Rates and processes of channel response to dam removal with a sand-filled impoundment

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Received 7 July 2010; revised 6 June 2011; accepted 13 June 2011; published 4 August 2011.

[1] Dam removal projects are playing an increasingly important role in stream restoration, and offer unparalleled opportunities to study sediment dynamics following disturbance. We used the removal of the ~4-m high Merrimack Village Dam (MVD) on the Souhegan River in southern New Hampshire to measure processes and rates of channel evolution in a sand-filled impoundment. From 2007 to 2010, we repeatedly surveyed 11 cross sections and the longitudinal profile, and collected sediment samples to measure changes in channel morphology and bed texture. The dam removal in August 2008 resulted in a nearly instantaneous base level drop of 3.9 m and caused a two-phased channel response. The initial, process-driven phase (2 months) was characterized by rapid incision and removal of the impounded sand (up to 1013 t d−1), followed by channel widening. Once incised to base level, the rate of sediment removal slowed (30.7 t d−1) and adjustments became event-driven, and the former impoundment segmented into a nonalluvial section and an alluvial section with erosion and deposition influenced by vegetation on the channel banks. Two years after the dam removal and two high-magnitude floods, the river has excavated 79% of the original sediment. Continued response will be substantially influenced by the establishment of bank vegetation within the former impoundment and the magnitude and frequency of high discharge events. Initial channel development and sediment erosion occurs rapidly (weeks to months) in sand-filled impoundments, but excavation of the remaining sediment occurs more slowly depending on vegetation feedbacks and flood events.


1. Introduction

[2] Many small dams throughout the United States, and especially in New England, are old, and a growing number of these aging small dams are physically deteriorating, at risk of failure, and are no longer economically viable. Doyle et al. [2003b] estimated that 85% of dams in the U.S. will be near the end of their operational lives by 2020. These factors, along with mandates to improve fish passage when some dams are repaired or rebuilt, can often make dam removal cheaper than continued operation and/or maintenance [Doyle et al., 2003b]. This has prompted many dam owners to consider dam removal, and this option is playing an increasingly larger role in river restoration [e.g., Hart et al., 2002; Doyle et al., 2003a, 2003b; Collins et al., 2007; Marks, 2007]. However, Hart et al. [2002] report that only 5% of the more than 450 dams removed in the twentieth century were accompanied by published ecological studies, underscoring the largely unknown effects of dam removal on river systems.

[3] Channel response rates in reaches upstream and downstream from a dam removal project have important consequences for engineering, ecological, recreation, and/or esthetic objectives. Project proponents are often interested in passive sediment management (i.e., sediment release rather than dredging) in impoundments with unpolluted sediments for a variety of economic and ecological reasons. Yet, the timescales required to develop a quasi-stable channel in the former impoundment, and to remobilize sediment delivered to the downstream reach, are not well quantified [Doyle et al., 2002; Pizzuto, 2002]. Thus, the duration of sediment impacts to downstream reaches is also unknown. Some researchers have studied dam failures, where preremoval data are typically unavailable [e.g., Walter and Merritts, 2008]. A number of recent studies document response rates and processes both within impoundments and in downstream reaches [e.g., Doyle et al., 2003a; Major et al., 2008, 2010], although relatively few of them include substantial preproject quantification of impoundment morphology and sediment storage. In this contribution, we use extensive surveys taken before, during, and after dam removal to quantify rates of channel development and sediment flux in, and downstream from, a sand-filled impoundment.

[4] Beyond their importance for guiding future projects, dam removal studies present excellent opportunities to study channel response to a major change in sediment load (similar
to that caused by mining, volcanic eruptions, or landslides), a classic problem in fluvial geomorphology [e.g., Gilbert, 1917; Graf, 1977; James, 1999]. Doyle et al. [2002] and Pizzuto [2002] evaluated the channel evolution model and sediment-wave literature to provide guidance for expected rates and processes of channel response to dam removal. We can now begin to turn this approach around: with high-resolution pre-and postremoval surveys, dam removal projects provide unparalleled opportunities to test and refine conceptual channel evolution models with well-constrained boundary conditions at the field scale [e.g., Schumm et al. 1984; Simon and Hupp, 1987; Thorne, 1999]. Further, we can measure rates of response with much greater precision, allowing us to test classic models for sediment yield after disturbance [e.g., Graf, 1977].

Pizzuto [2002] provided a conceptual framework for studying channel response to dam removal. He hypothesized that channel incision causes bank instability and eventual collapse into the channel. The bank sediment is then reworked into floodplains and eventually causes the formation of a quasi-equilibrium channel where sediment inputs are comparable to outputs. He postulated that this sequence requires at least a decade. Pizzuto [2002] also discussed how incision of the impounded sediments should vary on the basis of the grain size of the sediments: gravel-dominated impoundments could only be incised during high-flow events capable of mobilizing the coarse bed, while finer impoundments erode via various processes not inherently dependent on high discharge (e.g., bed form and suspended-load transport, knickpoint retreat, groundwater sapping, mass wasting, liquefaction, etc.). For this reason, Pizzuto [2002] categorized gravel-filled impoundments as “event-driven” and explicitly contrasted them with “process-driven” sand- and mud-dominated impoundments.

Walter and Merritts [2008] studied sediments deposited behind colonial-era mill dams breached during the past 100 years in the Pennsylvania Piedmont. They suggest that once a dam is removed from a river, the channel incises into the impounded or “legacy” sediments and then begins to widen. They found that bank erosion rates are as much as 0.05 m yr⁻¹ on many stream reaches upstream of twentieth-century dam breaches, indicating a persistence of legacy deposits and a long-lived influence of dams on channel morphology. Modern dam removals provide well-controlled cases to better quantify the timescales over which we should expect legacy sediments to remain in valley bottoms.

