A Hindcast Comparing the Response of the Souhegan River to Dam Removal with the Simulations of the Dam Removal Express Assessment Model-1

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A HINDCAST COMPARING THE RESPONSE OF THE SOUHEGAN RIVER TO DAM REMOVAL WITH THE SIMULATIONS OF THE DAM REMOVAL EXPRESS ASSESSMENT MODEL-1

a thesis

by

MARICATE CONLON

Submitted in partial fulfillment of the requirements

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Abstract
A hindcast comparing the response of the Souhegan River to dam removal with the simulations of the Dam Removal Express Assessment Model-1

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Advisor: Noah P. Snyder

Dam removal is a widely used river restoration technique. Historically, dams produced hydropower, controlled flooding, and provided water storage, but currently many dams in the United States, specifically low head dams in New England, are obsolete. This study aims to assess the ability of a simple morphodynamic sediment transport model, Dam Removal Express Assessment Model (DREAM-1), developed by Cui et al. (2006a). I compare simulations to a dam removal monitoring project that quantified the physical response of the Souhegan River to the removal of the Merrimack Village Dam (MVD), Merrimack, NH. Pearson et al. (2011) reported results of field monitoring from August 2007-May 2010 and found that the Souhegan River responded to dam removal in two phases: initial rapid incision of impoundment sediment induced by immediate base level drop of 3.9 m (~50% of impounded sediment eroded in ~2 months), followed by an event-driven phase in which impoundment sediment eroded primarily during floods. The reach downstream of the dam showed a similar two-phase response, with rapid deposition in the first three weeks after dam removal followed by bed degradation to the pre-removal elevation profile within a year. I have continued the field methods of Pearson et al. (2011) for the past two survey periods, June 2011 and July 2012. Using five years of comprehensive field data, I conduct a hindcast to compare the sediment erosion and deposition patterns predicted by DREAM-1 to the observed downstream response of the Souhegan River. I model the changes in bed elevation for the downstream and upstream
channel reaches at intervals that correspond with the dates of four longitudinal profile
surveys and seven annual cross-section surveys. Results of the hindcast show that
DREAM-1 predicts channel elevation accurately within one meter and with average
discrepancy of ±0.35 m when compared to average channel bed elevations of each cross-
section. DREAM-1 successfully simulates two phases of upstream channel response,
rapid impoundment erosion followed by a longer period of gradual sedimentation change.
However, DREAM-1 erodes to base elevation within 11 weeks after dam removal
(erosion of the 88% impoundment sand), leaving little sand for transport during the later
survey periods. This overestimation of impoundment erosion is likely the product of
limitations of the model, specifically the simplification of channel cross-sections with
constant width throughout the simulation. The model assumes uniform lateral sediment
transport in the impoundment and does not capture the variation in width due to incision
and channel widening. This hinders the ability of the model to simulate some details of
the sediment budget developed by Pearson et al. (2011) and extended with recent
surveys.
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1. Introduction

Dam removal is a widely used technique for river restoration. Historically, dams produced hydropower, controlled flooding, and provided water storage, but currently many dams in the United States are obsolete. Dams require maintenance to adhere to requirements for structural safety. Therefore, land owners may opt to remove dams rather than take on the financial responsibilities of ongoing maintenance. In addition to a financial incentive, benefits of dam removal include the restoration of free-flowing rivers and the revitalization of fish and wildlife (American Rivers, 2012). For many rivers, the potential to reduce negative geomorphic and ecologic impacts by removing dams now outweighs economic benefits of preserving dams (Burroughs, 2009).

The rate of dam removal has increased over recent decades. In the 1960s, the “golden age” of U.S. dam building (O’Connor et. al., 2008), only one dam was removed per year, but by the 1990s about twenty dams were removed per year (Pohl, 2003). Dams typically remain functional for ~50 years before requiring updates and maintenance to preserve structural integrity. Approximately 60,000 dams, 1.8 m in height or greater, are anticipated to reach 50 years of age by 2020, meaning in the coming decade many dams in the U.S. will need repair or face removal (FEMA and USACE, 1996).

Dam construction typically results in deposition and storage in the impoundment upstream and sediment starvation downstream. Previous observations of channel response to dam removal reported incision of the stored impoundment sediment followed by a phase of channel widening (Figure 1; Doyle et al., 2002). Geomorphologists explain the changes driven by dam removal with sediment transport processes such as channel incision and knickpoint development (Burroughs et al., 2009). Pizzuto (2002) developed a conceptual model describing channel response to dam removal in a series of stages.
Figure 1. Figure showing six stages of channel evolution according to Doyle et al. (2003). Channel response begins with incision into impoundment sediment followed by channel widening. Channel response to dam removal is depicted in the view of channel evolution in the reservoir sediment (a), cross section view of any given point in the channel (b), and a view of longitudinal channel evolution (c).
His model assumed initial incision into impoundment sediment followed by bank erosion and bed aggradation before the channel reaches a quasi-equilibrium state. He speculated that the process could take up to a decade after dam removal. Pizzuto (2002) further categorized the incision process with regard to sediment-size. Impoundments composed of gravel incise during high-flow events that are capable of mobilizing coarse sediment, while impoundments composed of sand and silt erode during many flows and by a variety of processes such as mass wasting or vertical headcut. Pizzuto (2002) described the incision caused by high discharge events as “event-driven” and incision caused by processes independent of discharge as “process driven.”

In the past two decades, research shifted from qualitative observations and conceptual models to quantitative field research (Roberts et al., 2007, Burroughs et al., 200, Kibler et al., 2011) and the development of numerical models that predict geomorphic response to dam removal (Cui et al., 2006a). Recent quantitative dam removal monitoring studies, such as Pearson et al. (2011), support the general concepts of channel response described by Pizzuto (2002). Pearson et al. (2011) observed a two-phase response, with incision of impoundment sediment followed by channel widening, on the Souhegan River, Merrimack, NH, after the removal of the Merrimack Village Dam (MVD) in August 2008. Emerging areas of dam removal research compare numerical sediment transport models to quantitative field studies. By comparing model projections to detailed and quantifiable dam removal monitoring case studies we can validate numerical models. Hindcasting, a method of testing numerical models by implementing known inputs of past events to assess how well the model output simulates the known
results, can help validate a model’s potential as a tool for predicting sediment transport induced by future dam removals.

1.1 Objectives

This study primarily aims to assess the applicability of a simple morphodynamic sediment transport model, Dam Removal Express Assessment Model-1 (DREAM-1), in the context of the Souhegan River field site studied by Pearson et al. (2011). I conduct a hindcast to evaluate the results of DREAM-1 simulations using five years of field data collected on the Souhegan River from August 2007 to July 2012, for model inputs. Comparing predictions of DREAM-1 to field observations will offer insight as to whether DREAM-1 can accurately predict sediment transport at this field site.

In addition, I aim to investigate the hypothesis of Pearson et al. (2011) regarding the two-phase channel response of the Souhegan to MVD removal. Pearson et al. (2011) found that the initial rapid erosion of the impoundment sediment and rapid deposition downstream was process-driven, meaning that the rate was largely independent of river discharge. By varying Souhegan River discharge inputs to DREAM-1, the question of whether the observed rapid response was process-driven or dependent on the hydrology will be explored.

A secondary objective of this study is to continue to monitor and document the physical response of the Souhegan River to MVD removal, building on the work of Pearson (2010) and Pearson et al. (2011). I quantify channel response in the most recent two survey periods, June 2011 and July 2012, with cross-section profiles, longitudinal
profiles, grain-size distribution of riverbed sediment, repeat photography, and with calculating the annual sediment budget.
2. Background

2.1 Previous Dam Removal Studies

Many previous dam removal studies have used methods similar to those of *Pearson et al.* (2011) to quantify channel response to dam removal. Case studies varied in location, sediment composition, and size of impoundment. Recently, *Sawaske and Freyberg* (2012) reviewed quantitative dam removal studies. Their objective was to specifically compare the rate of impoundment erosion for the various case studies and correlate any trends of rapid or gradual erosion with characteristics of the field site, such as sediment-size, sediment cohesion, channel width, or channel slope.

*Sawaske and Freyberg* (2012) compare 12 northern U.S. dam removal projects monitored and published in the past two decades. Case studies included the LaValle Dam in Wisconsin, impoundment comprised of fine sediment, and the Stronach Dam removal in Mainstee County, Michigan, with impoundment sediment comprised of gravel. The Marmot Dam, near Portland, Oregon, was also included and its impoundment classified as layered deposit primarily composed of non-cohesive gravel. This dam removal is the subject of the DREAM application reported in *Cui et al.* (in review). The work of *Pearson* (2010) reporting the erosion rate of impoundment sediment after the MVD removal in August 2008 through August 2009, was the only sand impoundment included in the *Sawaske and Freyberg* (2012) review. In comparison to the erosion rates of the other study sites, the MVD impoundment eroded much faster (Figure 2) losing >60% sediment volume within one year of dam removal.
Figure 2. Figure from Sawaska and Freyburg (2012) comparing erosion rates for twelve dam removal projects conducted in the past decade in the northern U.S. the MVD from August 2008 through August 2009.
2.1.1 LaValle Dam of the Barbaroo River, Wisconsin

Doyle et al. (2003) aimed to investigate and quantify the physical changes associated with low-head dam removal by examining the LaValle Dam on the Barbaroo River, southern-central Wisconsin. Channel monitoring continued for one year after dam removal, after which the channels were subject to anthropogenic modifications such as channel realignment, widening and stabilization. Methods for channel monitoring included cross-section surveys, bedload sampling, and sediment coring. The study intended to assess the accuracy of the conceptual model of channel response to dam removal developed in Doyle et al. (2002) and to measure the rate at which each river progressed through the stages of the channel response.

The LaValle Dam, formerly a grain mill constructed in the mid-1800s, impounded primarily non-cohesive fine sand and silt. In a region characterized by steep hill slopes and unglaciated terrain, the channel reach slope ranged from 0.0002-0.0005. Dewatering of the LaValle Dam reservoir began on July 11, 2000 with the remaining structure removed in February, 2001. Project engineers made no effort to stabilize impoundment sediment, but rip rap in the former dam site created a long, steep riffle for grade control. Following the initial flush of sediment, the Barbaroo River vertically incised the upstream channel bed within weeks. Incision led to mass-wasting on channel banks allowing channel widening and exposing an underlying layer of coarse sand that was later transported downstream as bedload. Doyle et al. (2003) observed erosion of the sand in the upper part of the reservoir and a large slug of sand deposited immediately downstream of the dam site. The sand deposit was temporary and cross-sectional area
immediately downstream of the dam returned to pre-removal conditions within three months of removal.

