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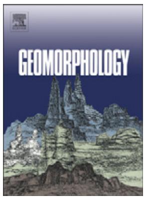

A comparison of past small dam removals in highly sediment-impacted systems in the U.S.

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ABSTRACT

The ability to predict the effects of dam removal in highly sediment-filled systems is increasingly important as the number of such dam removal cases continues to grow. The cost and potential impacts of dam removal are site-specific and can vary substantially depending on local conditions. Of specific concern in sediment-impacted removals is the volume and rate of reservoir deposit erosion. The complexity and potential accuracy of modeling methods used to forecast the effects of such dam removals vary substantially. Current methods range from predictions based on simple analysis of pre-dam channel geometry to sophisticated data-intensive, three-dimensional numerical models. In the work presented here, we utilize data collected from past dam removals to develop an additional tool for predicting the rate and volume of sediment deposit erosion. Through the analysis of sediment, discharge, deposit, removal timeline, channel, and watershed data, in conjunction with post-removal monitoring data from a wide range of dam removal projects, some significant trends in the evolution of reservoir deposits following dam removal can be seen. Results indicate that parameters such as median grain size, level of cohesion, spatial variability of the deposit, and removal timeline are among the most influential factors in determining the rate and volume of sediment erosion. By comparing local conditions of dams and reservoirs slated for removal with those of past removals, we hope that predictions of the rate and volume of sediment deposit erosion can be usefully constrained.

1. Introduction

There have been over 700 documented dam removals or decommissions in the past century (Gleick et al., 2009), with upwards of 350 such removals having occurred in the last decade (American Rivers, 2009). With dam removal continuing to increase in popularity and an inventory of over 80,000 registered dams in the United States (FEMA, 2009), there is a definite need for a set of reliable tools capable of predicting the geomorphic effects of the many dam removals to come. The potential geomorphic effects of dam removal are most extreme in situations where reservoirs have been substantially filled with deposited sediments that are then left to erode naturally via streamflow after removal. The fate of these deposited sediments following dam demolition is acknowledged as being the most poorly understood aspect of dam removal projects (Heinz Center, 2002; Stewart and Grant, 2005). There are numerous process-based models, conceptual (Doyle et al., 2002; Pizzuto, 2002) and numerical (Cui et al., 2006a, 2006b; Greimann and Huang, 2006; Langendoen, 2010), that have been developed over the past decade to predict the erosion and evolution of stored reservoir sediments following dam removal. However, comparison of model-generated predictions of deposit evolution following dam removal to actual post-removal monitoring data is quite rare. In studies where such testing of forecasts has been done, comparisons are made with only one or two removal cases. Most published dam removal studies deal specifically with the analysis of data gathered from individual removal projects. In a few instances, multiple removals have been monitored and compared in a single study (Doyle et al., 2003a; Wildman and MacBroom, 2005), and occasionally there has been some comparison of results from a new removal project with those of past removals (Riggsbee et al., 2007). However, in general there appears to be a significant lack of comparative analysis of post-removal monitoring data, particularly of the evolution of highly sediment-filled reservoirs following dam removal. Fortunately, as the number of independent case studies has grown over the past decade, so too has our ability to learn from, and make use of, the numerous data sets that are now available (Stewart and Grant, 2005; Kibler et al., 2010).

Included in the need for a broad comparison of currently available dam removal data sets is the need to test and validate some of the most basic concepts regarding which parameters are most influential in determining rates and volumes of streamflow-driven deposit erosion. Because of concerns over downstream channel and ecological impacts, stabilization of reservoir deposits, new channel development, and other issues (Grant, 2001; Heinz Center, 2002), a major

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question surrounding natural erosion of stored reservoir sediments is the volume, rate, and timing of their release following dam removal. Relatively accessible variables such as deposit geometry, sediment grain size and level of cohesion, and annual watershed sediment yield have long been suggested to have specific impacts on the erosional processes that determine the rate, volume, and form of deposit evolution (Harbor, 1993; Egan, 2001; Doyle et al., 2002; Pizzuto, 2002; Stewart and Grant, 2005). With the empirical support of the compiled data sets presented in this paper, we are able to identify the influence of specific parameters on the evolution of stored sediment deposits following dam removal.

2. Study sites

Although hundreds of dams have been removed within the last two decades, the results of only a surprisingly small percentage of these projects have been published. As of 2002, fewer than 5% of all removals had been published in the scientific literature (Hart et al., 2002). Of the few published studies available, there are even fewer that involve highly sediment-impacted systems. Furthermore, the amount and quality of post-removal monitoring data varies considerably from study to study.

Twelve small, highly sediment-impacted removal and failure case studies were determined to have a combination of sufficient, reliable, and compatible reservoir deposit erosion data sets such that they could be readily compared and analyzed. All data sets include a pre-removal deposit volume estimate and a minimum of one post-removal volume estimate. Published data were supplemented with inquiries to authors, project agencies, streamflow databases, and other sources. Fig. 1 shows the locations and Table 1 lists the specifics of the removal projects included in this analysis.

The study sites used in this analysis span from the West to the East Coast in primarily mesic watersheds in northern latitudes of the continental United States. Because the vast majority of dam removals to date have involved low head structures (Heinz Center, 2002), the database constructed in this study is dominated by such removals. The heights of the dams included range from 2 to 14 m, with a mean and median structure height of 4.2 and 3.4 m, respectively. As previously mentioned, in all cases included in this analysis the reservoirs were either filled with, or extremely impacted by, deposited sediments. An additional commonality between all selected studies is the inclusion of post-dam demolition data concerning sediment deposit evolution over time. These time series of deposit erosion allow for an analysis of changes in absolute volumes and rates of erosion with time.