Two recent, well-studied, controlled dam removals in different settings offer new insights into how streams physically respond to these changes [Doyle et al., 2003a; Major et al., 2008, 2010]. Doyle et al. [2002] hypothesized that earlier channel evolution models proposed by Schumm et al. [1984], Simon and Hupp [1987], and Thorne [1999] to describe channel response to disturbance, specifically base level lowering, would be applicable to dam removal. The Doyle et al. [2003a] study of two Wisconsin dam removals largely confirmed this and they suggested a conceptual model modified modestly from the earlier ones that is applicable to fine-grained, alluvial systems like those they studied. Major et al. [2008, 2010] studied channel response to dam removal in a high-gradient river (a slope of 0.006–0.009) with an impoundment dominated by sand and gravel.

Here, we study a sand-filled impoundment in a physiographic and geologic setting not well represented to date in the dam-removal literature. We quantify the geomorphic response rates of both the upstream and downstream reaches of the Souhegan River in southern New Hampshire after removal of the Merrimack Village Dam (MVD) and release of impounded sands by (1) documenting morphologic changes via cross section and longitudinal profile resurveys, (2) measuring bed sediment grain size changes, and (3) calculating a sediment budget before, during, and after the removal to measure response rates. Using these data, we investigate how hydrology, geology, and vegetation influence observed processes and rates of channel response. At our field site, we document a rapid, process-driven response over the first 2 months after the dam removal, followed by a slower, event-driven response over the next 2 years.

2. Study Area

The Souhegan River watershed is situated in southern New Hampshire (Figure 1), a landscape underlain by Paleozoic metamorphic and igneous bedrock and sculpted by Quaternary glaciations. The sediment moving in the river comes from a variety of sources including: erosion of glacial and fluvial deposits; sand spread on roads during winter; construction sites; unpaved roads and other anthropogenic sources; weathering; and erosion of bedrock in the river. Our Souhegan River study area extends from the Everett Turnpike Bridge for ~1 km downstream to the confluence with the Merrimack River (Figure 1). The Route 3 bridge is situated just downstream from the former MVD site. At this location, the river drains 568 km². The study area has two major parts characterized by 12 monumented cross sections (Figure 1).

2.1. Merrimack Village Dam

The MVD, built on the Souhegan River in Merrimack, New Hampshire in 1907 [Gomez and Sullivan Engineers, 2004] was a run-of-river hydropower dam (Figure 2a). It was located on the site of a gristmill and saw mill likely constructed in 1734 (New Hampshire Division of Historical Resources (NHDHR), Area from Merrimack Village historic area, pp. 111, 2006). The area upstream of the MVD includes the former impoundment (the main channel and adjacent floodplain and terraces; cross sections MVD02 through MVD08), an off-channel wetland influenced by the former dam (included in cross section MVD07), and a bedrock reach upstream of the former impoundment under the Everett Turnpike Bridge (reference cross section MVD01). The downstream part of the study area, from the former MVD to the railroad bridge at the confluence of the Souhegan and Merrimack rivers, includes a steep bedrock reach (a slope of 0.2) that extends from the former dam to ~0.1 km downstream from the Route 3 bridge. Below this is a sand-bedded alluvial reach (including cross sections MVD09 through MVD12), with a gradient of 0.0006 prior to the dam removal. We did not characterize the bedrock reach below the former dam location because no sediment is stored there, even over short time intervals.

Pennichuck Water Works (PWW), a public water supplier in Merrimack, NH, purchased the MVD in 1964 to...
serve as a water storage site. However, the impoundment was never used for this purpose [Gomez and Sullivan Engineers, 2004]. In January 2004, PWW was issued a Letter of Deficiency (LOD) by the New Hampshire Department of Environmental Services (NHDES) Dam Bureau because the MVD failed to meet several dam safety criteria. The LOD prompted the PWW to consider removing the dam to avoid costly repairs and ongoing maintenance of a dam they did not use [Gomez and Sullivan Engineers, 2004]. The dam was removed in August and September 2008 (Figure 2). Removal started with an initial controlled breach (Figure 2b) on 6 August and then progressed in stages from the left to the right bank (defined with respect to the downstream direction) over the next few weeks.

Uncertainty about the early history (pre-1907) of dam construction at the MVD site means the full extent of the reservoir deposit and the exact location of the prehistoric river channel are unknown. Erosion of impounded sand during high flows in March 2010 exposed in-place tree stumps along the left (north) side of the former impoundment, suggesting that the Souhegan River channel was approximately in its present position before the earliest dam construction at the site. Evidence including aerial photographs available starting in 1952, oblique aerial photographs from circa 1936, historic maps and documentation (NHDES, from the Merrimack Village historic area, pp. 111, 2006), cultural features exposed at the base of the impounded wetland stratigraphy, and flood-chute deposition at the southwest (upstream) end of the wetland suggest that the total area influenced by dam-induced accretion is larger than the modern impoundment (Figures 1 and 3). We therefore recognize two distinct areas influenced by dams at the site: (1) the total area of dam-induced accretion (Figure 3, green area) and (2) the modern (post-1907) MVD impoundment (Figure 3, pink area). We focused on the modern MVD impoundment that includes only the main channel, midchannel islands, and adjacent floodplain because this was the area expected to be accessible to streamflow postproject.

Gomez and Sullivan Engineers [2006] estimated that the modern impoundment contained 62,000 m³ of sediment, primarily sand-sized, of which ~67% would be mobilized after removal. These estimates were made by (1) measuring the depth of sediment every 3–6 m along seven

![Image](image-url)
transects across the impoundment (by driving a steel rod from the top of the sediment deposit to refusal); (2) multiplying average depths at these transects by the areas they represent and summing to estimate the total volume; and (3) assuming a postproject bankfull channel width and depth of incision through the stored sediment volume. In a companion study to this one, Santaniello et al. [2011] used ground-penetrating radar surveys of the MVD impoundment to estimate that it contained 66,900 m$^3$ of sediment, which closely matches the preproject estimate of Gomez and Sullivan Engineers [2006].