The volume of fine sand impounded by the LaValle Dam eroded 7.3% by May 2011, three months after removal, and an additional 0.5% by August 2001, six months after removal. Doyle et al. (2003) concluded that observations of upstream channel response on the Barbaroo River after LaValle Dam removal, including rapid impoundment erosion followed by gradual degradation and widening, were consistent with the stages hypothesized in the conceptual model of their previous work (Figure 1; Doyle et al., 2002). In comparison to the 12 other field sites evaluated by Sawaske and Freyberg (2012) the LaValle Dam removal had one of the slowest rates of impoundment erosion (Figure 2).

2.1.2 Stronach Dam of the Pine River, Michigan

Burroughs et al. (2009) monitored the response of the Pine River of Mainstee County, Michigan, using surveys after the removal of the Stronach Dam. The dam was constructed in 1911, 5.6 km upstream from the confluence of the Pine and Mainstee rivers. It was initially a hydroelectric dam with 5.49 m of potential head height. Due to high annual sediment discharge (~28,000 m³ per year) the Stronach Dam reservoir could not accommodate the rapid infill, which led to problems with operation of dam turbines. After failed attempts to remove impoundment sediment buildup in the 1930’s, the Stronach Dam was decommissioned. The dam owners, Consumers Power Company (CPC), chose a staged removal over a six year period, 1997-2001, in the hopes of gradual channel adjustment and dampened environmental impact.
Prior to removal, CPC estimated the Stronach Dam to impound 789,000 m³ of gravel and sand. In the ten years following dam removal, the Pine River eroded ~92,000 m³ of the impoundment sediment. The total net erosion over the decade equaled approximately 3.5 years of the annual sediment bedload discharge. Burroughs et al. (2009) reported that the annual volume of eroded impoundment sediment did not strongly correlate with the annual mean river discharge values, the annual peak discharge values, or the gradual removal of the dam structure.

The channel bed narrowed and deepened upstream of the Stronach Dam site thereby exposing underlying coarser sediment. Initially, erosion occurred most rapidly in close proximity to the dam site and it gradually progressed upstream in the first several years following dam removal. The staged removal of the dam resulted in a relatively constant rate of erosion of impoundment sediment for one decade following removal (Sawaske and Freyberg, 2012; Figure 2). The eroded impoundment sediment deposited downstream resulted in a wider, shallower channel. The system retained 13,599 m³ of sediment in the first 0.63 km downstream of the dam. The remaining sediment excavated from the impoundment eventually deposited onto downstream floodplains or the in the Tippy Dam Reservoir, the subsequent impoundment downstream of the Stronach Dam (Burroughs et al., 2009).

2.1.3 Marmot Dam of the Sandy River near Portland, Oregon

Major et al. (2008) observed the response of the Sandy River to removal of the Marmot Dam on October 19, 2007. The Marmot Dam was 14 m high and impounded 750,000 m³ of gravel and sand. When faced with expiring licenses and maintenance costs
the dam owners, Portland General Electric Company (PGE), opted to decommission the
dam in 2002 and prepared for removal. PGE removed the dam with an immediate “blow
and go” removal strategy and no dredging between July 1 and September 30, 2007.

In the first 12 hours following initial breach, the Sandy River incised impounded
sand and gravel and almost reached the pre-dam river bed elevation. The channel
widened due to mass wasting of the banks in the lower reservoir in the following 24
hours. By 48 hours, the Sandy River had eroded approximately 100,000 m$^3$ or
approximately 15% of the impoundment sand. The erosion of impoundment sediment
occurred under flow of approximately 50 m$^3$/s, 30% greater than the mean annual flow at
the Marmot Dam site (Major et al., 2008). Of the sites included in the Sawaske and
Freyberg (2012) review, the Marmot Dam had the second largest amount of eroded
impoundment sediment and second fastest rate of impoundment erosion (Sawaske and
Freyberg, 2012; Figure 2).

Major et al. (2008) measured suspended load and bed load at two gauging stations
downstream of the dam before, during and after the removal. Dam removal resulted in an
initial pulse of silt and clay, eroded from the thin layer capping the impoundment,
followed by incision and transport of the underlying sand and gravel layer. Within 6
hours of breach the rate of sediment flux increased from the steady low flux of $<10$ kg/s
to 60 kg/s and increased further to 70 kg/s by 18 hours after breach. For the first 18 hours
following removal, sweeping sand dunes passed by gauging stations and gravel transport
began after 20 hours. The downstream channel bed aggraded 1.5 m in 18 hours and 4 m
by 66 hours in the form of a sediment wedge tapering over 1.5-2 km downstream (Major
et al., 2008).
2.1.4 Comparison and Conclusions from Case Studies

From previous quantitative monitoring studies, several observations are consistent. Most dam removal monitoring projects observe a phase of initial rapid incision of impoundment sediment followed by a phase of channel widening. With the exception of the MVD removal, the Marmot Dam removal study reported the largest amount and fastest rate of impoundment erosion in comparison with other northern U.S. dam removals. Both the Marmot and MVD removals, one-shot or “blow and go” removals, resulted in faster erosion when compared to the staged removals of the LaValle and Stronach dams (Figure 2; Sawaske and Freyberg, 2012). Burroughs et al. (2009) reported a loss 15% of impoundment sediment within ten years of Stronach Dam removal and Doyle et al. (2003) reported loss of less than 10% of impoundment sediment within two years of LaValle Dam removal. Sawaske and Freyberg (2012) concluded that staged removals result in slower erosion rates in the impoundment. Further, Sawaske and Freyberg (2012) concluded that grain-size can also be an important factor influencing impoundment erosion rate. Several sites, such as the Rockdale Dam in southern Wisconsin and the Brewster Dam in northern Illinois, had cohesive and consolidated impoundment deposits. These sites retained 85-90% of the deposit volume following dam removal where as non-cohesive and unconsolidated deposits eroded larger volumes. These findings support conceptual models presented by Pizzuto (2002) and Doyle et al. (2002) proposing that cohesive deposits should experience less erosion than non-cohesive deposits due to variations in drying induced consolidates and strengthening of exposed sediments (Sawaske and Freyberg, 2012).
2.2 Modeling Efforts

Hydraulic models were used in early dam removal studies to estimate the likelihood of flooding downstream. Simulations of flooding were important for dam owners opting to remove dams and concerned about nearby infrastructure or breach of downstream levees. Many hydraulic models also calculate bed shear stress, which can be used to estimate sediment transport. Stillwater Sciences recently designed a pair of one-dimensional sediment transport models, the Dam Removal Express Assessment Model (DREAM; Cui et al. 2006a). DREAM-1 and DREAM-2 differ from previous models by focusing on sediment transport and bed morphodynamics based on hydraulics and hydrology.

2.2.1 Previous Hydraulic Models

Previous hydraulic models predicted water flow and flooding due to removal of dams. For example, in 1993 The U.S. Army Corps of Engineers (USACE) published the user manual for Hydrologic Engineering Center-6 (HEC-6), a one-dimensional movable boundary open channel flow numerical model that predicts the likelihood of flood events (U.S. Army Corps of Engineers, 1993). Harbor (1993) applied HEC-6 to a study proposing removal options for the Elwha and Glines Canyon dams on the Elwha River, Washington. The model predicted that rapid dam removal would cause downstream flooding, requiring an increase in levee height of 0.3-1.5 m.

The USACE later improved upon their original hydraulic model and developed the River Analysis System (HEC-RAS) that performs one-dimensional steady flow computations, unsteady flow computations, and water temperature modeling (U.S. Army Corps of Engineers, 2002). Roberts et al. (2007) used HEC-RAS to predict likelihood of
flooding both upstream and downstream upon removal of the Secor Dam on the Ottawa River, Ohio. Model simulations predicted the extent of flooding before and after the dam removal at 10, 25, 50 and 100-year flood recurrence intervals. Roberts et al. (2007) gathered model input data, such as locations of stream channels and cross-section profiles, from high resolution light detection and ranging (LiDAR) data and digital orthophotographs. Roberts et al. (2007) predicted dam removal would have little effect on flooding and that geomorphic adjustments due to the release of impoundment sediment would occur on the order of years.

2.2.2 DREAM Development and Previous Application

Cui et al. (2006a) rewrote the sediment pulse model of Cui and Parker (2005), which simulates gravel transport, to create two numerical models, DREAM-1 and DREAM-2 (Cui et al., 2012). Both DREAM-1 and DREAM-2 are one-dimensional and simulate sediment transport dynamics for varying dam removal strategies, such as staged removal and “blow-and-go” immediate removal and for varying amounts of impoundment dredging (Stillwater Sciences, 2002). DREAM-1 predicts sediment transport for reservoir deposits that are primarily composed of sand. DREAM-2 applies to reservoir deposits with a top layer of coarse gravel and a layer of gravel, sand and even finer sediment beneath. Both models are able to simulate subcritical, supercritical and transient flow conditions (Cui et al., in review).

Cui et al. (in review) reported the application of a pair of models, later revised to become the two DREAM models, to the removal of the Marmot Dam on the Sandy River in Portland, Oregon. Modeling results showed that a two-season staged dam removal provided little advantage over an immediate one-shot removal with regard to downstream
sediment deposition. Similarly, modeling 15% dredging prior to removal failed to predict a decrease in sediment deposition downstream of the former dam site when compared to simulations implementing minimal dredging. Partially based on the DREAM simulations, PGE removed the dam with a one-shot removal and minimal dredging during the summer of 2007 (Cui et al., in review). At the time, the removal of the Marmot Dam was expected to be the largest volume of reservoir sediment to ever be released in U.S. history (Cui et al., in review).

Cui et al. (in review) compared outputs of DREAM with field observations on the Sandy River reported in Major et al. (2009). PGE monitored cross-sections on the Sandy River with annual topographic surveys at four monitoring sites taken before (2005-2007) and after (2008-2011) dam removal (Major et al., 2009). To simulate the removal of the Marmot Dam, the inputs of DREAM-2 included a pre-dam removal longitudinal profile, bankfull width measured from aerial photographs, average annual rate of sediment flux, bed load grain-size distribution, and daily-discharge data. To account for the uncertainty of future hydrologic conditions, Cui et al. (in review) modeled the removal under a variety of discharge conditions, including a wet year, an average year and a dry year.

Field observations for post-removal change in the average bed elevation downstream of the dam site corresponded well with the three sets of discharge parameters, which did not drastically change the model output. Although DREAM-2 over-estimated channel aggradation 7-12 km downstream of the dam site, Cui et al. (in review) attributed this over-estimation to a low volumetric abrasion coefficient (the fraction of volume lost to abrasion for transport of a unit distance). The estimate was based on previous literature and case studies describing channels with similar lithology.
and bed material. The authors hypothesized that with a higher abrasion coefficient DREAM-2 predictions would have been more consistent with observations.

