to form a delta. This delta is composed of the larger bed load material, that falls out of transport upon reaching the point of confluence, or backwater, between the stream and the reservoir. Because the transport is partially a function of velocity, the delta tends to consist of finer material in the downstream direction. As the cooler river water enters the normally warmer surface of the reservoir, the cooler water plunges below the thermocline and carries silts and clays to be deposited further along the entire length of the reservoir. Any excess of the extremely fine materials that is sustained in transport throughout the reservoir accumulates immediately upstream of the dam, along the face. Depending on the length, storage capacity and sediment supply, the delta of small reservoirs can extend all the way to the dam and overlay the finer material deposited earlier as the original reservoir bed (Freeman 2004).

Changes to water quality. Since an impoundment inundates upstream riparian areas and dynamic zones between the upland and stream, flowing overbank events cease. Because of a reduction of overbank flow events, exchanges of sediments, nutrients, and organisms between aquatic and terrestrial areas become more limited (Bednarek 2001). Like water in a natural lake, dammed reservoirs exhibit a temperature profile that is typically characterized by a surface layer (the epilimnion) consisting of warmer, less dense water. As depth increases, temperature decreases and density increases. Because of differences in density, the coldest water remains stratified on the bottom (hypolimnion) and never mixes with the warmer surface. As a result of little or no photosynthesis and a lack of mixing, deeper water often has low dissolved oxygen and high biological oxygen demand (Yeager 1994). The temperature profile of a reservoir is a complex function of thermal dynamics and mass balance accounting for input and output of energy. Energy inputs include tributaries and solar radiation, while outputs consist primarily of discharge (Orlob and Selna 1970). A shallower reservoir having a proportionally larger surface area per unit volume may exhibit less variation in temperature, than a deeper reservoir with a smaller area per unit volume

When nutrient-rich water enters a reservoir, some of the nutrients precipitate out of solution and settle to the sediment-laden reservoir bed. The same is true for other solvents including heavy metals, pesticides, herbicides, and other pollutants (Bednarek 2001). In the case of urban storm water management, this settling can be perceived as a benefit, but in the case of rural, less-developed watersheds, the reduction of nutrient transport and associated nutrient cycling can be perceived as a negative impact to the downstream receiving systems. Such an excess of nutrients (primarily nitrogen and phosphorous) combined with increased temperatures of reservoirs often facilitates an exponential increase in bacteria, or algal blooms (Reynolds 1987). These bacteria populations consume much of the dissolved oxygen and as a result, minimize biological speciation, especially along the shoreline of the reservoir.

Changes in acidity can occur as a result of surface evaporation in reservoir waters. The concentration of dissolved solids in the water entering the reservoir increases over time as the volume of water is reduced. The increased concentrations of solids (commonly salt) increases the alkalinity of the remaining water, and the acidic water is ultimately discharged into less acidic downstream systems, where the biota is often adapted to low salinity conditions.

Supersaturation is a condition common to reservoirs in which atmospheric gases, such as nitrogen, become immobilized or buried beneath the hydrostatic pressure toward the bottom of the reservoir and ultimately forced into solution. If fish are exposed to these supersaturated waters these gases can enter their blood during respiration (Heinz Center 2002). As these gases are absorbed into the fish's bloodstream, they cause the blood to bubble oftentimes creating a debilitating and possibly fatal condition.

Changes to the ecology. Because dams impact hydraulics, geomorphology, and water quality, inevitable impacts to the ecology are to be expected. As discussed in the hydraulics section, the introduction of a small dam transforms the riverine/lotic ecology of the river to a more lacustrine/lentic ecology associated with a lake. Five hydraulic factors in riverine environments affect microhabitat diversity and the distribution and ecological success of biota: 1) suspended load, 2) bedload movement, 3) water column turbulence, 4) velocity profile and 5) near-bed hydraulics (substratum interactions). Additionally, the interactions of these factors and the resultant impacts on the morphology and behavior of the individual organisms affects the spatial distribution of aquatic biota (Gore 2001). Similar to changes in hydraulics, changes to the geomorphology also have ecological consequences.