2.2. Hydrology

[14] The United States Geological Survey (USGS) operates gauging stations on both the Souhegan and Merrimack rivers (Figure 1). The Souhegan River gauge is ~1 km upstream of the study area and has been operating since 1909 with a nearly continuous peak streamflow record over that period. The closest gauging station on the Merrimack River is upstream near Goff's Falls, below Manchester, NH, and has been operating since 1936. We use these records to provide context for our study of channel evolution from 2007–2010 (Figure 4).

[15] The Souhegan River stage downstream from the Route 3 bridge is partially controlled by the stage of the Merrimack River (Figures 1 and 4). As the Merrimack River rises, it backwaters the lower Souhegan River, acting as a hydraulic dam and reducing competence in the downstream part of the study area. Comparing the Merrimack and Souhegan hydrographs (Figure 4) to periods when we observed backwatering of the lower Souhegan River (21 April 2008 and 6 August 2008) suggests that the backwatering occurs at Merrimack River discharges greater than ~500 m$^3$ s$^{-1}$ (Figure 4a). The downstream part of the study area is depositional when backwatering occurs. Therefore, sediment delivery to the Merrimack River is controlled by the sediment load and transport capacity of the Souhegan River and the relative stage of the Merrimack River. As a result of the interplay between the two rivers, the...
Figure 4.  (a) The Merrimack River hydrograph with median flow, observed periods of backwatering, and an approximate threshold for backwatering. The period of record is 100 years. (b) The Souhegan River hydrograph with median flow, 1.5 year flood discharge, annual peak discharge, and the survey dates. The period of record is 94 years. Gaps in the record are due to ice disrupting the gauging station. (c) The sediment budget for the upstream (blue line) and downstream sections (black line) of the study area. See the text and Table 4 for calculation details. A yellow line marks the beginning of dam removal. A dashed exponential best-fit curve ($R^2 = 0.88$) is labeled for upstream response and the different modes of response are labeled with arrows.
morphology of the area downstream from the former MVD is (and was prior to dam removal) sand-bedded and dynamic.

3. Methods

[16] We quantified the response of the Souhegan River to dam removal through repeat surveys of 12 permanent cross sections (Figure 1) and the stream longitudinal profile, and sediment sampling, generally following guidelines described by Collins et al. [2007] (Table 1).

3.1. Cross Section Surveys

[17] We used a Leica TPS 1200 total station (relative accuracy ~2 mm) with an integrated global positioning system (GPS) unit and reflecting prism on a telescoping pole (hereafter, Leica) to survey the 12 permanent (monumented) cross sections in the study area (Figure 1) and measure longitudinal profiles. The cross sections were established in the summer of 2007 perpendicularly to the flow of the river (Figure 1). Survey points were at ~2 m intervals or at significant changes in slope, geomorphology, or substrate. We visually identified the geomorphology (e.g., terrace, bank, floodplain, bar, water surface or riverbed) and substrate (e.g., mud, sand, gravel, cobbles, boulders, or bedrock) of each survey point. For subaqueous survey points, we measured the water depth on the prism pole.

3.2. Longitudinal Profile Surveys

[18] We surveyed the channel longitudinal profile along the thalweg at ~10-m intervals. The profiles started at the Everett Turnpike Bridge and extended to the railroad bridge at the confluence of the Souhegan and Merrimack rivers (Figure 1). To obtain absolute coordinates, the GPS data collected at the base stations during the longitudinal surveys were exported and uploaded to National Geodetic Survey (NGS) Online Positioning User Service (OPUS) for differential correction. This analysis yielded a median absolute accuracy of 0.045 m in the horizontal and 0.114 m in the vertical for all points along the longitudinal surveys. The discontinuity in the August 2008 longitudinal profile at the former dam location was required by deconstruction activities ongoing at that time. The longitudinal profile was surveyed up to the work limits upstream of the dam site and continued on the downstream side of the Route 3 bridge.

3.3. Sediment Sampling

[19] We sampled sediment at each cross section to (1) quantify how the grain size distribution of the river bed responded to dam removal and (2) to measure the dry bulk density of the sediment stored and transported in the system to use in sediment budget calculations.

[20] To characterize bed sediment texture changes before and after removal, we took grab samples from the thalweg of the cross sections during the August 2007, June 2008, August 2008, and July 2009 surveys (Table 1). We split the thalweg samples using the cone and quarter method, dried them in an oven overnight at 80 °C, and allowed the samples to cool in a desiccator. We weighed and sieved the samples using half-phi intervals from 63 μm to 16 mm. Due to coarsening bed conditions in some locations of the former impoundment after removal grab samples were not always feasible. In these locations, we performed pebble counts (n > 100) using the Wolman [1954] method to characterize the bed.

[21] We collected samples from exposed banks at the cross sections in August 2008 for dry bulk density (ρdry) measurements. Upstream, postremoval impoundment dewatering and river incision exposed previously submerged riverbanks. Incision and widening into the midchannel islands in the former impoundment (Figure 1) also exposed stratigraphy that well represented the stratigraphy of the sediments stored in the former impoundment. We trenched the banks at each cross section to a limited extent to expose continuous, fresh vertical surfaces. We examined these exposures for significant changes in grain size and we took three plugs of known volume from each discrete sedimentary layer (Table 2). Downstream, newly deposited sediments were sampled at subaerially exposed banks at each cross section. We measured the depth of each layer from the top of the bank and recorded its thickness. The number of layers sampled at each cross-section varied by the total thickness of the exposed sediment and the number of distinct layers. We dried the sediment plugs overnight in an oven at 80 °C, allowed them to cool in a desiccator, weighed them, and then the mass of the sample was divided by its volume to yield ρdry.