This study builds on the work of Cui et al. (in review) by using DREAM-1 in a hindcast experiment in which I use known inputs (such as impoundment grain-size distribution, daily-discharge values, channel geometry, and annual sediment load) and assess how well model outputs compare with channel observations. This project will assess the results of DREAM-1 by comparing simulations of channel bed elevation profiles to surveys conducted during the MVD removal monitoring project, one of the most extensively quantified dam removal projects of the past decade.
3. Study Area

3.1 Merrimack Village Dam History

John Chamberlain, Merrimack town leader, constructed the first saw mill in Merrimack, NH, and the first dam on the Souhegan River in 1734. The location of this dam is not known exactly, however it was most likely near the modern MVD. Chamberlain remained Selectman, Surveyor of Highways and Town Meeting Moderator for the town of Merrimack until his death in 1800. Isaac Riddle, founder of the Souhegan Nail, Cotton and Woolen Manufacturing Company, gained control of the mill building in 1807 before selling it to David Henderson in 1840. In September of 1883, under the ownership of Gordon Woodbury, a fire destroyed the mill buildings. In 1906, Woodbury sold all of his Merrimack Village land to the W.H. McElwain Shoe Company (MSC; Pennichuck Water Utilities, n.d.). The MSC constructed the modern concrete structure which was located just upstream of the Route 3 bridge. In 1934, the MSC added a spray skirt to the dam, which was the final and most recent major structural addition to the MVD (Figure 3a). In 1953 ownership changed hands to Andrew J. Woronka and again in 1964 to the Pennichuck Water Works (PWW), the most recent owner (Pennichuck Water Utilities, n.d.).

The PWW, a public water supplier in Merrimack, NH, purchased the dam to divert water from the Souhegan River to the Pennichuck Brook watershed, however never actually used the dam for this purpose. The PWW also investigated the potential of using the dam as a hydroelectric facility, but the project was not found to be economically feasible. The removal of the MVD was initially considered in 2004 after the PWW received a Letter of Deficiency from the New Hampshire Department of
Environmental Services' Division of Dam Safety stating that the dam failed to meet safety criteria (Gomez and Sullivan Engineers, 2004). After four years of planning, the removal of the MVD began on August 6, 2008. Removal began with destruction of a section of the dam down to existing pre-dam bedrock causing a 3.9 m base level drop over a few hours (Figure 3). The dam was removed in pieces from right bank to left bank over the course of several weeks.
Figure 3. Photographs showing progression of MVD removal. The former MVD was four meters in height and photographed prior to removal (a) on July 16, 2008 (Pearson, 2010). Removal began on August 6, 2008 (b; Pearson, 2010), by breaching to pre-dam bedrock resulting in the immediate 3.9 m base level drop. The channel rapidly changed by August 27, 2008 (c) and incised into impoundment sediment by October 18th, 2008 (d; Pearson, 2010).
3.2 Study Area Overview

The study area ranges from Everett Turnpike Bridge, upstream of the MVD, downstream to the convergence of the Souhegan and Merrimack rivers (Figure 4). *Gomez and Sullivan Engineers* (2006) characterized the impoundment sediment as predominantly sand. They estimated the volume at ~81,000 yd$^3$ (62,000 m$^3$) and predicted dam removal to mobilize 67% of the deposit. A study using ground penetrating radar (GPR) surveyed the modern impoundment prior to MVD removal and reported a similar volume of impoundment sediment of 67,000 m$^3$ (*Santaniello et al.*, 2013). A large off-channel wetland, currently dry, existed because of the high water table created by the dam in place. Downstream of the former MVD (under Route 3) is a 0.1 km-long steep (slope of 0.2) bedrock-floored reach (Figures 4-5). Sand dominates the substrate in the remaining more gradual (slope of 0.0006) reach downstream from the dam site (*Pearson*, 2010).

*Pearson* (2010) and *Pearson et al.* (2011) developed a series of fieldwork techniques to measure and quantify the sediment budget and channel response of the Souhegan River after MVD removal. Techniques included topographic cross channel and longitudinal surveying and sediment grain-size analysis. *Pearson et al.* (2011) report field work and data analysis for this field site taken from August 2007 through May 2010. After the removal of the dam, base level dropped 3.9 m initiating rapid incision and narrowing in the impoundment during the first 24 days, observed in the August 2008 longitudinal survey (Figure 5). This initial process-driven phase (in the sense of *Pizzuto*, 2002) lasted two months and transported sediment at 1013 t/day, calculated from the two months following removal. At cross-sections farthest upstream, MVD01-MVD02B
(Figure 6), the river removed most impoundment sediment incising to boulders and bedrock within the first two months after MVD removal. Cross-sections closer to the former MVD, such as MVD03-MVD07, remained alluvial with more gradual slope (Figures 5 and 7-8). Channel widening characterized channel response downstream, at MVD09-MVD12, in the August-October 2008 survey period (Figures 9-10). After the river had incised to base level, the rate of sediment removal slowed to 30.7 t/day (measured from October 2008-August 2009). In this event-driven phase, sediment transport during the August 2009 to May 2010 survey period included two flood events in March 2010, with 5-10 year recurrence interval. One year after MVD removal, the impoundment had lost 65% of sediment, and by two years 78% had been excavated.
Figure 4. Map showing aerial photograph, taken May 2010, of the Souhegan River overlain by pin and thalweg locations from July 2012 (photo reference: NH Granit). Inset on the top left shows the elevation map of the Souhegan River watershed with field site outline in black (DEM reference: NH Granit).
Figure 5. Graph showing longitudinal profiles of the Souhegan River taken June 2008 through July 2012 and modified from Pearson et al. (2011). The most recent survey shows a similar upstream profile to that of May 2010 and erosion at ~450-500 m downstream of the MVD.
Figure 6. Graphs showing cross section profile evolution of MVD01 (a; located ~600 m upstream of the MVD), MVD02A (b; located 456 m upstream) and MVD02B (c; located 410 m upstream) from August 2007 through July 2012.
Figure 7. Graphs showing cross section profile evolution of MVD03 (a; located 412 m upstream of the MVD), MVD04 (b; located 328 m upstream), and MVD05 (c; located 277 m upstream) from August 2007 through July 2012.
Figure 8. Graphs showing cross section profile evolution of MVD06 (a; located 192 m upstream of the MVD) and MVD07 (b; located 75 m upstream) from August 2007 through July 2012.
Figure 9. Graphs showing cross section profile evolution of MVD09 (a; located 214 m downstream of the MVD) and MVD10 (b; located 254 m downstream) from August 2007 through July 2012.
Figure 10. Graphs showing cross section profile evolution of MVD11 (a; located 432 m downstream of the MVD) and MVD12 (b; located 538 m downstream) from August 2007 through July 2012.
4. Field Methods

In June 2011 and July 2012, I continued monitoring the response of the Souhegan River to the removal of the MVD using methods of Pearson (2010) and Pearson et al. (2011), which were derived from protocols of Collins et al. (2007).

4.1 Surveying

I quantified continuing geomorphic change in the Souhegan River with repeat cross-section surveys and a longitudinal profile survey. In 2011 and 2012, 12 permanent cross-sections and the longitudinal profile were resurveyed with a Leica TPS 1200 total station with integrated global positioning system (GPS) and a reflecting prism on a stadia rod (Figure 11). I input and analyzed data with Leica GeoOffice Combined software. Cross-sections, established August 2007, are perpendicular to flow and made permanent with rebar monuments, referred to as pins, on both the left and right banks (Figure 4). Cross-sections were surveyed from left pin to right pin (oriented downstream) at approximately 1-2 meter intervals or at significant breaks in slope. At each survey point, I recorded the geomorphology (terrace, riverbed, scarp, scarp top, scarp bottom, or floodplain), substrate (bedrock, boulders, sand, or silt), and water depth for subaqueous locations. In the same manner, in 2012, I surveyed the longitudinal profile moving the prism and stadia rod along the thalweg of the channel (Figure 11). The thalweg is defined as the part of the channel that carries most of the flow; typically this is the fastest and deepest part. The longitudinal profile starts at the Everett Turnpike Bridge and continues downstream to the confluence of the Souhegan and Merrimack rivers (Figure 4).
Figure 11. Images of surveying using Leica TPS 1200 total station equipment (a and b). Surveying the longitudinal profile called for a second field researcher to hold a stadia rod and reflection prism in the thalweg of the channel (c).
<table>
<thead>
<tr>
<th>Date</th>
<th>Notes</th>
<th># of sed samples</th>
<th>Data process state</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 27-28, 2007</td>
<td>Pre-removal full survey: 12 x-secs, sediment sampling, long profile, photo points</td>
<td>4</td>
<td>Completed</td>
</tr>
<tr>
<td>April 21, 2008</td>
<td>Photo points of all x-secs and GPS survey of pins</td>
<td>0</td>
<td>Completed</td>
</tr>
<tr>
<td>Jun 2-8, 2008</td>
<td>Pre-removal full survey: 12 x-secs, sediment sampling, long profile, photo points</td>
<td>10</td>
<td>Completed</td>
</tr>
<tr>
<td>August 25-29, 2008</td>
<td>During-removal full survey: 11 x-sec (no MVD08), sediment sampling, long profile, photo points</td>
<td>26</td>
<td>Completed</td>
</tr>
<tr>
<td>September 17, 2008</td>
<td>Photo points of all x-secs</td>
<td>0</td>
<td>Completed</td>
</tr>
<tr>
<td>October 25-26, 2008</td>
<td>Post-removal survey: 10 x-sec (no MVD01 or MVD08), no long profile, photo points.</td>
<td>0</td>
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</tr>
<tr>
<td>May 5, 2009</td>
<td>GPS survey of the backwater affect from the Merrimack River</td>
<td>0</td>
<td>Completed</td>
</tr>
<tr>
<td>July 13-21, 2009</td>
<td>Summer survey: 9 x-sec (no MVD01, MVD02A, MVD08, or MVD10), no long profile, most sediment samples</td>
<td>8</td>
<td>Completed</td>
</tr>
<tr>
<td>August 24-28, 2009</td>
<td>Summer full survey, 11 x-sec (no MVD08), long profile</td>
<td>1</td>
<td>Completed</td>
</tr>
<tr>
<td>May 13-26, 2010</td>
<td>Spring full survey, 11 x-sec (no MVD08), long profile, photo points, sediment sampling</td>
<td>10</td>
<td>Completed</td>
</tr>
<tr>
<td>June 9-13, 2011</td>
<td>Spring full survey, 10 x-sec (no MVD01 or MVD08), photo points</td>
<td>0</td>
<td>Completed</td>
</tr>
<tr>
<td>July 9-25, 2012</td>
<td>Summer full survey, 11 x-sec (no MVD08), long profile, photo points, sediment samples</td>
<td>14</td>
<td>Completed</td>
</tr>
</tbody>
</table>
I differentially corrected the GPS data from each total station setup with the National Geodetic Survey’s On-line Positioning User Service (OPUS). I input the corrected GPS data into the interface and the OPUS software used the National Spatial Reference System of fixed GPS monuments to improve the accuracy of the base station location recorded by the Leica instrument.