3. Approach

Because of the relative infancy of the practice of dam removal, there has yet to be a well-developed set of case studies with which to test hypotheses and gain knowledge regarding the drivers of deposit evolution over time and under varying conditions. Conceptual predictions of deposit evolution have primarily come from two sources. Originally, analogies between dam removal and more fundamental fluvial geomorphological processes were made (Doyle et al., 2002, 2003a). Similarities between dam removal in sediment-impacted reservoirs and channel disturbance processes such as base level change, increased sediment supply, and channel incision have allowed for such comparisons (Doyle et al., 2003a). More recently, as removal studies have become more common, the direct analysis of local conditions and their influence on specific processes of deposit evolution has allowed for further development of concepts. Here we test the general applicability of some of these geomorphic process-based concepts, as well as concepts based on observations from several recent removal projects. The extent of applicability of these concepts is assessed using data from a wide range of dam removal cases with variable conditions. Specifically, we look at the influence of local variables on the rate and volume of deposit erosion.

Deposit evolution rates and processes are dependent on many factors, including the duration of time since dam removal. The length of monitoring time following dam removal varies significantly among the 12 cases studied. However, two-thirds of the studies contain monitoring data lasting longer than one year, and the average duration of data acquisition following removal is more than two years. Throughout the analysis we make the assumption that the final estimates available for the volume of eroded material for each study are generally representative of the long-term total volume to be eroded from the deposit. Although additional erosion is likely to have occurred after the last survey was made, available data suggest that for most cases included here the relative magnitude of such erosion is small. Three of the data sets contain observations of erosion volume beginning just after demolition and continuing regularly through the first year following removal. All three show a reduction of >96% in the rate of sediment erosion over the course of the year. This supports the assumption that, although some erosion will continue after the first year or two, the relative significance of additional erosion is

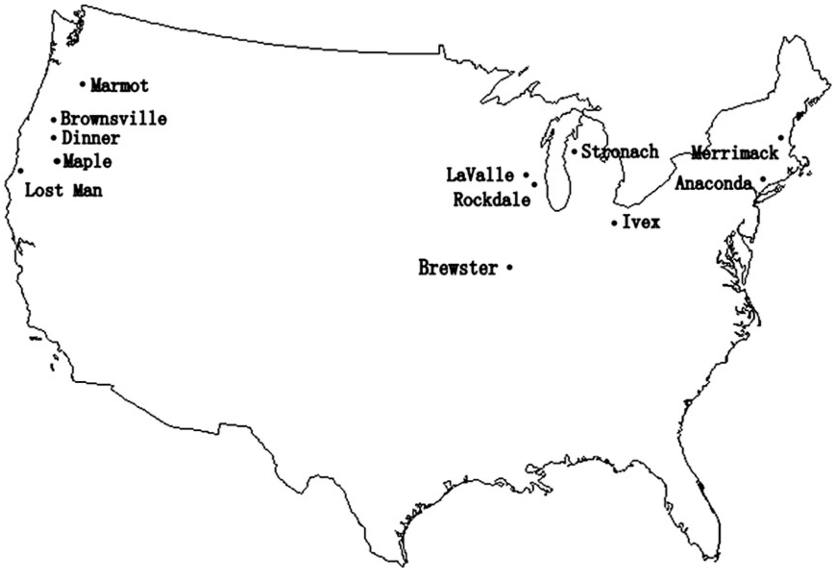

Fig. 1. Map showing locations of dam removal projects included in the study.

Table 1
Listing of dam removal case studies, locations, year of removal, dam height, deposit volume, watershed area, duration of data collection (period of erosion monitoring beginning at dam demolition, failure or first phase of staged removal), and primary sources.

Project title	Location	Removal year	Dam height [m]	Sediment volume [m^3]	Watershed area [km^2]	Duration of data collection [y]	Primary source
Anaconda	Naugatuck River, CT	1999	3.4	11,900	450	5.0	Wildman and MacBroom (2005)
Brewster	Brewster Creek, IL	2003–2004	2.4	17,849	36	3.3	Straub (2007)
Brownsville	Calapooia River, OR	2007	2.1	14,000	392	2.0	Walter and Tullos (2009)
Dinner	Dinner Creek, OR	2003	3.2	3000	21	0.9	Stewart (2006)
Ivex	Chagrin River, OH	1994 (failure)	7.4	236,000	88	0.2	Evans et al. (2000a, 2000b)
LaValle	Baraboo River, WI	2000	~2.0	140,100	575	1.1	Doyle et al. (2003a)
Lost Man	Lost Man Creek, CA	1989	2.1	2156	32	0.5	Ozaki (1991)
Maple	Maple Gulch, OR	2002	3.4	600	4	1.1	Stewart (2006)
Marmot	Sandy River, OR	2007	14.0	730,000	1300	2.0	Grant et al. (2008), Major et al. (2008)
Merrimack	Souhegan River, HN	2008	3.9	62,000	443	1.0	Pearson (2010)
Rockdale	Koshkonong River, WI	2000	3.3	396,000	360	0.9	Doyle et al. (2003a)
Stronach	Pine River, MI	1996–2003	3.6	789,428	686	10.0	Burroughs et al. (2009)

presumably minor when compared to the total from the first years following small dam removal (Doyle et al., 2005; Wells et al., 2007). Instances in which the first year following removal is characterized by exceptionally below average hydrologic events may be exceptions to this assumption. Additionally, the extension and application of this assumption to systems in more xeric environments not represented in the data set may be inappropriate.