3.4. Estimating the Bed Material Load Sediment Budget

[22] We used our cross section surveys and sediment data to calculate a bed material load budget that quantifies rates of channel adjustment in response to MVD removal for each survey interval. We calculated a bed material load sediment budget (equation (1)) because we sampled only the sediment fractions represented in the bed of the impoundment and downstream. The sediments were predominantly sand traveling as bed load and suspended load. We did not analyze the wash load (mud fraction) because it is not well represented in the bed or channel banks within our study area (Table 3) except for a few thin lenses with organic materials in the impoundment sediment. The Souhegan River sediment

<table>
<thead>
<tr>
<th>Dates</th>
<th>Cross Sections</th>
<th>Longitudinal Profile</th>
<th>Photo Points</th>
<th>Sediment Sampling</th>
<th>Discharge Range (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27–28 Aug 2007</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.74–0.76</td>
</tr>
<tr>
<td>2–8 Jun 2008</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2.55–3.79</td>
</tr>
<tr>
<td>25–29 Aug 2008</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>2.75–2.94</td>
</tr>
<tr>
<td>13–21 Jul 2009</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>6.51–9.83</td>
</tr>
<tr>
<td>24–28 Aug 2009</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3.85–6.48</td>
</tr>
<tr>
<td>13–26 May 2010</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>3.74–7.93</td>
</tr>
</tbody>
</table>
budget in the study area is a balance between upstream inputs, sediment eroded and deposited in the impoundment ($\Delta US$), sediment eroded and deposited in the channel downstream of the impoundment ($\Delta DS$) and output to the Merrimack River, or

\[
\text{Input} = \Delta US \text{ Sed} + \Delta DS \text{ Sed} + \text{Output}. \quad (1)
\]

[23] To quantify equation (1), we calculated the volumetric change in sediment for each survey interval ($\Delta v$) by finding the average change in thickness along each cross-section (denoted by the subscript $i$) between surveys and multiplying this by the representative area surrounding each cross section (Figure 1). We estimated a thickness-weighted dry bulk density for each cross section ($\rho_{dry,i}$), on the basis of August 2008 sediment sampling, using this summation:

\[
\rho_{dry,i} = \sum_{k=1}^{n} \left( \frac{m_{dry,i}}{V_{sed,i}} \right) z_k / z_i. \quad (2)
\]

where the mass of a sample ($m_{dry,i}$) was divided by the volume of the sample ($V_{sed,i}$) for each layer ($k$), multiplied by the thickness of the layer the sample came from ($z_k$), and divided by the total thickness ($z_i$) of the bank sediment sampled (generally from the top of the bank to the water interface). We then summed the layers of the cross section. We used the August 2008 ($\rho_{dry,i}$) at each cross section to convert all sediment volumes into masses for all of our estimates of storage changes. The standard errors for ($\rho_{dry}$) were calculated and propagated using standard methods. We calculated the change in mass for the cross section ($\Delta m_i$) for a given survey interval using

\[
\Delta m_i = \Delta v_i (\rho_{dry,i}). \quad (3)
\]

Finally, we summed the changes in mass for each cross section ($\Delta m_i$):

\[
\Delta M = \sum \Delta m_i. \quad (4)
\]

for the upstream cross sections ($\Delta M_{US}$) and for the downstream cross sections ($\Delta M_{DS}$).

[24] Our sediment budget requires three assumptions. First, we assume complete sediment trapping in the study area (no export to the Merrimack River) during the first interval of the cross section surveys (August 2007 to June 2008, before the dam removal). This allows us to estimate a minimum sediment “input” to our study area from upstream, which is necessary to balance our sediment budget. Second, we assume that no sediment is transported from the Merrimack River into the lower Souhegan River and deposited during backwater events (which is realistic based on observations). Third, we assume no input of sediment to the downstream part of the study area from the Baboosic Brook (Figure 1). We think this is reasonable because the drainage area of the Baboosic Brook is only 22% of the total drainage area of the Souhegan River and the signal of sediment from the MVD removal is much larger than the amount of sediment likely delivered by this tributary during the study period.

Table 2. Bulk Density Sampling Data Used for Sediment Budget

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Number of Intervals Sampled ($k$)</th>
<th>Total Thickness of Sampling Site ($z_i$, m)</th>
<th>Thickness-Weighted Dry Bulk Density ($\rho_{dry,i}$, g cm$^{-3}$)</th>
<th>SE</th>
<th>Representative Area ($A$, m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVD03</td>
<td>2</td>
<td>0.81</td>
<td>1.32</td>
<td>0.046</td>
<td>5587</td>
</tr>
<tr>
<td>MVD06</td>
<td>6</td>
<td>1.95</td>
<td>1.25</td>
<td>0.49</td>
<td>6959</td>
</tr>
<tr>
<td>MVD08</td>
<td>5</td>
<td>2.90</td>
<td>1.10</td>
<td>0.15</td>
<td>8488</td>
</tr>
<tr>
<td>MVD10</td>
<td>2</td>
<td>1.38</td>
<td>1.28</td>
<td>0.0026</td>
<td>9769</td>
</tr>
<tr>
<td>MVD12</td>
<td>1</td>
<td>2.47</td>
<td>1.31</td>
<td>0.029</td>
<td>6714</td>
</tr>
<tr>
<td>MVD09</td>
<td>1</td>
<td>1.00</td>
<td>1.26</td>
<td>0.034</td>
<td>6533</td>
</tr>
<tr>
<td>MVD11</td>
<td>1</td>
<td>0.56</td>
<td>1.28</td>
<td>0.018</td>
<td>8189</td>
</tr>
<tr>
<td>MVD12</td>
<td>1</td>
<td>0.50</td>
<td>1.28</td>
<td>0.020</td>
<td>8118</td>
</tr>
<tr>
<td>MVD08</td>
<td>1</td>
<td>0.50</td>
<td>1.28</td>
<td>0.020</td>
<td>7417</td>
</tr>
</tbody>
</table>