<p>| Table 2. Locations and elevations of pins from tied together surveys from July, 2012 field work on Souhegan River |</p>
<table>
<thead>
<tr>
<th>X-Sec</th>
<th>L Pin Northing</th>
<th>L Pin Easting</th>
<th>L Pin Elevation (m)</th>
<th>R Pin Northing</th>
<th>R Pin Easting</th>
<th>R Pin Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVD02B</td>
<td>4747986.58</td>
<td>296062.22</td>
<td>37.73</td>
<td>4747974.10</td>
<td>296072.88</td>
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<tr>
<td>MVD02A</td>
<td>4748063.09</td>
<td>296029.70</td>
<td>40.42</td>
<td>4748009.42</td>
<td>296053.09</td>
<td>39.22</td>
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<tr>
<td>MVD03</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>4748009.58</td>
<td>296113.60</td>
<td>40.40</td>
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<td>MVD04</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>4748020.84</td>
<td>296190.41</td>
<td>40.56</td>
</tr>
<tr>
<td>MVD05</td>
<td>4748158.83</td>
<td>296173.73</td>
<td>39.14</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>MVD06</td>
<td>4748191.63</td>
<td>296246.19</td>
<td>38.77</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>MVD07</td>
<td>4748262.69*</td>
<td>296304.30*</td>
<td>38.64*</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>MVD09</td>
<td>4748476.42</td>
<td>296405.88</td>
<td>34.03</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>MVD10</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>MVD11</td>
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<td>296581.75</td>
<td>31.96</td>
<td>4748533.26</td>
<td>296563.19</td>
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<tr>
<td>MVD12</td>
<td>4748545.58</td>
<td>296685.06</td>
<td>33.73</td>
<td>4748486.15</td>
<td>296651.50</td>
<td>33.66</td>
</tr>
</tbody>
</table>

Table 2. Asterisk denotes the center pin at MVD07. The horizontal datum is North American Datum (NAD) 1983 and vertical datum is North American Vertical Datum (NAVD) 1988. The coordinate system is Universal Transverse Mercator zone 19T.

Absolute coordinates for all survey points can be gathered if base stations are connected within the same survey, meaning azimuth is set to a previous base station set up (with corresponding differentially corrected position) rather than a random point. The “tying together” of base stations and most comprehensive survey of the entire study period (2007-2012) was done in July, 2012, in order to determine precise locations and elevations of at least one pin (left, right, or center) at each cross-section (Table 2). GPS solutions for the total station surveys have average absolute accuracies of 0.06 m in the horizontal and 0.14 m in the vertical (Armistead, 2013). Every pin location was not
obtained in the tied together survey because of tree cover limiting visibility to pins from total station set ups. Figure 3 shows locations of pins gathered with this comprehensive survey in comparison with data gathered on April 17-21, 2008 using a handheld Trimble GeoXT GPS instrument. Elevation from surveys and handheld GPS data agreed on average within one meter. The handheld survey was less accurate than the 2012 Leica 1200 Total Station surveys because it was not differentially corrected and hindered by tree canopy at the majority of the pin locations.

4.2 Photography: Repeat photography provides a qualitative measure of geomorphic change. I took photographs at each cross-section from both banks looking upstream, cross stream and downstream of the pin. This results in 6 photographs for each cross-section and 72 total photographs (Appendix A).

4.3 Sediment Budget: I calculated the sediment budget using the methods described by Pearson (2010) and Pearson et al. (2011; Figure 12b). This method is based on a series of equations that quantify the rate of channel adjustment and sediment erosion or deposition in the former impoundment and downstream. Pearson (2010) developed the sediment budget of the MVD impoundment system from the balance between upstream sediment input (Input), sediment eroded and deposited in the impoundment (ΔUS Sed), sediment eroded and deposited in the channel downstream of the impoundment (ΔDS Sed), and the sediment output to the Merrimack River (Output) with the general governing equation,

\[ Input + ΔUS Sed = ΔDS Sed + Output \] (1)
The terms in equation (1) can be defined for volume ($ΔV$) or mass ($ΔM$). Output was expected to be zero in first survey period assuming lack of significant sediment transport downstream of the former impoundment while the dam is in place. In later surveys, Output was calculated by summing $ΔUS\ Sed$ and $ΔDS\ Sed$ and subtracting the Input of the survey period. Pearson et al. (2011) estimated Input based on the two pre-removal surveys. Assuming perfect sediment trapping (zero output), the input between August 2007 and June 2008 was 3200 m$^3$. Using the time interval between these surveys the sediment delivery rate was 10 m$^3$/day. The Input for each following survey was then calculated by multiplying the interval between subsequent surveys by this sediment delivery rate.

Interpolation of consecutive pairs of the permanent cross-sections (Figure 4 and 6-10) into $n$ equally spaced points in the cross-stream ($y$) direction allowed me to estimate changes in sedimentation between annual surveys (Pearson, 2010). The average change in thickness ($Δz_i$) of each cross-section (denoted by the subscript, $i$) was determined by:

$$Δz_i = \sum ((z_2 - z_1)/n),$$

(2)

where $z_1$ is the more recent survey and $z_2$ is the previous survey (Pearson, 2010). When $Δz_i$ was negative, the channel had net erosion and when positive it had net deposition. The change in volume ($Δv_i$) was then calculated by:

$$Δv_i = Δz_i A_i,$$

(3)

where $A_i$ represents the area for each cross-section. Areas were calculated from polygons mapped on the orthographic image of the Souhegan River using ArcGIS (Figure 13).
cross-sections were connected left pin to left pin and right pin to right pin and then the connected polygons were divided in half (Pearson, 2010). Each \( A_i \) is half the distance upstream and downstream of each cross-section or half of each polygon is upstream and downstream of the given cross-section. The change in volume at each cross-section (\( \Delta v_i \)) was summed,

\[
\Delta V = \Sigma \Delta v_i, \tag{4}
\]

for both the upstream (\( \Delta V_{US} \)) and the downstream cross-sections (\( \Delta V_{DS} \)) (Pearson, 2010; equation 1).

The sediment budget can also measure change in mass at each cross-section (\( \Delta m_i \)) and was calculated using a constant dry bulk density (\( \rho_{\text{dry}} \)) of 1.3 g/cm\(^3\) from,

\[
\Delta m_i = \Delta v_i \rho_{\text{dry}} \tag{5}
\]

The change in mass was then summed,

\[
\Delta M = \Sigma \Delta m_i, \tag{6}
\]

for both the upstream (\( \Delta M_{US} \)) and the downstream cross-sections (\( \Delta M_{DS} \)) (Pearson, 2010).
Figure 12. Hydrograph showing Souhegan River discharge for the duration of project monitoring, August 2007 through July 2012 (a). Graph of sediment budget calculations upstream and downstream throughout the project monitoring period (b). The sediment budget shows rapid erosion of impoundment sediment and rapid downstream deposition by October, 2008. In following surveys impoundment erosion rate slows and downstream erodes toward pre-removal elevation.
Figure 13. Image showing the polygons surrounding cross sections created by Pearson et al. (2011) and used to measure area when calculating the sediment budget. Polygons, outlined in black, overlay the aerial photograph of the Souhegan River taken in May 2010 (photograph reference: NH Grant).
4.4 **Grain-size:** Thalweg grab samples were obtained during the July 2012 field campaign at each cross-section, except MVD01-03 and MVD07, using a hand-deployable box core. These samples, and ten previously unanalyzed samples gathered by Adam Pearson in May 2010, were dried overnight in an oven at 80°C. I split samples using the cone and quarter method, then massed and sieved at half phi intervals ranging from 63 microns to 16mm running samples for 15 minutes in a Ro-Tap shaker. Cross-sections MVD02A, MVD03, and MVD07 had gravel, boulder and bedrock substrate and grab samples were inappropriate. At these cross-sections, grain-size distribution was characterized using the Wolman pebble count method, measuring clasts in mm selected at random in two-step intervals across channel perpendicular to flow (Wolman, 1954).
5. Modeling Methods

5.1 DREAM Model Inputs and Outputs

The Dam Removal Express Assessment Models are simple morphodynamic sediment transport models developed by Stillwater Sciences. DREAM-1, the model used in this study, requires input data specific to the Souhegan River to be written into nine files (Table 3) using the graphical user interface DREAM1.XLS (Stillwater Sciences, 2002). The creators of this model make assumptions to simplify the input files, such as constant grain-size distribution throughout the field site (Stillwater Sciences, 2002). DREAM-1 also simplifies the channel cross-sections as rectangles with constant width. In reality, channel width varies in an impoundment after dam removal and the channel typically becomes narrower (e.g. Figures 1, 7-8). Cui et al. (2008) justifies this simplification with two reasons. One, typically overbank flow events occur for a small fraction of time and the cumulative sediment transport during these events accounts for a small portion of sediment transport. Two, potential simulation errors introduced by neglecting floodplains during overbank flow events are typically accounted for by other model uncertainties in the model calibration process which usually includes periods of overbank flow. Cui et al. (2008) assumes that approximating cross-section geometry will produce satisfactory results for most applications at reach averaged scale.

Outputs of DREAM-1 include the change in channel elevation and sediment thickness for the successive cross-sections upstream and downstream of the former dam site (Stillwater Sciences, 2002). Output estimates are given in weekly, daily, and hourly results immediately following dam removal. Output time frames reach up to 208 weeks (~4 years), 21 days (~3 weeks), and 24 hours respectively.
To validate the predictions of DREAM-1 I conduct a hindcast using the known model inputs, channel geometry (Figures 5-10), USGS average daily-discharge data (Figure 12a), and sediment-size distribution (Figure 14). Grain-size distribution is
determined from a weighted average of five thalweg grab samples taken at upstream cross-sections in June 2008. I evaluate how well the DREAM-1 output matches the observations of the channel response to MVD removal. The change in elevation is modeled for the downstream reach at intervals that best correspond with dates of the longitudinal profile surveys (Figure 5); at 21 days, 54 weeks, 148 weeks, and 205 weeks after MVD removal.

I graphically compared the results of DREAM-1 to the corresponding longitudinal elevation profiles (Figure 5) and quantitatively compared the elevation simulated by DREAM-1 to the average elevations for each of the cross-section surveys (Figure 6-10). Comparing DREAM-1 outputs to average cross-section elevations is necessary as the model output is a longitudinal profile which simulates an average elevation at each distance from the dam rather than simulating detailed cross-sections. The longitudinal profiles surveyed from June 2008 through July 2012 were taken through the thalweg of the channel and do not show the average channel elevation but the deepest point. To compare the DREAM-1 simulations to the average cross-section elevations, I took the average of the differences between DREAM-1 simulations and actual observations data to quantitatively evaluate DREAM-1 predictions. Lastly, I used the changes in elevation simulated by DREAM-1 at each cross-section located to develop a sediment budget curve comparable to sediment budget calculations of Pearson et al. (2011; Figure 12b)
Figure 14. Graph showing grain size distribution of the hindcast and sensitivity analysis model run using increased grain size (increased median grain size by one phi variation). DREAM-1 requires grain size input file to be cumulative percent finer (a). The input data is graphed again as weight percent (b).
5.2 DREAM-1 Governing Equations and Theory

DREAM-1 is governed by several fluid flow and sediment transport equations. The physical characteristics of the flow are calculated with both the standard backwater equation and quasi-normal flow assumption based on the Froude Number (Stillwater Sciences, 2002). Froude Number ($F$), or the dimensionless parameter that measures the ratio of inertia on fluid to the gravitational force, is defined as

$$F = \frac{u}{\sqrt{gh}}$$

(7)

where $u$ denotes flow velocity, $g$ is the acceleration due to gravity, and $h$ is the water depth. When the $F$ is greater than one flow is supercritical and when less than one flow is subcritical. The velocity in equation (7) is found using

$$u = \frac{Q_w}{B_f h}$$

(8)

where $Q_w$ is daily-discharge and $B_f$ is bankfull width (Stillwater Sciences, 2002).