Lotic environments offer a wide spectrum of diversity in microhabitats that provide conditions that support an equally diverse range of species. As with plants, animals in this ecosystem are adapted to a running-water environment. Impounding water introduces a lacustrine environment most suitable for aquatic species indicative of low diversity such as bloodworms, carp, catfish and other bottom feeders. Reservoirs may also promote dramatic changes in fish community structure (Taylor et. al 2000) promoting population growth in fish species that compete with or prey upon the indigenous residential and migratory species. Dams serve as both physical and hydraulic obstructions to upstream and downstream migration of various organisms (Stanford et al. 1996). Dams are often impassible for aquatic species, and the structure may promote shallow flow depths and high velocity that fail to meet physiological and habitat needs of residential and migratory species.

Downstream impacts following introduction of small dams

In order to understand the physical impacts of the introduction of a small dam, we must consider the interactive components that make up a river. Simply put, rivers drain the earth's surface, and river morphology is a function of hydrologic (precipitation and surface water inputs), geomorphologic (geology and physical properties of the watershed and channel substrate), and biological (inclusive of the aquatic, riparian and terrestrial ecological systems characteristic of the watershed and river corridor) characteristics. Surface water contributions require certain cross-sectional and longitudinal geometry (plan, pattern, and profile) to effectively dissipate their potential energy. In dissipating energy, channels collect and distribute sediment (silt, sand, gravel, and larger material) and as a result, form and reform their hydraulic and geomorphic qualities. Modification to the hydrology or sediment supply results in concurrent changes to the hydraulic geometry and geomorphology.

The downstream physical and ecological impacts resulting from the introduction of small dams are predominantly contingent on the management of water releases. Reservoir-release management may incorporate single or multiple management objectives including flood management, water supply, and power supply. Impoundments such as storm water detention ponds designed for flood management suppress peak flows and maintain a constant maximum discharge using hydraulic control structures. Water supply dams typically tend to demonstrate the most variability in discharge regime. Water supply reservoirs are intended to capture stream flow until the pool volume capacity is met, at which point additional flow passes downstream. Hypothetically, if the natural supply and human demand are equal, then the rivers' natural flow regime will only be impacted with regard to timing of flow as it is routed through the full reservoir. In an attempt to maximize vertical storage and associated power production, small hydroelectric dams incorporate active management of adaptive control devices to regulate bypass discharge. Depending on the management objectives, minor to extreme modifications in flow and sediment transport can have a profound effect on the downstream system.

Changes to hydraulics. Alluvial rivers are predominantly formed from three types of flow: base flow (average daily flows), bankfull (point of incipient flooding) and flood flows (extending out of bank and across wide floodplains). The most obvious impact to hydraulics following the introduction of a small dam is the change in timing and quantity of stream flow. The introduction of dams tends to smooth the natural variations of discharge and produce an entirely different flow regime (Nislow et al.). Some small dams may include partial or complete flow diversions. Through reductions of base flow discharge, such consumptive diversions produce conditions ranging from sustained and unusually low flows and dry soil to a mere reduction of bankfull discharge. Although small impoundments may effectively delay and reduce a storm peak discharge, they also allow for unnaturally prolonged periods of discharge that would otherwise occur for shorter periods of time. The modified flow regime can no longer effectively maintain the channel residual hydraulic geometry of the channel.

Changes to geomorphology. When the channel geometry is not in balance with the flow of water and sediment, it is said to be "out of regime" (Leopold 1994). In general, sediment transport may be best understood using Lane's proportionality: QS ~ QsD50 (Freeman 2004). This expression represents a simple balance between hydraulics (represented by flow, Q, and slope, S) and sediment transport (represented by capacity in the form of sediment discharge, Qs, and competency in the form of the median size of bed material, D50). It should be noted that slope and discharge increases must be offset by increases in competency and/or capacity. As previously noted, the introduction of a small dam typically reduces base flow discharge, Q, and because of the introduction of the upstream pool, reduces the sediment discharge, Qs. Reduced capacity, Qs, usually exceeds that needed to offset the imbalance of Lane's proportionality introduced by the impoundment. Therefore, reduced sediment capacity is often accommodated by reduction of slope and competency.