Table 3. Median Grain Size ($D_{50}$) and Percentage of Mud, Sand, and Coarse Material for Each Thalweg Sediment Survey

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>June 2008 Survey</th>
<th>August 2008 Survey</th>
<th>July 2009 Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_{50}$ (mm)</td>
<td>&gt;2 mm</td>
<td>63 m–&lt;125 m</td>
</tr>
<tr>
<td>MVD02A</td>
<td>0.9</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>MVD03</td>
<td>0.8</td>
<td>1.1</td>
<td>98.3</td>
</tr>
<tr>
<td>MVD04</td>
<td>0.5</td>
<td>0.2</td>
<td>99.3</td>
</tr>
<tr>
<td>MVD05</td>
<td>1.9</td>
<td>1.4</td>
<td>98.5</td>
</tr>
<tr>
<td>MVD06</td>
<td>1.4</td>
<td>1.2</td>
<td>98.6</td>
</tr>
<tr>
<td>MVD07</td>
<td>2.6</td>
<td>3.1</td>
<td>68.7</td>
</tr>
<tr>
<td>MVD09</td>
<td>1.5</td>
<td>3.3</td>
<td>96.5</td>
</tr>
<tr>
<td>MVD11</td>
<td>0.7</td>
<td>0.3</td>
<td>99.7</td>
</tr>
<tr>
<td>MVD12</td>
<td>0.5</td>
<td>0.8</td>
<td>98.8</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.1</td>
<td>99.9</td>
</tr>
</tbody>
</table>

*Data in italics are from pebble counts. A large amount of bedrock scour data for the July 2009 sampling at MVD02A not totaling 100%. We were unable to collect grain size data at MVD06 and MVD10-12 during the July 2009 survey because of high flows.*
We constructed the sediment budget by calculating the bed material transport into the study area on the basis of two preremoval surveys as described above. We used the time interval between these two surveys to calculate an average daily sediment delivery rate to the study area (Table 4). This average rate ignores hydrograph variations and is therefore approximate when applied to other time intervals. We multiplied the interval between subsequent surveys by the sediment delivery rate to determine a minimum “input” for each survey. Balancing the input with the change in storage terms of equation (1) yields a minimum “output” for each budget calculation.

4. Results

Our observations and measurements are grouped by study area geography, starting with the impoundment section and followed by the downstream section. For each part, we first present the morphologic data (cross sections and longitudinal profile), then the bed sediment texture data (grain size distributions), and finally show sediment budget calculations.

4.1. Impoundment Channel Changes

Before the removal of the Merrimack Village Dam (MVD) the impoundment cross sections (Figures 5 and 6) showed an overall trend of deposition in the thalweg and the slope of the water surface was gradual (0.0003; Figure 7). Removal of the MVD was followed by an initial interval of rapid incision (mean 1.5 m; max 2.2 m) and narrowing (mean 40 m; max 76 m) of the channel within only 24 days (Figures 5 and 6; Table 4). Through incision the longitudinal profile of the former impoundment split into two reaches differentiated by gradient. The upstream reach, where the river incised to boulders and bedrock and removed most of the impounded sediment, developed a steep slope (0.0091) while the downstream reach closer to the former dam location developed a slope an order of magnitude less (0.0009; Figure 7). The second interval, 58 days, was dominated by widening (mean 9.1 m; max 30 m) of the newly incised channel in the downstream reach along with further incision (mean 0.44 m; max 1 m; Figures 5 and 6; Table 4). More boulders and bedrock, characteristic of the reach just upstream, were exhumed at the upper end of the downstream reach and effectively extended the steeper, upstream reach farther downstream (Figures 5 and 7). This interval of widening also included recruitment of large woody debris (LWD) in the downstream reach. The third interval, 10 months, included to a lesser extent both widening (mean 5.2 m; max 28 m) and incision (mean 0.9 m; max 1.2 m) bringing the total incision in parts of the impoundment to 3.9 m (Figures 5 and 6; Table 4). The upstream reach further steepened while the slope of the downstream reach decreased slightly (Figure 7). The final interval, 9 months, had both minor amounts of incision (mean 0.2 m; Figure 6a) and aggradation (mean 0.57 m; Figures 6b and 6c) coupled with increased widening (mean 13 m; max 33 m; Figures 5d and 6; Table 4). The widening was substantial from cross-sections MVD04 to MVD06, which bracket the former midchannel islands (Figures 5d and 6), an area that stored a large quantity of impounded sediment since dam removal in 2008. Two low frequency floods in March 2010 (5-10 year recurrence interval) mobilized a large quantity of these sediments (Figure 4c). The slope of both the upstream and downstream reaches remained roughly the same over the last survey interval (Figure 7).

The sediment within the impoundment before dam removal was predominately sand (96%-100%) except at MVD07 (Figure 8; Table 3). Immediately following dam removal (August 2008), sediment within the impoundment coarsened in the upstream reach exposing boulders and bedrock, while the downstream reach had little change and even fined in some instances (Figure 8; Table 3). By July 2009, 1 year after removal, the sediment within the impoundment coarsened to be dominantly gravel at all cross sections except MVD04 (Figure 8; Table 3).

Assuming no sediment storage change between the June 2008 survey and the start of the MVD removal on 6 August (which is reasonable given the low flows during the period; Figure 4b), the initial erosion rate was 1013 t d$^{-1}$ during the first 3 weeks after removal (Table 4; Figure 4c).