4. Parameters

4.1. Sediment properties

In this section we look at the influence of sediment properties on the evolution of reservoir deposits. The primary sediment properties of interest are level of cohesion, consolidation, and grain size. The potential influences of sediment properties on deposit evolution are well documented (Egan, 2001; Pizzuto, 2002; Doyle et al., 2003a, 2003b; Stewart and Grant, 2005). The level of cohesion and grain size of sediments are directly connected to the erodibility of the material, including the dominant mechanisms and rates of erosion. The level of cohesion has a large influence on the critical bank height and the lateral migration of incising channels caused by bank instabilities (Osman and Thorne, 1988; Simon et al., 2002), as well as knickpoint migration (Brush and Wolman, 1960; Begin et al., 1981; Gardner, 1983; Pizzuto, 2002; Doyle et al., 2003a, 2003b). Other studies have shown that vertical layering of sediments can also have significant impacts on knickpoint processes (Robinson et al., 2000). It is not uncommon to observe such vertical stratification in reservoir deposits, and its role in deposit evolution must be considered as well.

To capture the effect of sediment properties, we broadly categorize the sediments of the 12 case studies texturally as gravels, sands, or fines (e.g., silts and clays, with grain sizes <sand) and as either cohesive or non-cohesive. Deposits with cohesive or consolidated sediments are classified together as “cohesive” as a measure of their resistance to erosion, whereas deposits with non-cohesive or unconsolidated sediments are classified together as “non-cohesive” representing a lesser degree of resistance to erosion relative to the “cohesive” deposits. We additionally categorize deposits as layered or nonlayered on the basis of the presence of significant stratification of the deposit sediments. A layered classification was given when widespread, easily detectable vertical layering of the deposit was identified in deposit profiles or photos provided, or was otherwise mentioned as noteworthy by authors. Many of the deposits exhibited a range of sediment properties. In such instances, when quantitative distributions of sediment properties were available the median value was used to represent the deposit. When only qualitative assessments of deposits were available, the listed dominant property was used to represent the deposit as a whole. For instance, grain size classifications are based on either the median grain size from distribution data provided, or from the otherwise listed most abundant grain size. The cohesion classification is based on study descriptions of the sediments and their degree of consolidation, cohesion, or lack thereof. Although not ideal, the broad range of sediment data detail provided in the case studies dictated the use of such qualitative measures.

Fig. 2A, B, C, and D illustrate the results from the analysis of the influence of sediment properties on deposit evolution. Fig. 2A highlights the effects of the level of cohesion on the percentage of total deposit volume eroded. Although there are other processes and conditions involved, what we can gather from the data available for the removals in this study is that deposits with primarily cohesive sediments typically retain a far greater percentage of their original volume than those of non-cohesive deposits. None of the three deposits composed of primarily cohesive sediments experienced >15% erosion of its volume. The possible reasons for this lack of erosion are many and varied. The high critical shear stresses of cohesive sediments (Vanoni, 2006), colonization of the deposit by riparian vegetation (Bennett and Simon, 2004), and the development of highly-erosion resistant dried and consolidated clays and muds (Partheniades, 2009), are all likely causes. Both Ivex and Brewster experienced rapid and extensive revegetation of deposits following removal. The Ivex study also notes rapid drying and consolidation of reservoir sediments following dam failure. These results are in agreement with past studies (Doyle et al., 2003a) and conceptual models (Pizzuto, 2002; Doyle et al., 2003a) that suggest cohesive or consolidated deposits will experience less erosion relative to non-cohesive or unconsolidated deposits. Additional differences in critical bank height and knickpoint form (discussed in following paragraphs) between cohesive and non-cohesive deposits have been hypothesized to be responsible for differences in deposit erosion processes (Pizzuto, 2002; Doyle et al., 2003a). The large range of eroded volume fractions seen in the non-cohesive case studies implies that in such deposits there are many additional factors responsible for determining rates and volumes of erosion. Because of correlations between grain size and cohesion, Fig. 2B, which shows the percentage of erosion vs. grain size, has similar trends as those in Fig. 2A. The average percentage of volume eroded for fine sediment deposits is 11% compared to 39% for deposits composed of sands and gravels.

Fig. 2C demonstrates the influence of cohesion and deposit stratification on the efficiency with which a deposit is eroded. Deposits classified as layered were plotted as such, and non-layered deposits were classified as either “cohesive” or “non-cohesive” following the conventions discussed earlier. We have defined erosional efficiency (Eq. (1)) as a dimensionless parameter representing the ratio of the