When Froude Number is low the model applies the standard backwater equation,

$$\frac{dh}{dx} = \frac{S - S_f}{1 - F^2} \text{ if } F < 0.9,$$

(9)

in which $x$ represents the distance downstream, $S$ represents local channel slope, and $S_f$ represents the frictions slope, or slope of the water surface profile. When $F$ is high, DREAM-1 applies the quasi normal flow assumption (Stillwater Sciences, 2002):

$$S_f = S, \text{ if } F \geq 0.9$$

(10)

In both equations (9) and (10) $S$ is calculated with,

$$S = \frac{-\delta (\eta_b + \eta_g + \eta_s)}{\delta x}$$

(11)

Equation (11) measures slope as the change in elevation with respect to change in distance downstream ($\delta x$). Thickness of bed material is divided into several parts.
\( \eta_b \) is elevation of non-erodible material such as bedrock, \( \eta_g \) is gravel deposit thickness, and \( \eta_s \) is sand deposit thickness.

DREAM-1 uses Brownlie’s bed material equation (Brownlie, 1981) to calculate transport capacity of sand through the system. The equation was empirically derived and measures sediment concentration, \( C \), as

\[
C = 7100 c_f \left( S^{1/3} F_g - S^{1/3} F_{go} \right)^2 \left( \frac{r}{D_{50}} \right)^{-1/3},
\]

(12)

where \( F_g \) is the grain related Froude number, \( F_{go} \) is the critical grain Froude number associated with critical shear stress, \( r \) is hydraulic radius, and \( D_{50} \) is median grain-size (Brownlie, 1981). Further, the lateral sand supply rate \( (q_{sl}) \), measured for each cross-section input width, is calculated with

\[
q_{sl} = (1 - \lambda_p) B_f \left( \frac{\delta \eta_s}{\delta t} + \frac{\delta Q_s}{\delta x} \right),
\]

(13)

where \( \lambda_p \) denotes porosity, \( \delta \eta_s/\delta t \) denotes change in sand deposit thickness over time, \( Q_s \) represents the volumetric sand transport rate (determined from annual bedload and washload inputs) and \( x \) denotes downstream distance (Stillwater Sciences, 2002).

Deposition of washload, the portion of sediment carried by the flow that remains in suspension, downstream of the impoundment after dam removal is not accounted for in DREAM-1. The model assumes washload stored in the impoundment sediment will be eroded and transported downstream without re-deposition within the system.

The model can simulate “one-shot” removal (dam is completely removed at one time) or staged removal projects (dam is removed in stages over an extended period of time ranging from months to years). It can also incorporate minimal or significant dredging prior to dam removal. For staged dam removals, when the dam is removed in sections beginning with the top, the model assumes a free surface flow. When the
scenario includes partial dredging, or mechanical removal of reservoir sediment, the model assumes that dredging removes the top layer sediment without mixing layers *(Stillwater Science, 2002)*. These additional assumptions do not impact this study as the MVD removal employed a one-shot removal with no dredging.

### 5.3 The Zeroing Process

Users implement the DREAM-1 zeroing process, similar to a model calibration, prior to simulating dam removal. DREAM-1 zeroing process runs the model with all known inputs while the dam is in place. The zeroing process produces a downstream elevation profile that represents the long term equilibrium state with no net deposition or erosion (Figure 15). The dam removal simulations are compared to this starting condition equilibrium profile. The zeroing process profile should be similar to the downstream profile observed prior to dam removal. However, ideally the zero process profile should be similar to the longitudinal profile before the dam was installed. This information is unavailable for the MVD field site. The purpose of the zeroing process is to simplify complicated physical processes and model inputs taken from field data which tend to have large margins of uncertainty. This often results in irregular aggradation and degradation in various reaches of the channel *(Cui et al., 2006b)*.

The zeroing process for this project included known inputs of channel geometry and sediment-size distribution taken from field sediment sampling and surveying. Base elevation for the input profile was chosen to be lower than the observed deepest points of the thalweg at each cross-section. Upstream, the base elevation follows the observed longitudinal profiles taken after dam removal showing the deepening of the channel at
~300 m upstream of the MVD (Figure 15). Downstream, base elevation was input as 26 m thereby lower than the deepest point of the thalweg observed in June 2008 and assumed to be an elevation at which the channel could not erode further. Annual sediment load input was 3800 m$^3$/year, based on the Pearson et al. (2011) measurements of input sediment load between the pre-removal surveys, August 2007-June 2008. The hydrograph used in the zeroing process ran from point of dam removal through four years after removal, August 6, 2008 through August 4, 2012. While the zeroing process outputs the reference state for the downstream, the upstream profile initial state is input to the model. The upstream profile was input from upstream cross-section geometry, channel width and average elevation, observed during the surveys taken before MVD removal in August 2007 and June 2008. Pearson et al. (2011) reported a pre-removal gradient in the downstream sand reach as 0.0006 while the zeroing process using these inputs produced a downstream elevation profile with gradient of 0.0007 (Figure 15).
Figure 16. Graph of the reference state of DREAM-1 simulations. The downstream profile is the graphical output of the zeroing process showing the one dimensional profile of the bed elevation. The upstream profile, input by the user, is based on average channel bed elevations from the cross sections of June 2008. Upstream base elevation follows shape of May 2010 and July 2012 longitudinal profiles and is below the deepest scours. Downstream base elevation is at constant 26 m elevation below deepest scours of the pre-removal longitudinal profiles.
DREAM-1 zeroing process differs from a model calibration because the user is not changing any parameters. During the process, the model slightly adjusts several input parameters including sediment supply, downstream channel gradient, and downstream channel width. Cui et al. (2006b) notes that these input parameters have margins of uncertainty and can lead to spurious periods of aggradation or degradation. The model adjusts these parameters to minimize excessive changes to the downstream profile and allow for only minor aggradation and degradation over time. If the zero process results in a downstream longitudinal profile with spurious aggradation or degradation then the input parameters required excessive modification and DREAM-1 may be inapplicable. Assuming the profile produced by the zeroing process is the quasi-equilibrium state of the channel, patterns of erosion and deposition produced in later model simulations are results of dam removal rather than hydrological events (Cui et al., 2006b).
6. Fieldwork Results: June 2011 and July 2012

The second objective of this study is to continue the work of Pearson et al. (2011) and Pearson (2010). For the most recent two survey periods (May 2010-June 2011 and June 2011-July 2012), I continued to monitor and quantify the response of the Souhegan River with field work and data analysis.

6.1 Cross-section and Longitudinal Surveys

The permanent cross-sections were resurveyed in June 9-13, 2011 and July 9-25, 2012. Cross-sections in far upstream reach exhibited nearly identical profiles with very little erosion or deposition. Specifically, MVD02A and MVD02B (Figure 6) have eroded to bedrock and have not changed since August 2008. Note that during the 2010 to 2011 survey period the left pin at MVD01 was buried under rip rap due to Everett Turnpike Bridge maintenance and in the July 2012 survey MVD01 was surveyed from the right pin to the left bank on top of the rip rap. The MVD01 profile extended over the left bank to the top of the rip rap abutting the Everett Turnpike Bridge. Cross-section MVD03 (Figure 7a), with substrate characterized by boulders and bedrock, also changed little in the most recent survey periods.

More proximal to the former dam site, MVD04 (Figure 7b) changed in the recent two surveys. In June 2011, I observed slight scouring in channel left, which continued through July 2012. The exposed sand bar in the center of the channel remained with no measurable accretion or degradation. MVD05, the longest and one of the most dynamic cross-sections, continued to change since May 2010 (Figure 7c). By June 2011, the mid-channel island continued to erode on the river right slope. Also during this survey period,
the left channel eroded up to 1 m. The following survey, July 2012, showed negligible erosion or deposition, however the thalweg completely shifted from the right to the left side of the mid channel island. The June 2011 survey showed erosion up to 1.25 m in the middle of the channel at MVD06 (Figure 8a). The elevation profile remained essentially unchanged from June 2011 to July 2012. The channel at MVD07 remained similar in the recent two survey periods (Figure 8b). The wetland portion to the west of the channel at MVD07 remained dry, heavily vegetated, and characterized by narrow channels.

Cross-sections downstream of the former impoundment were more dynamic in terms of localized deposition and erosion during the past two survey periods than those upstream, as was the case prior to dam removal. In June 2011, I observed accretion through the center of the channel at MVD09, maximum infill of 1.5 m, and deep scour in channel right (Figure 9a). By July 2012, the scour hole filled, channel bed elevation increase by 1.3 m. The June 2011 survey also documented substantial change to the MVD10 profile (Figure 9b). The thalweg at this cross-section flows through channel left with a large sand deposit extending approximately 70 m to the channel right pin. From May 2010 to June 2011, the channel scoured the thalweg approximately 2 m. In addition, the exposed bar eroded almost 2 m of sand to the right of the thalweg. The July 2012 profile at MVD10 remained similar to the June 2011 survey.

The two cross-sections farthest downstream also varied slightly in the final two surveys. At MVD11 (Figure 10a) the channel deepened ~0.75 m from May 2010 to June 2011. This trend continued in the most recent survey with scour of ~0.4 m in channel right. At MVD12 (Figure 10b), the channel eroded in channel right from May 2010 through June 2011. In channel left the channel bed aggraded and exposing sand bed
above the water surface. By July 2012 the exposed sand in channel left degraded. In the mid channel, the riverbed section continued to scour. This deepening was likely the result of a downed white pine tree lodged in the channel. The white pine diverted flow around the trunk which most likely created the steeply rising exposed mud bar in river right (Figure 10b).

6.2 Sediment Budget

Gomez and Sullivan (2006) estimated that prior to MVD removal there was 62,000 m$^3$ of sediment in the impoundment. Upon removal of the MVD in August 2008, the Souhegan River began rapidly eroding this sediment. The majority of the mobilized impoundment sediment in the three weeks following dam removal was deposited immediately downstream. This deposit was later mobilized and exported to the Merrimack River. Specific details on annual sediment mobilization can be found in Table 4, which is a continuation of research presented in Pearson et al. (2011).