### Table 4. Bed Material Load Budget for the MVD Study Area

<table>
<thead>
<tr>
<th>Time Interval: Dates (Duration (days))</th>
<th>Input$^b$</th>
<th>$\Delta US$ Sed$^a$</th>
<th>$US$ Rate$^a$</th>
<th>$\Delta DS$ Sed$^a$</th>
<th>$DS$ Rate$^a$</th>
<th>Output$^b$</th>
<th>Percent Impounded Sediment Remaining$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug 2007 to Jan 2008 (307)</td>
<td>3,200 (4,070)</td>
<td>2,150 ± 1,200</td>
<td>7.00 (8.83)</td>
<td>1,050 ± 674</td>
<td>3.42 (4.43)</td>
<td>0 $^f$ (0$^f$)</td>
<td>100$^f$</td>
</tr>
<tr>
<td>Jun 2008 to Aug 2008 (24)</td>
<td>250 (318)</td>
<td>−19,100 ± 2,250</td>
<td>796 (−1,013)</td>
<td>18,500 ± 1,600</td>
<td>771 (1,004)</td>
<td>850 (518)</td>
<td>70</td>
</tr>
<tr>
<td>Aug 2008 to Oct 2008 (58)</td>
<td>605 (769)</td>
<td>−13,800 ± 2,080</td>
<td>238 (−300)</td>
<td>−3,950 ± 657</td>
<td>−68.1 (−88.4)</td>
<td>18,400 (23,300)</td>
<td>48</td>
</tr>
<tr>
<td>Oct 2008 to May 2010 (257)</td>
<td>3,190 (4,057)</td>
<td>−7,410 ± 1,090</td>
<td>24.2 (−30.7)</td>
<td>−4,490 ± 1,020</td>
<td>−14.7 (−19.1)</td>
<td>15,100 (19,300)</td>
<td>37</td>
</tr>
</tbody>
</table>

$^a$Negative numbers represent net erosion, and positive numbers represent net deposition. Boldface rows show postdam removal survey data.

$^b$Unit for the first value is m$^3$, and unit for the value in parentheses is metric tons.

$^c$Unit for the first value is m$^3$ d$^{-1}$, and unit for the value in parentheses is metric tons d$^{-1}$.

$^d$The percent remaining for the last interval (August 2009 to May 2010) is a minimum estimate because some material not included in the Gomez and Sullivan [2006] volume estimate was eroded from the northwest side of the impoundment during the March 2010 floods (Figure 4). Output is assumed to be zero for first interval to determine the minimum sediment delivery rate.

$^f$We assume there was no change between the end of the June 2008 survey and when the dam was removed on 6 August 2008. We set the quantity of sediment in the impoundment at this time equal to the volume estimated by Gomez and Sullivan Engineers [2006]. Percentages are calculated on the basis of the percent of mass remaining.
This excavated 24,300 t, or 30%, of the estimated impounded sediment. During the second interval (58 days) another 17,400 t of sediment eroded, or 22% more of the estimated impounded sediment and the rate of export had slowed to 300 t d\(^{-1}\). A year after removal the river eroded another 9380 t of sediment, or another 12%, from the impoundment and the rate of sediment export slowed again to 30.7 t d\(^{-1}\). Two years after removal, the March 2010 floods caused an increase in the average erosion rate from the former impoundment to 48.2 t d\(^{-1}\) and eroded another 12,400 t of sediment (another 15%). By the summer of 2010, only 21% of the original estimated quantity of impounded sediment remained (Table 4; Figure 4c).

4.2. Downstream Channel Changes

Before the MVD removal, the slope of the downstream reach of the study area below the dam and bedrock falls was 0.0006 (Figure 7) and the cross sections showed net deposition between August 2007 and June 2008 (Figures 1 and 9; Table 4). Erosion of sediment in the impoundment upon dam removal caused an interval of substantial

Figure 5. A comparison of the cross sections within the former impoundment (a) MVD01, (b) MVD02A, (c) MVD03, and (d) MVD04. Cross-section locations are shown in Figure 1. All of the cross sections are oriented from river left (north) to river right (south). The height of the water surface during the August 2007 and June 2008 surveys indicates the approximate elevation of the dam spillway.
deposition (24 days) that aggraded the bed up to 3.2 m (mean 2.1 m), narrowed the channel by 34 m in places (mean 17 m; Figure 9), and steepened the slope (0.003; Figure 7). Over the second postremoval survey interval (58 days), the Souhegan River began to incise (mean 0.35 m; max 0.60 m) and widen (mean 11 m; max 38 m) a channel through the sediment delivered during the first interval (Figure 9; Table 4). Incision (mean 1.2 m; max 1.7 m) and widening (mean 9.3 m; max 49 m) continued below the dam 1 year after removal (Figure 9; Table 4) lowering the thalweg to predam-removal levels in some locations, with a slope of 0.0009, similar to that of the preremoval survey (Figure 7). The final survey interval had net deposition within the channel (mean 0.24 m; max 1.5 m) and net widening (mean 16 m; max 58 m) with the slope (0.0008) remaining relatively constant (Figures 7 and 9; Table 4). The bed sediment grain size distribution downstream of the dam was sand before the removal and remained dominantly sand after the removal, although there is some evidence of bed coarsening (Figure 9; Table 3).

Figure 6. A comparison of the cross sections within the former impoundment (a) MVD05, (b) MVD06, and (c) MVD07. Cross-section locations are shown in Figure 1. The height of the water surface during the August 2007 and June 2008 surveys indicates the approximate elevation of the dam spillway. Note that we do not include MVD08 cross-section surveys because we could not make measurements at this location after the MVD was removed.
Sediment was frequently transported over the dam while it was in place as evidenced by net deposition of 1360 t between August 2007 and June 2008 (Figure 4c; Table 4). During the first interval after removal (24 days), 24,100 t of sediment deposited at a rate of 1004 t d\(^{-1}\) as the deposit prograded to the confluence of the Merrimack River. Almost all of the sediment delivered to the downstream part of the study area aggraded in the vicinity of MVD09 and MVD10 because of the high stage of the Merrimack River when deconstruction began (Figure 4). Over the course of the following 2 months the river removed 5130 t (21\%) of this initial deposit at a rate of 88.4 t d\(^{-1}\). This continued, and 1 year after removal another 5830 t of sediment had eroded at a rate of 19.1 t d\(^{-1}\) (24\%). Two years after removal, and including two high discharge events, the downstream section had a net deposition of 2110 t of sediment at 8.21 t d\(^{-1}\) (Figure 4c; Table 4).