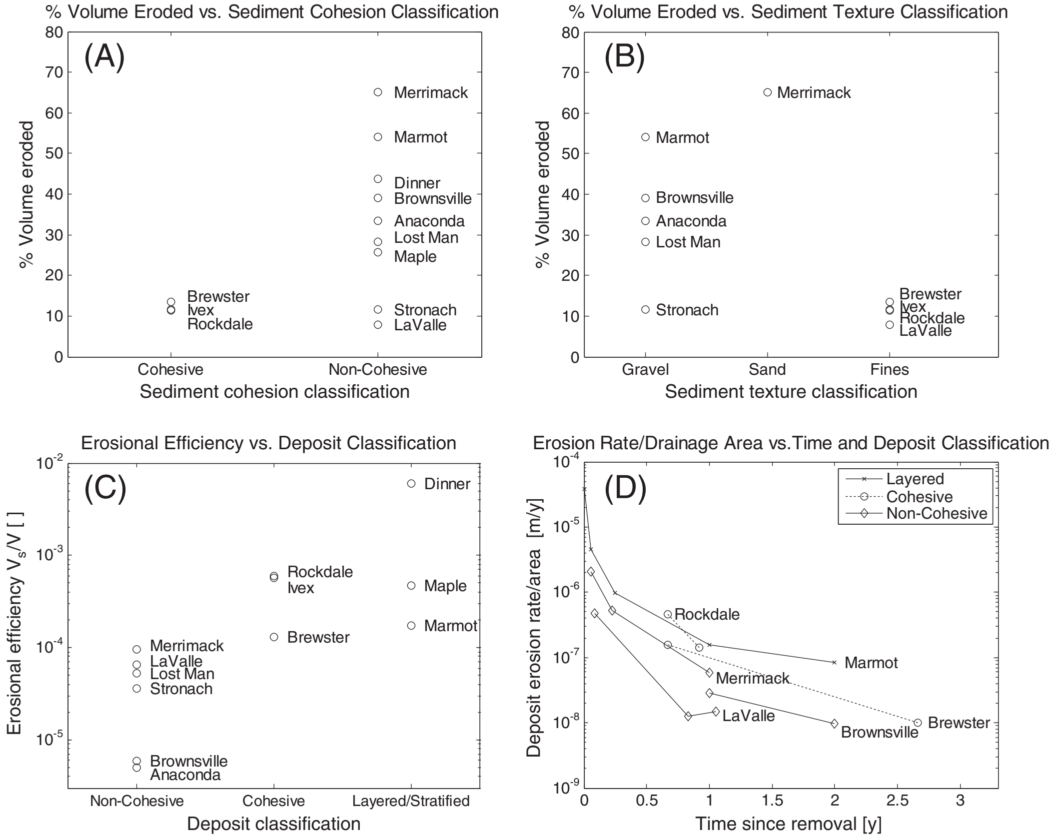

Fig. 2. Relationships between sediment deposit classifications and erosion statistics. (A) Level of cohesion vs. percentage of deposit eroded; (B) sediment texture vs. percentage of deposit eroded; (C) sediment deposit classification vs. erosional efficiency; (D) deposit erosion rates over time normalized by drainage area for layered, cohesive, and non-cohesive deposits.

volume of sediment eroded during a specific time interval to the total volume of streamflow passing though the system during the same interval:

$$\mathit{Erosional\ efficiency} = \frac{V_{\mathrm{sediment}}}{V_{\mathrm{streamflow}}} \qquad (1)$$

Controls on how much and how efficiently sediment is removed from a deposit are obvious management concerns. Comparison of this measure of erosional efficiency with deposit characteristics gives insight into the conditions under which the most sediment can be eroded per unit of streamflow. Fig. 2C demonstrates that layered or cohesive deposits result, on average, in one to two orders of magnitude greater efficiency of stored material removal. The primary cause for this division is likely because of differences in knickpoint form and migration rate between the three groups. Because of differing definitions of headcut and knickpoint used in the case studies, photographs, longitudinal profiles, and descriptions by authors were instead used when available to classify these erosional fronts as either nonstepped or stepped knickpoints (headcuts). Significantly layered or cohesive deposits typically have been shown to produce a stepped knickpoint, or headcut, following a base level lowering event such as dam removal (Pizzuto, 2002; Doyle et al., 2003a; Stewart, 2006; Straub, 2007). Non-cohesive nonlayered sediments that experience a similar base level lowering are more likely to form a nonstepped knickpoint (Brush and Wolman, 1960; Doyle et al., 2003a). The studies presented here tend to support these concepts. All cohesive or layered deposits (Brewster, Dinner, Ivex, Marmot, Maple, Rockdale) experienced stepped knickpoints at sometime during their evolution, while 3 (Anaconda, Brownsville, LaValle) out of 4 non-cohesive nonlayered deposits from studies containing sufficient documentation experienced nonstepped knickpoints. Direct comparison of migration rate and sediment yield between stepped and nonstepped knickpoints is difficult because of the varying conditions under which they occur. However, based on the data presented here in the context of dam-removal-induced knickpoint formation, stepped knickpoints apparently erode substantially more material per unit of streamflow than nonstepped knickpoints.

Fig. 2D illustrates differences in erosion rates with time based on deposit classification. The figure includes only data sets with more than one survey following dam demolition and excludes Maple and Dinner because of their highly variable erosion rates, dependent on infrequent individual large precipitation events. Erosion rates have been normalized by drainage area to allow for better comparison between the sites. The results mirror those of Fig. 2C, where likely due to differences in knickpoint form, layered or cohesive deposits (stepped knickpoints) tend to exhibit elevated erosion rates relative to those of non-cohesive nonlayered deposits (nonstepped knickpoints).

4.2. Deposit geometry

In this section we look at the influence of deposit geometry on the evolution of sediment deposits. The primary properties of interest are the depth and average width of the system. Deposit depth has the potential to influence erosion rates through connections with critical sediment height and bank stability, as well as knickpoint form (Pizzuto, 2002). Others have speculated that the width of the deposit and the ratio of the deposit width to the upstream-of-reservoir or pre-dam channel width could be used as a measure of the ability of the stream to access and erode the deposit (Randle et al., 1996; Morris and Fan, 1997; Heinz Center, 2002).