Pearson et al. (2011) postulated that the response of the Souhegan River to MVD removal occurred in two phases, rapid impoundment incision followed by a phase of gradual erosion, accelerated during high flow events (Table 4; Figure 11). Impoundment sediment rapidly eroded following dam removal losing ~50% of sediment by the October 2008 survey. Pearson et al. (2011) concluded this rapid incision and erosion of impoundment sediment was process-driven (Pizzuto, 2002) and induced by the initial 3.9 m base level drop. The loss of impoundment sediment slowed in the subsequent surveys, August 2009 through July 2012, indicating an event-driven response. In the most recent two surveys, June 2011 and July 2012, the loss of impoundment continued at a slower
rate, 1-2% loss per year, continuing the asymptotic trend of gradual erosion observed from August 2009-May 2010 by Pearson et al. (2011). Further, impoundment sediment is not retained in the downstream reach of the system. I hypothesize that in future years high discharge events, similar to those 5-10 year recurrence interval floods in March 2010, would most likely be necessary to erode impoundment sediment at a rate exceeding 1-2% per year (Figure 11). After the initial stage of incision, further erosion of the impoundment sediment occurs by channel widening (Figures 6-8). High discharge events are necessary to access and erode sediment on the banks of the Souhegan River in the former impoundment.

### Table 4. Sediment Budget Calculations from August 2007 through July 2012

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Input</th>
<th>ΔUS Sed</th>
<th>US Rate</th>
<th>ΔDS Sed</th>
<th>DS Rate</th>
<th>Output</th>
<th>Percent Impoundment Remaining</th>
</tr>
</thead>
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<td>08/07-06/08</td>
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<td>1982 ± 1130</td>
<td>6.5</td>
<td>987 ± 690</td>
<td>3.2</td>
<td>0</td>
<td>100.0</td>
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<td>307 days</td>
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<td>1282 ± 940</td>
<td>4.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>06/08-08/08</td>
<td>230</td>
<td>-17674 ± 2130</td>
<td>-736</td>
<td>18834 ± 1640</td>
<td>785</td>
<td>930</td>
<td>71.5</td>
</tr>
<tr>
<td>24 days</td>
<td>300</td>
<td>-2294 ± 1850</td>
<td>-932</td>
<td>24484 ± 2650</td>
<td>996</td>
<td>1703</td>
<td></td>
</tr>
<tr>
<td>08/08-10/08</td>
<td>560</td>
<td>-12814 ± 1920</td>
<td>-221</td>
<td>-4041 ± 670</td>
<td>-70</td>
<td>17415</td>
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</tr>
<tr>
<td>58 days</td>
<td>710</td>
<td>-16138 ± 2050</td>
<td>-274</td>
<td>-5253 ± 770</td>
<td>-89</td>
<td>22101</td>
<td></td>
</tr>
<tr>
<td>10/08-08/09</td>
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<td>-23</td>
<td>-4539 ± 1040</td>
<td>-15</td>
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<td>-28</td>
<td>-5901 ± 1230</td>
<td>-19</td>
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<td></td>
</tr>
<tr>
<td>08/09-05/10</td>
<td>2500</td>
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<td>-42</td>
<td>1816 ± 670</td>
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<td>11371</td>
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<td>257 days</td>
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<td></td>
</tr>
<tr>
<td>05/10-06/11</td>
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<td>-2799 ± 1060</td>
<td>-7.4</td>
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</tr>
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<td>379 days</td>
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<td>06/11-07/12</td>
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<td>-3779 ± 740</td>
<td>-9.6</td>
<td>9353</td>
<td>18.7</td>
</tr>
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<td>-4913 ± 890</td>
<td>-12</td>
<td>11891</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.** Bolded values indicate calculations from surveys after the MVD removal. Volumes are measured in m³ except values in italics, which are masses measured in metric tons. Negative numbers indicate net erosion for the survey period and positive numbers indicate net deposition. Output is expected to be zero in first survey period assuming lack of significant sediment transport downstream of the former impoundment while the dam is in place (Pearson et al., 2011). This study assumes a constant sediment budget from the June 2008 survey to the time of dam removal on August 6, 2008. Percentages of impoundment remaining are masses calculated in relation to the initial impoundment sediment volume estimated by Gomez and Sullivan Engineers (2006). Information in Table 4 is also available in Figure 19.
6.3 Grain-size

Grain-size data showed monotonic coarsening (Table 5; Figure 16) at MVD02 and MVD03 for sediment samples taken after June 2008. During the most recent survey, pebble counts at MVD03 (Wolman, 1954) remained dominated by boulders and bedrock. MVD04 had similar median grain-size, coarse sand, as previous sample taken in May 2010. MVD05 and MVD06 remained sandy except for coarsening at MVD07, characterized with pebble count in July 2012. Cross-sections downstream of the former dam site remained sandy in the most recent survey.

Table 5. Comparison of median (mm), mean (mm), and standard deviation (mm) for grain-size distribution.

<table>
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<tr>
<th>Date</th>
<th>MVD</th>
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<th>03</th>
<th>04</th>
<th>05</th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
<th>10</th>
<th>11</th>
<th>12</th>
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<tr>
<td>Jun-08</td>
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<td>0.61</td>
<td>0.62</td>
<td>0.34</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.47</td>
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</tr>
<tr>
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<td>Mean</td>
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<td>0.59</td>
<td>0.37</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
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<td>0.34</td>
<td>0.60</td>
</tr>
<tr>
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<td>std. dev.</td>
<td>0.67</td>
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<td>0.55</td>
<td>0.59</td>
<td>0.59</td>
<td>0.40</td>
<td>0.58</td>
<td>0.58</td>
<td>0.61</td>
<td>0.41</td>
<td>0.71</td>
</tr>
<tr>
<td>Aug-08</td>
<td>median</td>
<td>31</td>
<td>49</td>
<td>2</td>
<td>0.54</td>
<td>0.75</td>
<td>0.82</td>
<td>0.81</td>
<td>1</td>
<td>1</td>
<td>0.80</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>123</td>
<td>159</td>
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<td>0.53</td>
<td>0.76</td>
<td>0.87</td>
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<td>2</td>
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<td>std. dev.</td>
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<td>0.62</td>
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<td>0.54</td>
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<td>0.36</td>
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<td>0.59</td>
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<tr>
<td>Aug-09</td>
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<td>174</td>
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<td>18</td>
<td>X</td>
<td>17</td>
<td>X</td>
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<td></td>
<td></td>
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<tr>
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<td>277</td>
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<td>X</td>
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<td>X</td>
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<tr>
<td>May-10</td>
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<td>0.61</td>
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<td>188</td>
<td>2</td>
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<td>0.71</td>
<td>X</td>
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</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>149</td>
<td>215</td>
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<td>0.51</td>
<td>0.58</td>
<td>0.51</td>
<td>X</td>
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<td>0.20</td>
<td>0.64</td>
<td>0.58</td>
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<tr>
<td>Jul-12</td>
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<td>237</td>
<td>2</td>
<td>0.77</td>
<td>1</td>
<td>10</td>
<td>X</td>
<td>0.53</td>
<td>1</td>
<td>0.57</td>
<td>0.77</td>
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</tr>
<tr>
<td></td>
<td>mean</td>
<td>309</td>
<td>1</td>
<td>0.57</td>
<td>1</td>
<td>85</td>
<td>X</td>
<td>0.33</td>
<td>1</td>
<td>0.46</td>
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</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>X</td>
<td>248</td>
<td>0.27</td>
<td>0.31</td>
<td>0.53</td>
<td>215</td>
<td>X</td>
<td>0.26</td>
<td>0.52</td>
<td>0.28</td>
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</table>

Table 5. Comparison of grain-size distribution from August 2007-July 2012. Shaded cells are cross-sections at which pebble counts were used to characterize the substrate. Cross-sections with X denote that substrate was unable to be characterized at that time.
Figure 16. Graph of median grain sizes in the Souhegan impoundment and downstream of the former MVD. Sediment is primarily sand but boulders and bedrock characterized cross sections MVD02, MVD03 and MVD07.
7. Hindcast Results and Discussion

DREAM-1 successfully captured the two phase channel response, rapid initial response followed by period of gradual change, both upstream and downstream from the former location of the MVD. Later analysis (Section 8) aims to determine the impact of hydrology, specifically discharge, driving the two phase reaction. Here, I visually compare model simulations to the longitudinal profile surveys taken annually to semi-annually (Figure 17). Next, I compare model simulations to average elevations of each cross-section (Figure 18). Finally, I replicate the sediment budget for each model run and compare those calculations to the sediment budget response reported by Pearson et al. (2011).
Figure 17. Graph comparing hindcast DREAM-1 simulations and longitudinal profiles taken from June 2008 through July 2012. Longitudinal profiles appear visually to the simulations predicted by the DREAM-1 hindcast.
Figure 18. Graph showing average elevations of annual cross sections in comparison with hindcast simulations. Average elevations agree within one meter of elevation simulated by DREAM-1.
7.1 Profiles

DREAM-1 simulations show erosion of impoundment sediment within three weeks of dam removal, corresponding to the August 2008 longitudinal survey, and rapid deposition downstream of the MVD (Figure 17-18). The downstream deposit takes form of a ramp with maximum thickness of approximately 1.7 m at end of the steep bedrock reach, 100 m downstream from the dam site (Figure 17). The model simplifies the channel geometry into rectangles instead of detailed cross-sections meaning DREAM-1 simulates an average channel bed elevation at each distance upstream and downstream from the former MVD. Due to this simplification, simulations of DREAM do not include scour and fill in the cross-stream direction. To account for this, I compare and plot the average elevation of each cross-section to the projections of DREAM-1 that correspond with the distance from the former MVD and time of the survey (Figure 18). Again, DREAM-1 longitudinal profiles appear to capture the observed average cross-section elevations.