5. Discussion
5.1. Impoundment Response: Channel Development and Erosion Rates

The response of the Souhegan River to MVD removal and the subsequent 3.9-m drop in the local base level occurred in two phases with different rates and controls on channel adjustments and associated sediment loads. It resulted in a segmenting of the former impoundment into two geomorphically distinct reaches (Figure 7). The upper reach (MVD01 to MVD03; Figures 5a–5c) became nonalluvial as all of the sand-sized sediments were exhumed, armoring the bed with boulders and bedrock. The lower reach (MVD04 to MVD07; Figures 5d–6) remained alluvial and both degraded and aggraded. The lower reach became controlled largely by the base level of the bedrock beneath the former dam (MVD08), and erosion and collapse of vegetated banks. Rates of sediment erosion from the impoundment changed dramatically during the study. The first phase (August–October 2008) was characterized by rapid erosion rates (300–1013 t d\(^{-1}\); Figure 4c; Table 4) as the Souhegan River removed over 50\% of the estimated impounded sediment through process-driven erosion (in the sense of Pizzuto [2002]) and reached the bedrock base level at the dam site. Subsequent intervals were characterized by slower erosion rates (30.7–48.2 t d\(^{-1}\); Figure 4c; Table 4) that were limited by a lack of access to the stored sediment, and thus the magnitude and frequency of high discharge events. During this second, event-driven phase, bank vegetation influenced erosion rates. Here we evaluate our...
findings in the context of (1) channel evolution models and (2) controls on the rates of fluvial response to disturbance.

[33] Not surprisingly, the channel evolution models proposed by Schumm et al. [1984], Simon and Hupp [1987], Thorne [1999], and Doyle et al. [2003b] for alluvial channels do not well describe channel response in the nonalluvial reach in the upstream part of the former MVD impoundment. Although the alluvial downstream reach conforms to parts of the channel evolution models, such as the sequence of incision, widening, and then deposition, controls on these mechanisms at MVD reveal important differences. Whereas the incision and widening in the MVD impoundment, as with the channel evolution models, was a response to lowered base level, increased water velocity, and mass wasting of impounded sediment, what little subsequent deposition we observed in the main channel was actually the result of large woody debris (LWD) recruitment that altered the reach hydraulics.

[34] Widening into banks recruited several large trees, causing a pool and riffle to form immediately downstream, a typical response to LWD additions [Daniels and Rhoads, 2007]. Later, high flows caused the trees to armor the banks and limited further widening [Keller and Swanson, 1979; Hickin, 1984; Daniels and Rhoads, 2007]. The trees also initiated the formation of point bar deposits. Deposition by these mechanisms contrasts with the mechanism described by earlier channel evolution models [Schumm et al., 1984; Simon and Hupp, 1987; Thorne, 1999; Doyle et al., 2003b], where sedimentation within the channel is caused by a substantial influx of sediment from upstream degradation that decreases the competence of the river and causes aggradation. We surmise that the aggradation mechanism described by the channel evolution models was not an important mechanism at MVD because the extent of degradation was substantially limited by the nonalluvial reach upstream that is protected by a boulder and bedrock bed.

[35] Pizzuto [2002] hypothesized that a sand-bedded impoundment response to dam removal would be dominantly process-driven. Although Pizzuto made no explicit estimates of removal rates for sand-bedded impoundments, he did suggest that it would likely take at least a decade for a quasi-stable channel to form at dam removal sites. Importantly, our work at MVD suggests that sand-bedded impoundments respond both as process-driven and event-driven systems, and the channel evolution rates can be substantially faster than Pizzuto [2002] anticipated. In the first 3 months after removal, the river rapidly eroded the stored sediment during all discharge conditions, indicative of a dominantly process-driven system. During this time, sand bedforms visibly moved downstream continuously. Note in particular the modest, and falling, discharge over the first survey interval (August 2008) which showed the most rapid erosion rate of the study (Figures 4b and 4c). During the August–October 2008 interval, several comparatively high flows created a situation where much of the remaining sediment between cross sections MVD04-MVD06 became inaccessible to the flow except during much larger flow events, none of which occurred in 2009 (Figures 4–6). The dominantly process-driven incision during this period, enhanced by modest events, created a negative feedback such that ever larger events were required to access and mobilize a substantial quantity of the impounded sediment. This negative feedback contributed to a shift from a dominantly process-driven system to an increasingly event-driven system after October 2008.

[36] Slower erosion rates characterized the October 2008–May 2010, reflecting the inability of the stream to access stored sediment because of the discharge magnitudes during this period (Figures 4b and 4c). During the final survey interval of this study (August 2009–May 2010), the sediment-export curve steepened because of two large events in March 2010 (5–10 year recurrence interval),
demonstrating the dominantly event-driven nature of the system during this period (Figure 4c).

[37] One might expect an exponential model to describe the rate of sediment erosion from an impoundment [e.g., Graf, 1997]. However, the best-fit curve on Figure 4c shows substantial departure from an exponential decline and the contrast highlights the two-phased response described above. Put simply, we find that the first ‘half-life’ of impounded sediment excavation is much faster (<3 months) than the second (~2 years; Table 3). Major et al. [2010] show a similar response curve for a sand and gravel impoundment, characterized by rapid initial sediment excavation during a period of comparatively modest storm flows followed by reduced erosion rates over a longer period, including some considerably higher stormflow discharges. In a study of channel response to a volcanic eruption, Gran et al. [2011] also found an exponential model to be insufficient because of changing processes during the response. In summary, rivers responding to a large influx of sand appear to consistently exhibit two phases of response rates controlled by different factors.