Data for this analysis were collected from cross-sectional profiles, estimations from aerial photographs, descriptions of study sites, and discussions with authors. For deposit width, average values of deposit and stream width, pre-dam or upstream of deposit, were used when available. Complex deposit shapes required a greater detail of width estimates from cross-sectional profiles and aerial photographs in order to accurately calculate a representative average width. For deposit depth, the maximum value reported, typically near the dam, was used.

Fig. 3A and B illustrate the results from the analysis of the influence of sediment deposit geometry on deposit evolution. Based on Fig. 3A, the percentage of volume eroded appears unrelated to deposit depth. The minimal variability in deposit depths, along with the relatively small absolute depths of deposits may be responsible for reducing the influence of this parameter on erosional processes. Deposit depth undoubtedly has an effect on the evolution process but, based on the data currently available, other parameters apparently are more influential in driving the erosional processes from small dam removals. Deposit depth may be a more influential driver of erosion in larger dam removals with greater deposit depths. Fig. 3B demonstrates a noteworthy connection between the deposit width to channel width ratio and the percent volume eroded. Of the cases in which the width ratio is greater than ~2.5, none of the deposits lost more than 15% of their original volume to erosion. There are a number of possible explanations for why this width ratio may have such an influence on erosion, including issues of both access to and retention of material. Although the developing channel within the reservoir deposit following dam removal will not be exactly the same width as upstream or historical pre-dam channels, it is likely to have a similar dimension such that comparisons between the two can be made for estimation purposes. In cases where the deposit is much wider than the incoming and developing channel, it is unlikely that the new channel will laterally erode or migrate across the full extent of the deposit width (Randle et al., 1996; Heinz Center, 2002). As a consequence of this lack of access to the full deposit, sediment not immediately eroded can dry and consolidate as well as be colonized by vegetation, both of which increase the shear strength of the material (Morris and Fan, 1997; Heinz Center, 2002). It should be noted that of the 5 deposits with width ratios > ~2.5 and volumes of erosion < 15%, 3 are classified as cohesive and 2 as non-cohesive. The combined effects of width ratio and sediment classification on the volume of erosion are discussed in Section 4.5.

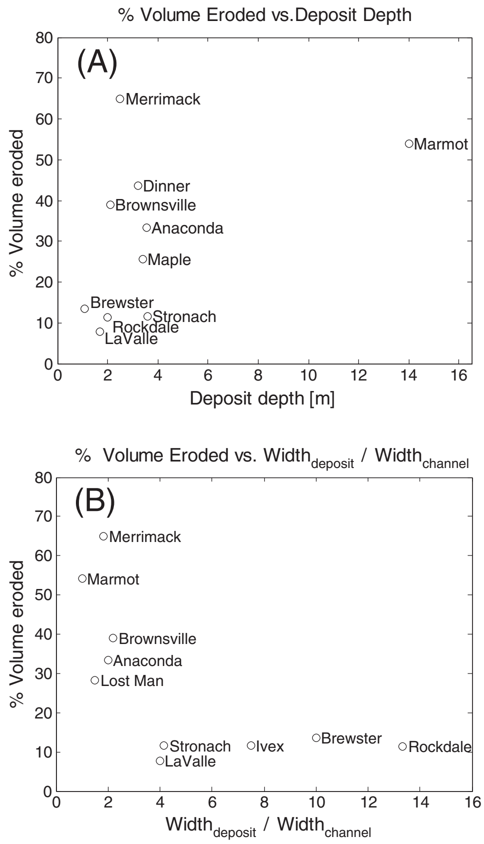

Fig. 3. Relationships between deposit geometry and the percentage of volume eroded. (A) Deposit depth vs. the percentage of volume eroded; (B) the ratio of deposit width to channel width vs. the percentage of volume eroded.

4.3. Watershed and channel characteristics

In this section we look at the influence of watershed and local channel properties on the evolution of sediment deposits. These properties range from basinwide annual sediment yields to local bed slopes. As drivers of sediment erosion, local bed slope, peak flowrates, and average flowrates have been theorized to play an important role in governing new channel development and deposit erosion (Egan, 2001; Doyle et al., 2002; Pizzuto, 2002; Stewart and Grant, 2005). The ratio of annual watershed sediment yield to the volume of sediment stored within a reservoir deposit has been described as a potential indicator of the level of disturbance associated with dam removal (Heinz Center, 2002; MacBroom and Loehmann, 2008). This ratio is thought to reflect a stream's ability to erode and transport reservoir sediments through the stream system. We therefore examine the relationship between annual watershed sediment yield and the rate of deposit erosion.

Data for this analysis were collected from a wide range of sources. Flow data were obtained directly from published studies or via the USGS streamflow database. Bed slope values were obtained directly from studies or were estimated based on longitudinal and cross-sectional profiles provided. Estimates of annual sediment yield upstream from reservoir sites were acquired directly from removal studies and from additional studies on sediment production for the specific catchment or similar nearby watersheds. Watershed sediment yield estimates are based on bedload, suspended load, total load and reservoir trapping data. Although sediment yield estimate methods vary between study sites, each is assumed appropriate given the primary sediment classifications of the individual sites. For instance, suspended load based watershed yields are used only when deposits are composed predominantly of fines, and bedload based estimates are used only with deposits dominated by sand or larger grain sizes (Table 2).