Because the introduction of a small dam reduces the amount of available sediment, fluvial processes will adjust to reduce the channel's transport capacity (Brandt 2000).

This adjustment is accomplished by washing down of fine sediments resulting in the coarsening of the bed and subsequent reduction of slope. In order to achieve the slope reduction, the channel relocates sediment in the channel banks in order to migrate laterally, ultimately lengthening its course. Reduction of slope is often accompanied by reduced depth (Chin et al. 2002), increases in channel width to depth ratios, ultimate aggradation of fines and loss of riffle-pool sequences, and ultimate abandonment of one alignment in favor of one or more others. This process of abandonment produces a braided shallow stream system. These sand-filled gravel and cobble beds will then evolve in one of two ways. Either substantial reservoir releases will mobilize and wash out the fine sediments, or else the braided channels will ultimately develop cut-off channels that produce scouring and head-cut activity delivering excessive amounts of sediment to the active channel at accelerated rates. The magnitude and discrepancy between actual channel dimensions downstream of a dam, and those of an undisturbed system, diminishes in the downstream direction. Although changes in geometry are to be expected to accommodate changes in flow and sediment supply, pronounced reductions in channel capacity could have long-term impacts on the sediment delivery through a system (Chin et al. 2002).

Changes to water quality. Water quality is a function of both the physical and ecological environmental conditions of a stream. A well-functioning, undisturbed stream may effectively cycle nutrients through a diversity of microhabitats, some adding nutrients and some storing nutrients through natural decay and consumptive processes. Similarly, a diverse riparian canopy and bed structure promotes a range of temperatures to which associated flora and fauna are adapted. Reduction of sediment supply generally reduces the transport of nutrients downstream and directly or indirectly impacts the associated ecological structures (Kondolf 1997).

Stream temperature varies with season. However, the introduction of small dams can have adverse impacts on the natural temperature regime of the downstream system. When small dam releases occur over the top of a spillway, it is not unlikely for the released water to have been over-warmed during its course through the upstream lake. To compound the temperature problem, a shallow and over-widened channel lacking in temperature-reducing vertical diversity, such as pools or undercut banks, typically receives the over-warmed reservoir release. These downstream channels act to maintain or increase the already high temperatures. In cases where releases occur from the bottom of the reservoir, cold temperatures and low dissolved oxygen may be a stress on aquatic biota depending on the season and the natural cycle temperature variation. Regardless, temperature and water quality parameters of a natural river vary from that of a managed river. Significant changes in temperature and water quality may alter downstream benthic habitat to some degree.

Changes to the ecology. Dams dramatically alter river flow regime by blocking water passage, storing water in both large and small artificial reservoirs (Poff et al. 1997) and disrupting the cycles upon which many aquatic organisms depend. Dam releases are designed to meet human demands for water supply, navigation, power production, and recreation, and often disregard the needs of the aquatic organisms (Bednarek 2001).

Consequently, non-natural fluctuation in flow caused by dams can promote an aquatic community limited to a few generalist species that able to withstand the altered flow conditions of the river (Bednarek 2001). Some hydroelectric dams maintain a flow regime characterized by an unnaturally high range in flow. In some cases, hydroelectric dams may manage flows for recreation during non-peak energy consumption seasons allowing a more natural flow regime. Alternatively, during peak energy consumption years, a hydroelectric dam may drain the river of all flow to redirect the river for power generation. In other cases, the hydroelectric dams may manage a flow regime with excessive range of flows and timing. When out of sequence with the natural variation of flow, such regulated seasonal, daily, and hourly flow management programs can be damaging to river ecosystems. Diversions for power generation or other consumptive create unnatural drought conditions and reduce river health by inhibiting riparian vegetation growth and stranding insects, fish, and bird nests (American Rivers 2002). Alternatively, too much flow too fast creates unnatural flood conditions that physically scour aquatic organisms and reducing populations of river fauna (American Rivers 2002).