[38] Further evolution of the former impoundment will likely only be accomplished by widening (e.g., further erosion of the NMCI) or by a drastic event (i.e., avulsion) during a flood. Removal of small quantities of impounded sand will continue, but this will likely be influenced by the

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Figure 9. A comparison of the downstream cross sections (a) MVD09, (b) MVD10, (c) MVD11, and (d) MVD12. The cross-section locations are shown in Figure 1. The MVD11 left monument was lost after the first survey resulting in a minor position change for all future surveys.
growth of vegetation on these deposits. On the basis of the longitudinal profile (Figure 7), the bed through this section is probably consummate with the predam river surface, but the water depth at the time of the May 2010 survey precluded careful observations of its composition.

5.2. Downstream Response

[39] Our preremoval survey data, inspection of historical aerial photographs, and visual observations after an approximately 20–25 year recurrence interval flood event in April 2007 (Figure 4b) all suggest that before MVD removal the downstream part of the study area was characterized by episodic deposition and remobilization of sand transported over the dam during large discharge events (Figures 9a and 9b). The frequently synchronous backwater flooding of the Merrimack River would enhance deposition, especially at MVD09 and MVD10 (Figures 9a and 9b). After the backwater receded, the Souhegan River would slowly incise the delivered sediment. The river at, and just downstream from, cross sections MVD09 and MVD10 (Figures 9a–9b) was extremely dynamic with cutting and filling of pools and shifts of the thalweg between the left (north) and right (south) channels. Cross sections MVD11 and MVD12 (Figures 9c and 9d) were more static and would only store sediment remobilized from MVD09 and MVD10 for a brief time before it was exported to the Merrimack River.

[40] In general, the downstream part of the study area postremoval responded much the same way it did before the dam removal when it would episodically receive sand transported out of the impoundment (Figures 7 and 9). The quantity delivered after the dam removal was certainly larger than during preremoval floods (e.g., April 2007; Figure 4), but the downstream system of sediment transport, influenced by Merrimack River backwater events, remained the same pre- and postremoval. Similar to the type of system in the upstream section and contrary to Pizzuto [2002], the downstream section is also a hybrid process- and event driven system. Events drive the episodic accretion in the section both through sediment delivery from the upstream section and deposition during backwatering of the Merrimack River, while process dominates the periods between events (both on the Souhegan and Merrimack rivers) with progressive removal of sands to the Merrimack River (Figures 4c, 7, and 9).

[41] One key postremoval difference is the availability of a larger sediment size for delivery from upstream of the former dam site. Before, during, and after the removal most of the sediment leaving the upper section was sand-sized. However, as shown in Figure 8 and Table 3, the bed of the channel through the former impoundment did coarsen in many areas indicating the availability of coarser sediment to be deposited in the downstream part of the study area. There is already some evidence of a postremoval bed coarsening at MVD09 and MVD10 (Table 3). Whether the backwater-influenced, downstream section has sufficient competence during high-frequency floods to transport substantially coarser sediment remains to be seen.

6. Conclusions

[42] Our study documents the postdam removal geomorphic response rates of channels upstream and downstream from a structure that impounded sand-sized sediments. We find rapid upstream sediment excavation and evolution toward a quasi-stable channel, and rapid remobilization of the sediment pulse delivered to the downstream part of the study area upon dam removal. The key finding of our analyses is that sandy impoundments respond in two modes, which we have referred to as “process-driven” and “event-driven” using the terminology of earlier dam-removal conceptual models [Pizzuto, 2002]. The river eroded over 50% of the impounded sediment within the first 3 months during the dominantly process-driven phase, while rates during the subsequent event-driven phase were much slower (Figure 4; Table 4).

[43] Flood events can affect sediment transport and channel response in complex ways not previously described for sand-bedded impoundments. As expected, high flows can accelerate erosion of the impounded sediment and channel response, as we observed in the weeks and months immediately after dam removal. However, dominantly process-driven, rapid incision enhanced by even small floods can create a negative feedback in the system such that large quantities of the original sand deposit become accessible to only much larger floods. Later, our study period included two relatively large floods (5–10 year recurrence interval), which substantially contributed to the total quantity of sediment excavated within 2 year of removal and accelerated the response trajectory, underscoring the importance of high-magnitude events after the initial process-driven response (Figure 4; Table 4).

[44] Our results and analyses lead us to suggest several general conclusions that may be useful for planning future dam removals in similar sand-dominated settings. The first two statements are more broadly relevant to channel disturbances involving large influxes of sediment (e.g., landslides, volcanic eruptions, mining; Doyle et al., [2002]).

[45] 1. Rapid, process-driven incision and sediment excavation enhanced by small flood events can cause negative feedbacks for geomorphic response by recruiting large woody debris and stranding large quantities of impounded sediment that can be accessed and transported only by rare floods, potentially delaying complete response upstream and downstream, and shifting the system to dominantly event-driven. This suggests that although channels respond quickly, some stored sediment may persist for long periods [e.g., Walter and Merritts, 2008], particularly if it is stabilized by vegetation and/or if few high-magnitude floods occur.

[46] 2. Large quantities of sand delivered to a low gradient reach subject to episodic backwatering (either fluvial or tidal) can be remobilized relatively rapidly because sand moves even during relatively modest flows.

[47] 3. Bedrock controls at the dam site and upstream of the impoundment substantially constrain impoundment response spatially and temporally and increase prediction confidence.

[48] 4. Sand-filled New England impoundments can be dynamic when dams are in place. As documented at MVD, high discharges can scour impounded sediments and transport them downstream. Low-head run-of-river dams can be inefficient sediment traps [Brune, 1953], even for some bed load size fractions.

[49] Acknowledgments. This work was supported by the NOAA Open Rivers Initiative through a project with Gomez and Sullivan
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