Thus far we have primarily compared local parameters with the percentage of deposit volume eroded. An additional means of assessing the evolution of sediment deposits is through the calculation of erosion rates and how they change over time. For the removals considered here, comparisons of rates of erosion with average discharge and watershed area indicate positive correlations. These expected trends are attributed to increases in the erosional ability associated with increases in discharge. Conversely, no such connections are apparent between the percentage of volume eroded and peak or average discharge. This is attributed to the highly variable deposit volumes of the studies. Although erosion rates among a set of studies may correlate well with discharge, because of differences in absolute deposit volumes, the same trend does not follow for percentage of volume eroded. Additionally, the ratio of peak discharge to mean discharge does not indicate a correlation with percentage of volume eroded, efficiency, or rate of erosion. Comparisons of bed slopes with erosion statistics – including the volume, rate, and efficiency of erosion – do not show any significant trends either. One might expect increased rates of erosion with increased values of reach bed slope, but the data do not support this conclusion. This is attributed to the difficulty in obtaining reliable bed slope measurements

Table 2
Annual watershed sediment yield estimates, including type of load, method of estimation, primary data sources and deposit classification.

Project title	Deposit sediment classification	Watershed sediment yield [m^3/y]	Type of load	Method of estimation	Primary source
Brewster	Fines	3896	Suspended sed. load	Regional studies	Bonini et al. (1983), Bhowmik et al. (1986)
LaValle	Fines	65,714	Total load	Regional studies	Hindall, 1976; Trimble, 1983
Lost Man	Gravel	229	Bedload	Measurement	Ozaki (1991)
Marmot	Gravel	100,000	Bedload	Regional studies, measurement	Major et al. (in press)
Merrimack	Sand	3840	Total load	Reservoir trapping	Pearson (2010)
Stronach	Gravel	28,000	Total load	Measurement	Hansen (1971)

capable of representing the system as a whole and to the fact that the influence of a single parameter cannot always be identified in such complex systems.

Fig. 4 displays the relationship between annual watershed sediment yield and erosion rate of the deposits. Erosion values used in this analysis are limited to data representing cumulative erosion for times greater than six months, but primarily less than two years after the removal date. We think that this provides the best estimate of the average annual sediment erosion volume during the most active first year or two following removal and that it is the most appropriate statistic for comparison with the annual watershed sediment yield. All of the reservoir–stream–watershed systems included in this analysis experience significant rates of production and transport of sediment, thus resulting in the filling of reservoirs. If we make the assumption that these systems are transport limited, then we can take the watershed sediment yield as a measure of a system's ability to transport sediment. The similar drivers of the transport of sediment through a stream system and the erosion of a reservoir deposit suggests that measures of these two processes should be related. Indeed, Fig. 4 illustrates that annual watershed sediment yield appears to provide a satisfactory approximation of the annual sediment deposit erosion rate. Deviations from a linear log–log relationship are less than one order of magnitude. This suggests that when appropriate watershed sediment yield data are available they can be used as a broad estimate of the sediment deposit erosion rate to within an order of magnitude for the initial years following removal.

4.4. Dam removal timeline

In this section we look at the impacts the timeline of dam removal can have on the erosion and evolution of reservoir sediment deposits. We categorize the timeline of dam removal based on the time required for complete removal of the structure. Removals are considered to be either a staged process, taking on the order of months or years to gradually lower the height of the structure, or nonstaged, in which case the structure is removed in one phase. We have also included one removal case in which a grade control structure was placed at the site of the removed dam (LaValle). Because of the similarities in the effects on base level change and erosion, the grade control structure case has been categorized as a staged removal method. Conceptual models and a limited set of past studies have indicated that the effects of the rate and method of dam demolition on deposit erosion can be numerous (Harbor, 1993; Pizzuto, 2002; Doyle et al., 2003a; MacBroom and Loehmann, 2008). Staged removal has the potential to allow for the stabilization of exposed deposit sediments and thus reduces the likelihood of their eventual erosion. Stabilization of the deposit can be from drying and consolidation of exposed reservoir sediments (Heinz Center, 2002; Pizzuto, 2002), as well as colonization by riparian vegetation (Heinz Center, 2002; Doyle et al., 2003a). In addition, the form, step size, and rate of migration of the knickpoint that develops following dam demolition are directly related to the degree of base level change induced by dam removal (Leopold et al., 1964; Holland and Pickup, 1976; Begin et al., 1981; Robinson et al., 2000). Staged removals inherently reduce the rate of base level change associated with dam removal when compared to single phase removals. In cohesive or consolidated sediments, implementation of a staged rather than single phase removal can consequently reduce the step height, rate of migration, and sediment production of stepped knickpoints (headcuts) that develop (Robinson et al., 2000). Similarly, bank heights of incising channels within the deposit can be controlled by the degree of base level change. If the base level change and resulting channel bank heights are less than the material's critical height, channel widening may be limited resulting in less erosion of the deposit (Pizzuto, 2002; Doyle et al., 2003a).

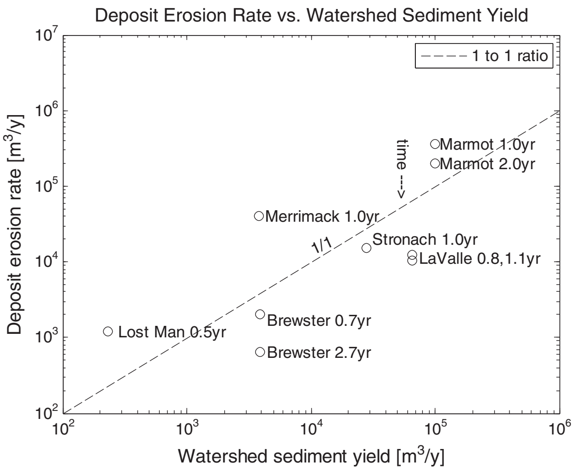

Fig. 4. Relationship between annual watershed sediment yield from the area upstream of the dam and the rate of sediment deposit erosion following dam removal.