One study (Growns et al. 2001) examined the effects of flow regulation on macroinvertebrates and periphytic diatoms in the Hawkesbury-Nepean River system in Australia. Regulated sites below eight dams or weirs were compared with unregulated sites located above the impoundments and on two nearby unregulated streams. The managed sites experienced one of two types of flow regulation: 1) ample water supply releases and 2) relatively small or no releases. The macroinvertebrate communities in three habitats and periphytic diatoms below the dams and weirs differed from the biota at the unregulated sites. The number of macroinvertebrate taxa in riffle and pool-rock assemblages was significantly lower at regulated sites when compared with unregulated sites. However, the number of stream edge macroinvertebrate and diatom taxa was unaffected by regulation. Although macroinvertebrate assemblages from riffle-pool and rock features differed between the two types of regulation, periphytic diatom and edge habitat macroinvertebrate assemblages did not. Review of environmental variables associated with the change in the biota suggested that these changes likely occurred in response to changes hydrology more than changes to water quality (Growns et al. 2001).

Natural rivers experience variation in flow regime, sediment regime, as well as temperature and nutrient loading. Aquatic flora and fauna adapted to survive and proliferate under these dynamic conditions are sensitive to changes to the natural dynamism that do not mimic natural processes. The inundation regime of downstream floodplains is substantially affected following impoundment (Nislow et al. 2002). One example of physical change followed biological change is the dewatering of natural floodplains and active channel terraces associated with managed discharge. In addition to reducing the moisture availability, this dewatering can limit overbank sediment deposits and associated nutrients and seed propogules. Over time, the riparian wetland often either becomes overrun with upland species or falls victim to low seral opportunistic invasives (Nislow 2002).

Channel vegetation may experience a similar phenomena associated with regulated discharge. Some in-channel vegetation adapted to scour require flood flows to recolonize on newly scoured or deposited features. Without experiencing diversity in flows, reductions in turbidity may cause a change in bed vegetation toward dominance by sub-aquatic vegetation, such as Cladophora (Stevens et al. 1997). Until a river receives inputs of sediment and temperature from downstream tributaries, such changes in benthos may produce a spike in biomass production facilitating explosion in non-native or invasive species of fish.

Even waterfowl are not exempt from impacts associated with introduction of small dams. Flow regulation may yield negative or positive changes to bird habitat. Many migratory species thrive in riparian ecosystems that have a wide variation of flow regime, though such ecosystems may not be desirable for year-round residence. Typically changes to the riparian ecosystem resulting from changes in hydrology produce changes in inhabitation. The damming of the Platte River reduced scouring flows that promoted wet meadow development. As a result, areas typically dominated by wetlands were overrun by larger trees, which promoted island development and subsequent anastomizing, or braiding of the channel. The braided channels continued to dewater the floodplain and ultimately destroyed preferred habitat of the Sand Hill cranes (Fischenech 2002).