The average absolute difference between cross-section elevation and DREAM-1 simulation for the upstream region is DREAM-1 is ±0.35 m (Table 6). MVD03 has the lowest average difference between modeled and surveyed elevations among all cross-sections, at 0.13 m. The remaining upstream cross-sections exhibit higher average differences between modeled and surveyed elevation ranging from 0.33-0.44 m. Analysis of the cross-sections downstream shows similar results when compared with the hindcast. The average difference between average elevation of the downstream cross-sections and DREAM-1 simulations is 0.40 m (Table 6). Individual discrepancies between DREAM-1 simulations and average cross-section elevations values are within
one meter. There are several outliers with higher discrepancies between DREAM-1 and average elevation such as MVD06 during October 2008 with a difference of 0.93 m and MVD10 during May 2010 with a difference of 0.90 m. These data do not suggest that results change with time after dam removal. Each cross-section exhibits fluctuations at various survey intervals. There does not appear to be a clear trend in the data set that would suggest the results of DREAM-1 are dependent on proximity of simulations to dam removal.
<table>
<thead>
<tr>
<th>Dates</th>
<th>Weeks</th>
<th>MVD02</th>
<th>DREAM</th>
<th>Difference</th>
<th>MVD03</th>
<th>DREAM</th>
<th>Difference</th>
<th>MVD04</th>
<th>DREAM</th>
<th>Difference</th>
<th>MVD05</th>
<th>DREAM</th>
<th>Difference</th>
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<th>DREAM</th>
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<td>36.09</td>
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**Averages**  
0.34 ± 0.08  
0.13 ± 0.11  
0.40 ± 0.25  
0.41 ± 0.23  
0.44 ± 0.26  
0.36 ± 0.30

Table 6. Differences between DREAM-1 and cross section elevations are reported in meters and as absolute values. Standard deviations of the difference calculations are done for each cross section from June 2008 through July 2012 and measure less than 0.30 m.
7.2 Sediment Budget

The hindcast sediment budget (Figure 19c) overestimates the erosion of the impoundment in the first three weeks after MVD removal, simulating loss of 70% impoundment sediment (Figure 19). By 11 weeks the hindcast shows 13% impoundment sediment remaining and later surveys (48-204 weeks) result in 10-11%. Essentially, the hindcast shows two phases of upstream response. As discussed in section 6.2, Pearson et al. (2011) explains the initial rapid impoundment erosion as process-driven and the following phase of slower erosion as event-driven. The hypothesis of an event-driven phase is based on the notable increase in erosion from the impoundment from August 2009 through May 2010 and its correlation with two flood events in March 2010 (Figure 11). DREAM-1 does not simulate the increase in impoundment erosion in May 2010, 93 weeks, because the impoundment has already eroded almost to the base elevation. The overestimation of impoundment sediment loss impedes the ability of the model to detect whether the second phase of gradual erosion is influenced by hydrology.

The choice of base elevation, defined as the point at which the channel cannot erode below (e.g., the bedrock surface), could influence the overestimation of impoundment erosion. Upstream base elevation follows the minima observed on longitudinal profiles taken after dam removal and downstream base elevation was input as 26 m thereby lower than the deepest point of the thalweg observed in June 2008 (Figure 5; section 5.3). As observed by Pearson et al. (2011) the MVD was built on bedrock and the bedrock reach extends 0.1 km downstream. The bedrock at the dam site sets the minimum elevation for the pre-dam river profile, and the rest of the former impoundment could not have been far below this elevation, constraining the base
elevation model input values. The hindcast simulation shows channel erosion to base
elevation throughout the majority of the impoundment by 3-11 weeks (Figure 17-18).
Base elevation could be important in the former impoundment because the model erodes
to it very rapidly (compared to observations), but it cannot erode lower because of the
known elevation of underlying bedrock. A decreased input base elevation profile may
allow the channel simulation to erode as deep as permitted by the user, meaning accuracy
of this parameter is important.

A likely explanation for the model’s overestimation of impoundment erosion rate
is that DREAM-1 does not allow for variation in width during the simulation. Pizzuto
(2002) and Doyle et al. (2003) explain that after initial channel incision the impoundment
undergoes a period of channel widening (Figure 1) during which high-flow events erode
sediment stored on channel banks. By not allowing channel width to vary and assuming
rectangular cross-sections, DREAM-1 assumes laterally uniform sediment transport (Cui
et al. 2008) out of the reservoir and no possibility for sediment storage on the sides of the
evolving channel in the former impoundment. By predicting uniform lateral erosion of
impoundment sediment, DREAM-1 predicts channel incision to base elevation and loss
of the majority of impounded sand within 11 weeks, and the model fails to predict any
upstream erosion attributed to the March 2010 floods.

The downstream response simulated by DREAM-1 more accurately captures the
observations of Pearson et al. (2011; Figure 19c). The hindcast shows a downstream
deposit of 33% of the eroded impoundment sediment within the first 3 weeks,
comparable to the 30% reported by Pearson et al. (2011). Pearson et al. (2011) observed
the downstream retaining 24% by 11 weeks and 17% by 54 weeks and the simulation
shows similar results as the deposit retains 31% and 16%, respectively. During the next survey period, corresponding with August 2009 through May 2010, the hindcast fails to simulate the observed 3% increase and shows that the deposit continues to retain 16% of the transported impoundment sand. In the final two survey periods, DREAM-1 shows the downstream reach retains 11% at 148 weeks and 9% at 204 weeks, approximately four years after removal, identical to the final downstream sediment budget calculation for the July 2012 survey period (Figure 19c).

The downstream part of the study area also shows a two-phased response, with fast deposition in the first three weeks followed by a phase of slow erosion of that deposit (Figures 11 and 19c). Similar to the upstream response simulated by DREAM-1, the hindcast does not capture the slight increase in deposition (3%) that occurred from August 2009 to May 2010 (Figure 12b). This is likely because DREAM-1 predicts little to no sand remaining in the impoundment to erode during the March 2010 floods (Figure 19c). Without erosion and transport of sediment stored on channel banks, the channel has no sediment to transport and deposit downstream. Again, the model simulates two phases but the second phase cannot capture the event-driven change seen in May 2010, likely because of the model’s inability to capture deposition on channel banks and variation in channel width.
Figure 19. Graphs comparing hydrographs and sediment budgets for various model runs. Comparison of the DREAM-1 scenario hydrographs, doubled initial and half initial discharge scenario (a), are highlighted from the actual Souhegan hydrograph (b). Sediment budgets for each DREAM-1 scenario, including varying hydrographs and varying impoundment sediment size, compared to the sediment budget calculated by Pearson et al. (2011) show a two phase response in all DREAM-1 simulations both up and downstream of the MVD (c).
8. Hydrology Discussion

8.1 Pearson et al. (2011) Hypothesis Overview

According to the two-phase response suggested by Pearson et al. (2011), hydrology did not drive the initial rapid response of the Souhegan River impoundment, meaning that an increase or decrease in discharge during the time of removal would not greatly alter the rapid impoundment erosion. Further, Pearson et al. (2011) hypothesized that high discharge events should induce periods of deposition and erosion from August 2009 through July 2012. Specifically, the March 2010 floods caused an increase in impoundment erosion and downstream deposition in the May 2010 survey (Figure 12b). My hydrology analysis aims to investigate both parts of this hypothesis and evaluate how hydrology influences the results of DREAM-1 modeling during the initial and later channel responses.

8.2 Process-Driven Phase Investigation

To investigate the hypothesis of Pearson et al. (2011) claiming the process-driven phase as independent of discharge, I vary the discharge input of DREAM-1 for the first 6 weeks (double the first survey period length) after dam removal by a factor of two (Figure 19a) and compare models runs to field data for the varied discharge scenarios. First, I compare the zero process simulations for the hindcast, doubled discharge and halved discharge. The zero process profile with double discharge is slightly more gradual, 0.0006, and halved discharge slightly steeper, 0.0008 (Figure 20).
Figure 20. Graph of zero process simulations when varying the daily discharge values. The graph shows a steeper profile in the zero process for low discharge values and a gentler sloping profile with high discharge values.
Increased discharge during the first six weeks after dam removal does not impact the modeled response of the Souhegan River (Figure 21). In the simulation with doubled discharge, there is a slight increase in the amount of impoundment sediment eroded in the first three weeks. Downstream, the profile appears similar to that of the hindcast with a slightly more gradual ramp of sediment. By 6 weeks, the hindcast shows scouring immediately downstream of the steep bedrock reach. These scours fill gradually by 9 and 12 weeks and are no longer evident by 24 weeks after removal. The profiles modeled with double discharge do not indicate scouring immediately downstream of the bedrock reach at 6 weeks. The longitudinal profiles were surveyed in August 2008, ~3 weeks after removal, and October 2008, ~11 weeks after dam removal (Figure 5). The field data lacks quantitative information of channel response during the time between these surveys, a potential limitation when analyzing the ability of DREAM-1 to accurately simulate the process-driven phase. The profiles simulated at 12-54 weeks are extremely similar in the downstream reach. DREAM-1 simulations show channel incision to base elevation in the impoundment within the first 3-6 weeks meaning a lack of sedimentation change after 12 weeks (Figure 15).

Decreased discharge in the first 6 weeks after dam removal also fails to show much impact on the modeled response. The half discharge scenario yields a slight decrease in the amount of impoundment sediment eroded in the first three weeks (Figure 22). Downstream, two scours occur at 350-400 m from the former MVD. These scours erode to the pre-removal profile but are temporary and not apparent at 6 weeks. The low discharge scenario simulates a slower impoundment erosion rate, observed at 3 and 6 weeks, than that simulated in the hindcast scenario. By 12 weeks, the simulations of the
hindcast and half discharge scenarios appear to coincide in both the upstream and downstream reaches. By 24 weeks profiles of the two DREAM-1 scenarios are almost identical. This is consistent with the observation that at some point each scenario shows the impoundment incising to the base level set by bedrock at the former dam site.

To quantitatively evaluate the varied discharge scenarios during the process-driven phase, I calculate the sediment budget in comparison to the sediment budget of the hindcast (Figure 19a). All DREAM-1 scenarios greatly overestimate the rate of impoundment erosion by 40-60% in the first three weeks following removal (Figure 12b). Doubled initial discharge produces the highest rate of erosion, loss of 85% of impoundment sediment in the first survey period and low initial discharge simulates impoundment sediment erosion of 67% (Figure 19c). By the time of the October 2008 survey, 11 weeks, each scenario simulates similar amounts of impoundment sediment remaining, 10-13%. DREAM-1 scenarios have more success in simulating the downstream response. The hindcast simulates deposition of 33% of impoundment sediment, 3% greater than that observed in sediment budget by Pearson et al. (2011; Table 4; Figure 12b). The high initial discharge scenario simulates more deposition, 40%, and the low initial discharge scenario simulates less deposition, 28%. All three DREAM-1 scenarios capture the initial rapid downstream deposition in the first 3 weeks followed by gradual channel bed degradation back towards the pre-dam removal elevation profile.