Fig. 5A and B demonstrate the reduction in sediment volume erosion attributed to staged dam removal compared to nonstaged removal. The figures show that, in general, markedly less sediment is eroded from reservoir deposits that experience staged removal versus those that undergo immediate dam demolition. Fig. 5B demonstrates that, over time, the relative volumes of erosion are significantly less in systems that have staged dam removals. The average percentage of volume eroded for nonstaged cases is greater than three times that for staged cases (35% vs. 11%). Of the staged removals considered, none released more than 14% of its original deposit volume as of last survey. These results support conceptual models and past studies suggesting reductions in sediment deposit erosion of staged removals relative to nonstaged ones due to consolidation and colonization of deposits, and reductions in incising channel bank heights (Harbor, 1993; Pizzuto, 2002; Doyle et al., 2003a).

4.5. Parameter combinations and interactions

While single predictor variables reveal relationships with reservoir deposit evolution following dam removal, in such multifaceted systems dependencies are much more likely to be multivariate than univariate. It is often the interaction of two or more variables that best captures the processes that control the erosion of reservoir deposits. Other workers have often discussed the role interactions of

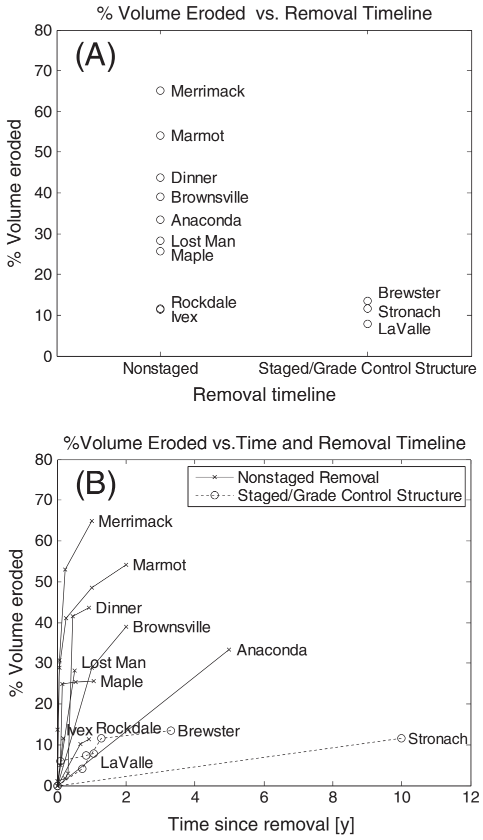

Fig. 5. Relationships between the timeline of dam removal and deposit erosion statistics. (A) Dam removal timeline vs. the percentage of volume eroded; (B) the percentage of volume eroded over time for both staged and nonstaged removals.

two or more variables have on deposit evolution (Egan, 2001; Pizzuto, 2002; Doyle et al., 2003a; Stewart and Grant, 2005). In this section, we discuss the role of interactions between parameters and the effects of specific combinations of parameters on deposit erosion.

Fig. 6A highlights the joint control that both sediment texture and removal timeline can have on the relative volume of deposit erosion. All staged removal cases and those in which deposit sediments are classified as fines retained >85% of their original deposit volume as of last survey. The combination of potentially high critical shear stresses associated with cohesive fine sediments and reduced erosional power attributed to staged dam removal are likely responsible for this trend (Pizzuto, 2002; Doyle et al., 2003a). Fig. 6B shows the combined importance of sediment texture and the deposit width to channel width ratio in determining the percent volume of erosion. Systems with fine sediments and/or width ratios > ~2.5 show a retention of >85% of their original sediment volume. The potential low erodibility of fine sediment deposits combined with the limited access of streamflow to erode deposits associated with high deposit to channel width ratios possibly explains this trend. Lastly, Fig. 6C shows a connection between local bed slope, the deposit to channel width ratio, and the percentage of volume eroded. The ratio of bed slope to width ratio is nondimensional and can be thought of as a measure of the relationship between a stream's ability to erode a deposit and its access to the entire deposit. In situations with a small bed slope and high deposit to channel width ratio, the likelihood is poor that a great deal of the deposit will be eroded. Conversely, in situations with a large bed slope and low deposit-to-channel-width ratio, there is an increased likelihood of significant deposit erosion.