Changes to connectivity. Connectivity describes the continuous and contiguous nature of a riverine system. Although difficult to measure, anecdotal data and intuitive reasoning suggest that connectivity serves as a major component of riverine functions such as maintenance of flow, sediment transport, water quality, temperature (Taylor et. al 2000). Connectivity allows for continuous upstream and downstream passage of organisms and facilitates fulfillment of life cycle needs such as food sources, spawning habitat and safety from predators (Ward and Stanford 1995). Dams usually fragment the river corridor by creating colonization obstacles for both flora and fauna, isolate populations, and disrupt interactions between terrestrial and freshwater systems (Ward et al. 1999). Small dams fragment the river continuum and typically act as either physical and/or hydraulic blockages. Physical blockages prevent migration by exceeding the capacity of fish to jump or slither. Hydraulic blockages are more species specific. Different fish have different abilities to maintain burst, prolonged, and sustained speeds (Acharya and Katopodis 2000). Connectivity may also be impacted by the inability of fish to spawn. As mentioned previously, the tendency of a stream to adjust hydraulically and geomorphically may impact spawning grounds by filling in the preferential interstitial voids. This filling may either prevent some fish from spawning in that particular location, or else prevent the roe from surfacing and ultimately surviving. Failure to spawn is very likely to predicate reduction in distribution of species richness and diversity, and as a result, impact the overall connectivity of the system.

Impacts associated with removal of small dams

Impoundment removal essentially reconnects a segmented series of different systems. Because the dam removal promotes a series of streamwise processes, it may be best to consider the physical and ecological impacts to the upstream and downstream collectively.

Changes to hydraulics. Simply put, removal of dams in rural settings immediately restores the natural flow regime. However, in less than rural settings, urban and residential development of watersheds can have profound impacts on the natural hydrologic regime, and the downstream channel may not be equipped to handle the introduction of the restored natural flows. In order to predict how well the channel will perform under restored flows, proposed (post-dam removal) discharge data needs to be developed using empirical or analytical techniques. This usually requires a knowledge of past and present watershed conditions to effectively model and understand changes in the hydrologic inputs.

Changes to geomorphology. In order to predict changes and level of damage to upstream and downstream systems following dam removal, understanding and analysis of sediment transport and geomorphic processes are critical. Removal of small dams impounding small amounts of sediment, their removal may result in mobilization of only a fraction of sediment, while most remains in storage in the former reservoir pool. In some cases, dam removal can restore a river's natural sediment balance, allowing for the downstream redistribution of sediment having an impact comparable to that of a single large storm event (Freeman 2004). In other cases, dam removal, can be the most environmentally damaging alternative such as in the case where contaminated or excessive amounts of sediment pose a threat to the downstream habitat and species (American Rivers and Trout Unlimited 2002).

While sediment transport models may provide an estimate of the magnitude of material to be relocated, they often tend to underestimate the amount of sediment that moves due to upstream channel meandering and widening subsequent to dam removal (Freeman 2004). Consider again Lane's proportionality: QS ~ QsD50. Immediately following removal of a dam, incision occurs after failure of the leading edge of the deposited sediment (Wong et al. 2004). Next, the slope increases through the previously impounded upstream reach. As the slope increases, the sediment load must increase proportionally in pursuit of the balance. If the slope increases by a factor of four, say from 0.00015 to 0.00060, then a fourfold increase of capacity must occur, since the D50 remains constant. This constancy is the case until the bed incises down to layers of coarser material such as the original bed. Under hypothetical conditions, reservoirs tend to deposit finer material below courser material, coarsening in an upstream direction (Wong et al. 2004). Under conditions of gradual release, this deposition may provide the channel with the necessary size sediment for natural armoring downstream as incision migrates upstream. Although these types of calculations may be in error by an order of magnitude, the results may be generalized as follows: If the ratio of stored sediment expected to erode to the annual sediment transport is small, then the impacts will likely be small, and if the ratio of stored sediment expected to erode to the annual sediment transport is large, then the impacts will likely be large.

Sudden removal of an impoundment causes erosional narrowing concurrent with an increase in slope. During the early stages of incision immediately following dam removal, the channel may become narrower as degradation occurs. The incision and narrowing propagate upstream over a very short time period. However, over a longer period of time, depositional contribution from channel side slope failure accommodates the increases in discharge and slope and sediment supply ultimately surpasses the channels transport capacity. At this point, excess material deposits forcing the channel to widen and the slope to reduce to a state of equilibrium. This time evolution of channel width is a function of the streamwise gradient of sediment transport and fluvial erosion of the channel bank material (Wong et al. 2004).