The two phases observed in the hindcast, fast initial response followed by a longer period of gradual response, are also apparent in the varied discharge scenarios (Figures 19, 21, and 22). In both the high and low discharge scenarios, I observe an initial period of rapid erosion in the impoundment. DREAM-1 predicts slightly faster erosion to the
base elevation profile with high discharge during dam removal and slightly slower erosion with low discharge (Figure 19c). However, reduction and increase in discharge during removal does not inhibit fast impoundment erosion, and the initial response remains consistent with the process-driven hypothesis. The DREAM-1 scenarios simulate two distinctly sloping curves, steep rapid erosion and a gradually sloping arc of slower erosion (Figure 19c) combining to form an asymptotic response of impoundment erosion similar to the curve observed by Pearson et al. (2011) and shown in Figure 12b.
Figure 21. Graphs showing DREAM-1 simulations using doubled discharge of daily hindcast for the first 6 weeks after dam removal.
Figure 21 (continued). Graphs showing DREAM-1 simulations using doubled discharge of daily hindcast for the first 6 weeks after dam removal.
Figure 22. Graphs showing DREAM-1 simulations using halved discharge of daily hindcast for the first 9 weeks after dam removal.
Figure 22 (continued). Graphs showing DREAM-1 simulations using halved discharge of daily hindcast for the first 6 weeks after dam removal.
8.3 Event-Driven Phase Investigation

As discussed previously, the rapid erosion of the impoundment to base elevation in the first 3-11 weeks hinders the model’s ability to simulate sedimentation changes in later survey periods. The results of the event-driven phase are not evident in the DREAM-1 simulations because the model excavates close to the full impoundment volume prior to the March 2010 floods (Figures 17-19). Variations in discharge after that time do not produce variations in erosion and deposition because there is no longer much impoundment sediment available for transport. The results suggest that DREAM-1 is unable to simulate the event-driven phase as the process-driven phase dominantly shapes the response of the impoundment. To test this interpretation and investigate the event-driven phase further, I vary the discharge values from March 14-April 1 (all reported as greater than 29 m$^3$/s by USGS gauge 01094000) by a factor of two to observe further change to the sedimentation rate with varying hydrographs (Figure 23).

As expected, the scenario of doubled March 2010 (83-84 weeks after removal) discharge yields almost identical longitudinal profiles upstream and downstream of the MVD when compared to the hindcast at 83 weeks (Figure 24a-b). By 84 weeks, the increased discharge scenario reports a slight increase in impoundment erosion at approximately 350 m upstream from the MVD. When the March 2010 discharge is reduced by factor of two, DREAM-1 again produces profiles similar to that of the hindcast at 83 weeks (Figure 24c-d). By 84 weeks, the upstream profiles simulated with this scenario and the hindcast remain almost identical. Even when doubling and halving input discharges at 83-84 weeks DREAM-1 fails to result in changes to the downstream
sedimentation because the impoundment lacks stored sand and is completely eroded to base elevation.
Figure 23. Graph comparing doubled and halved discharge during the March 2010 (83-84 weeks) high discharge events (a) are highlighted from the actual Souhegan hydrograph (b).
Figure 24. Graphs showing DREAM-1 hindcast simulations compared to simulations inputting doubled discharge values for 83 weeks (a) and 84 weeks (b) after dam removal, correlating with the March 2010 floods.
Figure 24 (continued). Graphs showing DREAM-1 hindcast simulations compared to simulations inputting half discharge values for 83 weeks (c) and 84 weeks (d) after dam removal, correlating with the March 2010 floods.
8.4 Impoundment Grain-size Distribution Investigation

Pizzuto (2002) describes impoundment incision with regard to grain-size stating that gravel impoundments erode during high flow events (event-driven) whereas sand and silt impoundments erode by a variety of processes, some of which are not directly dependent on discharge (process-driven). This hypothesis suggests that a coarser impoundment input should result in DREAM-1 simulating a slower impoundment response as larger grains require more energy for transport and result in less sediment transport in the far downstream reach and out of the system. To investigate this, I increase the grain-size distribution input by shifting the median grain-size up by one phi (Figure 14). The median grain-size is then characterized as coarse sand (1-2 mm diameter). Results of the model run show slower impoundment erosion in the first three weeks (Figure 25), with erosion of 53% impoundment volume (Figure 19c). However the model simulates that even with increased grain-size distribution in the impoundment the channel still erodes to base level by 11 weeks (Figure 25). This DREAM-1 scenario follows the trend of earlier scenarios with the two-phased impoundment response. Specifically, I continue to observe two distinct slopes in the upstream sediment budget response meaning increased grain-size did not greatly diminish the process-driven phase (Figure 19). Downstream, the simulation results in increased deposition by three weeks, 47% of impoundment sediment. The channel erodes the downstream deposit to 39% of impoundment sediment by 11 weeks. By 204 weeks the downstream reach still retains 24% of impoundment sediment (Figure 19c). This DREAM-1 scenario results in the highest retention of sediment downstream by 204 weeks.
Cui et al. (2006b) found that grain-size distribution impacts model outputs more than any other input parameter. After conducting several sensitivity tests, Cui et al. (2006b) further concluded that the grain-size distribution of the reservoir sediment is the most important piece of information to collect in the field and that other parameters are less influential on model results. This study’s model run of varied grain-size distribution shows similar results. Increased grain-size distribution results in slower impoundment erosion in the first three weeks. The scenario also results in higher volume of deposition downstream in the first three weeks and a slower return toward pre-removal elevation profile downstream at four years after dam removal. Increased grain-size fails to decrease overall impoundment erosion and the channel was still able to incise to base level (Figure 25). This implies there is a different cause of the excessive impoundment erosion. As previously proposed, this cause is likely the inability of the model to evolve channel width during the simulation resulting in uniform lateral impoundment erosion and overestimation of erosion rate.
Figure 25. Graph of model run with increased grain size distribution. Input file is altered by shifting median grain size up by one phi.

(Figure 14) Model run results in slower erosion rate upstream and slower and failure to return to pre-removal profile downstream. At three and eleven weeks DREAM-1 simulates scour at 0.0-275 m downstream of the former location of the MVD.
9. Conclusions

9.1 Summary and Implications for Future Studies

The MVD removal monitoring project is one of the best quantified dam removal studies in the past decade. Sawaske and Freyberg (2012) review 12 projects, including the first year of the Souhegan River upstream response as reported by Pearson (2010). I update the Sawaske and Freyberg (2012) comparison figure by extending the erosion rates of the Souhegan River impoundment to include the data of Pearson et al. (2011) and the results of surveys taken in June 2011 and July 2012 (Figure 26). With the additional erosion rate included in the Sawaske and Freyberg (2012) summary figure, the MVD removal remains the case study with the fastest erosion rate and most extensive overall loss of impoundment volume. The extended sediment budget measures total loss of 81% by four years after dam removal, 35% more sediment lost than any of the other rivers. The MVD removal project also has the second longest monitoring duration, second to the Stronach Dam removal, which was monitored for ten years after dam removal. The extensive channel surveying, sediment sampling, and the quantified response of the Souhegan River to dam removal make the MVD case study ideal for a hindcast using DREAM-1.

The surveying methodology used by Pearson et al. (2011), adapted from Collins et al. (2007), provides a simple, comprehensive set of parameters to measure and quantify the rate of channel response. These methods can be used in future dam removal or hindcast studies to attain accurate input parameters necessary to run DREAM-1. Dam removal modeling studies would benefit from having either quantitative or qualitative information regarding the state of the channel prior to dam construction. Such
information would be valuable when conducting the zeroing process of DREAM-1, which simulates the channel in a quasi-equilibrium state over the long term. If this information is not available, knowledge and topographic surveys of the channel prior to dam removal is sufficient. Another essential piece of information is accurate impoundment grain-size distribution. As found in Cui et al. (2006b) and in section 8.4, grain-size distribution, determined from a weighted average of samples taken in the survey before MVD removal, has some impact on rate of impoundment erosion and sediment retention downstream of the dam site. DREAM-1 shows moderate slowing of impoundment response with coarser impoundment grain-size. Prior to dam removal, DREAM-1 users should gather ample impoundment sediment samples to determine accurate grain-size distribution for the model input.
Figure 26. Figure showing the extension of the Sawaske and Freyberg (2012) results and including erosion rates of the MVD impoundment from May 2010 through July 2012.


9.2 Conclusions

The hindcast analysis indicates that DREAM-1 simulates an initial phase of rapid impoundment erosion and downstream deposition, followed by a phase of gradual impoundment and downstream erosion (Figures 16 and 21). Downstream, DREAM-1 simulates channel response accurately by predicting deposition followed by degradation of the channel bed back towards the pre-removal elevation profile. The clear observations of two phases indicate that the hindcast is successful in modeling the response observed on the Souhegan River during the monitoring period, August 2007 through July 2012. However, the driving causes of these phases are not clear from various modeling scenarios. Pearson et al. (2011) describes the initial rapid response as process-driven and the later phase of gradual change as event-driven, influenced by high flow events. After modeling analysis, it appears DREAM-1 may not show two phases because of the process and event-driven forces, but potentially due to a limitation of the model inputs.

DREAM-1 simulates the initial phase of rapid impoundment erosion in all model scenarios and therefore is arguably process-driven (Figures 17-19 and 21-22). Increase and decrease in the daily-discharge during dam removal did lead to expediting or delaying the erosion to base elevation, however the initial rapid response occurred in all model runs independent of hydrology. The rapid incision of the impoundment to base elevation in the first 11 weeks of the simulation leads to negligible sand left in the impoundment. The erosion of impoundment to base level is attributed to DREAM-1 simplification of detailed cross-sections into rectangular cross-sections leading to uniform lateral erosion of the impoundment rather than incision followed by a period of channel widening during high discharge events (Figures 1, 17-19). The modeled
excavation of the impoundment sand stored in channel banks leaves little sediment left to
erode in later surveys. Therefore, the model fails to simulate impoundment erosion as
observed by Pearson et al. (2011) during the March 2010 flood events (83-84 weeks;
Figure 11).

These findings suggest that both the lack of width evolution during the simulation
and the chosen base elevation impact the results of DREAM-1. Simplified cross-sections
allow uniform lateral erosion and the channel cannot narrow or leave sediment stored in
banks and terraces for later access. Sediment storage in channel banks is an important
contribution to the Souhegan River post-removal sediment budget, meaning DREAM-1
would require width adjustment throughout the simulation in order to accurately predict
the dynamic sedimentation changes and to capture the forces driving the two-phase
response. In addition to the issue of evolving channel width, base elevation is another
influential factor on model simulations. DREAM-1 simulations show rapid erosion (3-11
weeks) to base elevation in the impoundment regardless of hydrology and impoundment
sediment-size (Figures 17-19), suggesting the importance of this parameter. It is
necessary to know the elevation of bedrock in the system, which is a firm constraint on
the base elevation model input.

I conclude from comparison of hindcast simulations to the observations from the
MVD removal monitoring project that DREAM-1 is successful in achieving part of this
thesis project’s objectives. The model was able to simulate a channel response similar to
that observed at the Souhegan River field site, however was unable to evaluate fully the
hypotheses regarding hydrology put forth by Pearson et al. (2011). Despite the
limitations regarding the model’s overestimation of impoundment erosion, I conclude
DREAM-1 would be valuable as an additional tool, in combination with quantitative case studies and qualitative conceptual models, in future sand impoundment dam removal projects aiming to predict sedimentation response.
10. References


Appendix A. Images of cross sections taken viewing downstream, across stream, and upstream. Images of MVD09-MVD12 were taken July 13th, 2012 and MVD01-MVD07 on July 25th, 2012.

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MVD11

Downstream  Across Stream  Upstream

MVD12