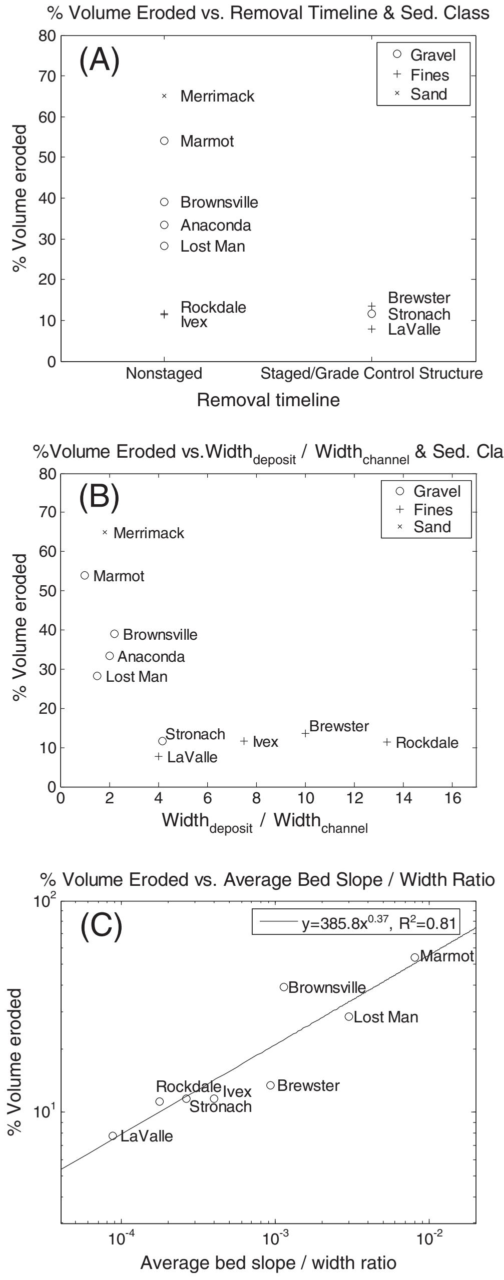

Fig. 6. Combined effects of multiple parameters on the percentage of volume eroded. (A) The influence of both removal timeline and sediment deposit texture classification on the percentage of volume eroded; (B) the influence of both the deposit to channel width ratio and sediment deposit texture classification on the percentage of volume eroded; (C) the ratio of average bed slope to the deposit to channel width ratio vs. the percentage of volume eroded.

5. Summary and conclusions

We have attempted to identify and validate the potential influences that specific parameters have on the relative rates and volumes of reservoir deposit erosion following small dam removal. Through the compilation of 12 case studies of primarily low head dam removal projects in northern latitudes of the continental U.S., we have assembled a data set that allows for the direct comparison of the results of the individual removals. An analysis of this data set supports some previous notions as well as some new ideas concerning the role certain parameters, individually or in combination, have on sediment deposit evolution.

For the studies meeting our criteria for inclusion, deposits composed of predominantly fine and cohesive or consolidated sediments have a significant tendency to retain upwards of 85% of their original deposit volume following dam removal. Conversely, non-cohesive or unconsolidated deposits classified as either sands or gravels do not show such a common trend. These results are in agreement with the work of Pizzuto (2002) and Doyle et al. (2003a) that suggest cohesive or consolidated deposits should experience less erosion relative to non-cohesive or unconsolidated deposits due to differences in critical bank height, drying induced consolidation and strengthening of exposed sediments, and knickpoint form. The efficiency with which a deposit erodes was demonstrated to be dependent on the sediment texture as well as the structure of the deposit. Likely because of their propensity to produce actively eroding and migrating stepped knickpoints (headcuts), cohesive and layered deposits have average erosional efficiencies nearly two orders of magnitude greater than that of nonlayered non-cohesive deposits. All cohesive, consolidated, or layered deposits experienced stepped knickpoints (headcuts) at some point during the evolution process, whereas nonlayered, non-cohesive or unconsolidated deposits tended to result in non-stepped knickpoints. Consequently, area normalized erosion rates follow the same trend as erosional efficiency, with layered, cohesive or consolidated deposits exhibiting higher rates than nonlayered, non-cohesive or unconsolidated deposits. High ratios of average deposit width to channel width were also shown to reduce the relative percentage of deposit volume eroded. For cases in which the width ratio was $> \sim 2.5$, the maximum percent volume eroded was $<15\%$ the original deposit volume. These results support conceptual work presented by Randle et al. (1996) and Morris and Fan (1997) suggesting that high width ratios result in a reduced ability of the system to access and erode the deposit, in addition to an increase in colonization and stabilization of exposed material by vegetation. No connections were found between the percentage of deposit eroded and deposit height or discharge statistics (mean, peak, ratio of peak to mean). When reliable annual sediment yield values are available, they may provide rough estimates of the rate of deposit erosion in the first few years following dam removal. When considering monitoring data only for times >6 months after removal, we see that all comparisons of annual watershed sediment yield and deposit erosion rates are within one order of magnitude of each other. The data presented here also suggest a strong correlation between removal timeline and the percentage of volume eroded. Of the three case studies with either staged removal or the implementation of a grade control structure, none lost more than 15% of their volume. These results coincide with conceptual models presented by Harbor (1993), Pizzuto (2002), and Doyle et al. (2003a) suggesting reduced relative erosion in staged removals due to reduced incising channel heights and increased exposure, consolidation, and vegetation colonization of deposit material. The combination of fine or cohesive sediment deposits with either staged removal methods or high width ratios was shown to result in significantly reduced relative erosion volumes. Lastly, the bed slope to widths ratio was demonstrated to be a very good indicator of the relative percent volume of erosion across a range of deposit texture and cohesion classifications.

Although the analysis of the 12 studies included here has been revealing, future well-documented removal projects are necessary to further elucidate the influence of parameters such as those developed here on reservoir deposit erosion. A larger database of more quantitative data sets is needed to better evaluate statistically the influence of variables on deposit evolution. The majority of the results reported here support conceptual models of the impacts that fine and cohesive sediments, layered deposits, removal timeline, and high deposit to channel width ratios may have on deposit evolution following low head dam removal. Conversely, case studies involving coarse and non-cohesive sediments, low deposit to channel width ratios, and nonstaged removals typically did not exhibit significant consistencies in their erosion rates and relative volumes. This lack of coherence suggests that these are complicated multifaceted systems with many parameters capable of influencing the evolution of reservoir deposits. Combined variables such as the bed slope to widths ratio presented here exhibit good agreement across a wide spectrum of removal cases and may be the key to establishing reliable parameters capable of predicting deposit evolution for dam removal projects in the future.

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