Changes to water quality. Just as reservoirs serve as nutrient sinks when a dam is introduced, they serve as a nutrient source when a dam is removed. The rural pastoral land use and application of fertilizers to agricultural and urban property results in excess nutrients (phosphorus, potassium, nitrogen) delivered to the stream and reservoir. The only way to know what has accumulated over the years is to sample and test the reservoir lakebed. If impounded sediment and transport subsequent to removal is not properly addressed, re-suspension into free-flowing streams, although temporary, could produce short-term rapid, and possibly catastrophic, increases in turbidity and water quality damaging spawning grounds (Born et al. 1996), and adversely impact water quality, habitat and food quality of the benthic/aquatic systems downstream. With proper analysis and planning concerning the stored sediments, decision makers can mitigate for the effects of such impacts.

The impacts of natural seasonal temperature variations caused by damming on the impounded downstream system were discussed previously. Removal of a dam can restore the natural water temperature range (American Rivers 2002). Similarly, depending on the difference in temperature between the impounded and downstream systems, rapid introduction of a volume of water with a great difference could impose immediate changes in downstream temperatures that could adversely affect microhabitats over the short term. Unfortunately, few studies provide measured effects of dam removal on water temperature.

Changes to the ecology. The majority of dams transform a portion of a river into a lake-like habitat. Many of the upstream alterations of rivers following introduction of an impoundment can be reversed over time following the removal of the impoundment.

Removal of a dam can impose short-term and long-term effects on the biodiversity and aquatic ecosystem of a river. Because dam removal can decrease the richness or diversity of organisms that prefer slower moving open water and wetlands of the impoundment, removal may in some cases reduce aquatic biodiversity. Riparian buffers that surround the impounded lake may be stressed because of depleting water tables following removal of dams (Stanley and Doyle 2003). While loss of wetland and reservoir habitat may have a negative impact on some species, such as duck and muskrat, whereas other species, such as reptiles, amphibians, and other mammalian macrofauna, may persist in reconstructed riverine wetland habitat following impoundment removal (Bednarek 2001). While in some cases dam removal has an adverse impact on the upstream environment, in other cases, dam removal promotes the redevelopment of native ecosystems and supports the recovery of indigenous aquatic organisms (Heinz Center 2002). Once a dam is removed and critical upstream habitat becomes available, migratory fish populations rebound, including threatened and endangered species. In some cases, dams provide a barrier preventing colonization of undesirable invasive or exotic fish species. Removal of dams in these cases can negatively impact the upstream populations. Although very few published articles document accurate or precise changes in population sizes, species richness, diversity, or distribution, fish migration into formerly inaccessible areas has been reported for a number of streams (American Rivers et al. 1999). One such case occurred on the Kennebec River of Maine where the removal of the Edwards Dam resulted in migration of striped bass, alewife, shad, Atlantic salmon, and sturgeon beyond the location of the former dam site (Stanley and Doyle 2003). Unfortunately, despite such anecdotal data of apparent fish passage success, the contention of dam removal and fisheries management continues while fish runs decline in other rivers in need of restoration.

Management Considerations

Typical of natural resource management, the solution to a problem is only as complete and valuable as the level of understanding of the problem. Although stimulating and glamorous, dam removal is not always the solution to riparian and riverine management problems.

Minimizing impacts associated with small dam removal. Once removal is identified as a politically feasible alternative, the first step to minimizing impacts is to study the existing physical and biological conditions. This study does not necessarily require exhaustive efforts collecting data to serve as evidence of the existing condition. However, it does require a sufficient background research including acquisition of available relevant documents, mapping, and reports. Assessment of this material is paramount to understanding the past, current, and ongoing activities and processes occurring in the watershed. Once the office reconnaissance is complete, it is best to employ a multidisciplinary team of experts to perform a comprehensive analysis of the systems of concern. It is typical that following the field reconnaissance, additional data may be necessary to adequately understand the problem enough to evaluate and prescribe treatment alternatives. Observations made by the field team should produce converging lines of evidence. The collaborative efforts of experts should be documented to serve as guidance in determination of process and techniques to be utilized in minimizing impacts associated with dam removal.

Effective sediment management before, during, and after dam removal can dramatically minimize impacts to the downstream physical and biological systems. Sediment management may include impoundment dredging, dewatering and excavation, or phased removal of the structure. Dredging may be most desirable when pollutants or toxic constituents are present in the impounded water. Dredging operations allow for controlled removal of the sediment and minimize the dispersion of undesirable constituents. Dredged material may be slurried or trucked offsite to an area where controlled dewatering and drying may be performed.

Similar to dredging, but typically less expensive, dewatering and excavation are another form of sediment removal and are probably most applicable when water constituent quality is not an issue. Dewatering can easily be achieved by utilizing a form of controlled siphon to introduce stored water into the downstream system. One benefit of dewatering is that it allows for natural drying of accumulated bed materials, minimizing the costs associated with handling wet material. If necessary, the material can still be placed in a controlled environment for further drying and disposal. If the material is not contaminated, then it can be utilized in construction of the proposed channel/floodplain both upstream and downstream of the dam scheduled for removal.

Phased removal of the dam allows for controlled introduction of flow and sediment to the downstream system. This technique reduces the impacts associated with immediate removal and permits the system to adjust slowly to the revised conditions. Phased removal minimizes head-cut and scour development, minimizing the associated sediment loads.

Alternatives to dam removal. In cases where complete removal of a dam is not practical or acceptable alternatives to removal should be considered to achieve desired management objectives. For example, if the objective of fish passage is provoking consideration of dam removal and the existing impoundment serves practical and economic functions, then alternative fish passage techniques should be considered. One common and conventional technique is retrofitting the existing spillway with a fish ladder. Although the fish ladder requires maintenance, if properly designed, it can provide a hydraulic environment (depth and velocity) conducive to fish passage. Since a fish ladder is most practical in the case of a managed structure, the maintenance issue (cleanout and incidental repair) often can be incorporated into routine management activities. Careful consideration for this alternative includes an understanding of current and future operational discharge of the dam in the context of current and future contributions of the upstream watershed.

In the case where cost and risk of complete dam removal may exceed the level of comfort of the participants, partial dam removal should be considered as an alternative to restore discharge regime and/or incorporate fish passage. Partial dam removal can be as simple as incorporating new objectives into the management of the existing structure, or as complex as lowering or resizing the existing spillway. New management objectives may allow for removal or lowering the stage of the gate or other stage control structure. Like the fish ladder, this alternative does not accomplish stream restoration, however it may accommodate some of the needs of the downstream system, and if the modified stage and discharge through the gate is appropriate, some fish species with leaping or slithering capabilities may migrate upstream of the structure. More literally, partial dam removal may require the physical modification of a spillway to maintain sufficient discharge through the natural or constructed downstream channel to accommodate objectives, such as stream restoration and associated fish passage. Oftentimes, in order to maintain control of the hydraulics, the retrofit is connected to the downstream channel by way of a constructed feature such as a rock ramp, step-pool (Gilman 2004) or other nature-like fishway. Many of these features have demonstrated structural and ecological success

(American Rivers 2002). Retrofitting an existing structure includes the taking of a certain amount of risk and is not a technique to be taken lightly. Hydraulic engineers are needed in collaboration with natural scientists to ensure success of the retrofit.

In some cases, the endeavor to remove or retrofit a dam meets insurmountable obstacles and a more sophisticated compromise may be met by way of relocating the mainstem or flow-through channel. This approach essentially bypasses a minimum flow around the impounded reservoir, reconnecting the downstream channel with the upstream system using a more natural transition (Wildman et al. 2002). Though more complicated more difficult to promote, this technique satisfies both the dam manager's interest to maintain the dam, and the resource manager's interest to promote and restore a self-sustaining system.

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