EVALUATING EFFECTIVENESS OF FLOODPLAIN RECONNECTION SITES ALONG THE LAMOILLE VALLEY RAIL TRAIL: A BLUEPRINT FOR FUTURE RAIL-RIVER PROJECTS

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Final Report 2020-04

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16. Abstract

Floodplains perform many functions of value to society, including conveyance and storage of floodwaters for reduced downstream impacts, sediment and nutrient deposition to support soil formation, and maintenance of pulsed overbank flows to support diverse habitats. When constructed along Vermont's river valleys in the mid-to-late 1800s, railroads often isolated large areas of natural floodplain, leading to decreased flood and sediment storage, and increased downstream flood stages, sediment and nutrient delivery. Where rail lines have been federally-banked and converted to recreational trails, floodplain reconnection could be achieved by modifying the rail embankment through lowering or installing cross culverts or bridges. With the Lamoille Valley Rail Trail (LVRT) in the Lamoille and Missisquoi River basins as a focal study area, this research has generated tools and planning frameworks for transportation and river managers to identify and prioritize candidate reconnection sites, and to holistically evaluate the benefits of these projects alongside potential impacts to adjacent infrastructure or land uses.

Effectiveness of completed and proposed floodplain reconnection sites along the LVRT was evaluated at various spatial scales using a suite of tools. At the watershed and reach scales, a screening protocol was developed, leveraging stream geomorphic assessment data to prioritize potential floodplain reconnection sites for further vetting through field inspection. Ten out of twelve floodplain reconnection sites completed along the LVRT in 2006-2008 were predicted as a priority in a retrospective application of this screening protocol. Low-complexity (Height Above Nearest Drainage) hydraulic modeling results confirmed that most completed projects provided significant increases in the floodplain capacity for floods of 2- to 500-year recurrence intervals. Event-scale monitoring conducted at selected sites has confirmed accumulation of fine sediment and phosphorus. A conservative estimate of a half-ton of phosphorus deposited during one storm on 57 acres highlights the water quality benefits of restoring floodplains. Reconnection alternatives were evaluated in more detail using two-dimensional hydraulic modeling (2D HEC-RAS) at a demonstration reach of the Black Creek near East Fairfield spanning two completed reconnection sites and one proposed site on the LVRT. Modeled reconnection alternatives resulted in modest changes in flooding parameters due to an unexpected, existing degree of cross connection between floodplains of the Black Creek and Elm Brook tributary. Nevertheless, this research project has created a framework for more holistic analysis of floodplain reconnection opportunities at similar sites across Vermont and beyond. The hydraulic modeling products and scenarios developed for this project are being adapted to support analysis and modeling of fine-sediment and phosphorus attenuation as the Vermont Agency of Transportation continues to collaborate with the Vermont Agency of Natural Resources and other stakeholders to develop a phosphorus-crediting framework for floodplain reconnection projects.

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Table of Contents

1.0 INTRODUCTION

1.1 Motivation

Floodplains perform many functions of value to society, including conveyance and storage of floodwaters for reduced downstream impacts (Watson et al., 2016; Johnson et al., 2020), sediment and nutrient deposition to support soil formation (Noe & Hupp, 2005), and maintenance of pulsed overbank and near-channel flows to support diverse riparian and floodplain habitats (Junk et al., 1989; Tockner et al., 2000). The historic installation of railroads and roads along river valleys has led to the lateral disconnection of river channels from their floodplains and a subsequent reduction of these floodplain functions (Blanton & Marcus, 2009). Additionally, a history of channel modifications including straightening, dredging, berming and armoring in the Northeast (Scott et al., 2019) and in Vermont (Kline and Cahoon, 2010) has led to channel incision and a vertical disconnection of channels from their floodplains.

Laterally- and vertically- reconnected floodplains have the potential to reduce downstream phosphorus delivery on two fronts: (1) by attenuating floodwaters and storing fine sediments and nutrients in the floodplain, and (2) by reducing scour velocities in the channel adjacent to the site and in downstream reaches, thereby reducing streambank and bed erosion – an additional source of phosphorus (Fox et al., 2016; Ross et al., 2018).

Recent research has called for restoration and conservation projects to reconnect rivers to their floodplains for the attendant ecological and societal benefits (Opperman et al., 2009; Johnson et al., 2020). Projects to lower, relocate or notch levees have seen increasing application in the northeast and worldwide (Bernhardt and Palmer, 2011; Guida et al., 2015). Rail corridors represent a possible opportunity for floodplain reconnection, although this practice has been less commonly employed. Rail corridor modification projects for enhanced floodplain connection must consider the multiple uses and functions of river and rail corridors, along with the potential impacts and benefits to adjacent infrastructure, human health and safety, agricultural uses, and the environment. Transportation engineers and water resource managers are in need of holistic design tools to more effectively prioritize projects that have maximum societal and environmental benefits, and that minimize detrimental impacts.

1.2 Background

When constructed along Vermont's river valleys in the 1800s, rail line embankments effectively isolated large areas of natural floodplain (Beers, 1878; Schiff et al., 2008). These encroachments led to decreased valley cross sections, locally increased velocities and flood stages, decreased floodwater and sediment storage, and increased sediment and nutrient export from rural watersheds (Kline & Cahoon, 2010). With the decline of rail traffic in the late 1900s, many rail segments have been rail-banked and repurposed to recreational use (i.e., rail trails). "Rail-banking …is a voluntary agreement between a railroad company and a trail agency to use an out-of-service rail corridor as a trail until a railroad might need the corridor again for rail service."[1] The Vermont Agency of Transportation (VTrans) owns, or has a stakeholder interest in maintaining, more than 145 miles of rail bed around the state that are federally rail-banked and used (or being developed) for rail trails (Fig. 1).

In some Vermont communities, former rail trail segments have been lowered to the original floodplain elevation to restore floodplain function, dissipate floodwaters, and reduce inundation and erosion hazards to downstream communities and infrastructure (Schiff et al., 2008). Where reconnected, floodplain sites may also provide an opportunity to attenuate fine sediments and nutrients (Noe & Hupp, 2005). Within the Lake Champlain Basin, successful floodplain reconnection projects along formerly-active rail lines represent an opportunity for the Vermont Agency of Transportation (VTrans) to achieve reductions in pollutant discharges from impervious surfaces under its Phosphorus Control Plan required under its stormwater general permit to meet the Total Maximum Daily Load (TMDL) for the Lake (VT DEC, 2017). A protocol for identifying and prioritizing candidate floodplain reconnection sites would help to optimize management along river/ rail corridors.

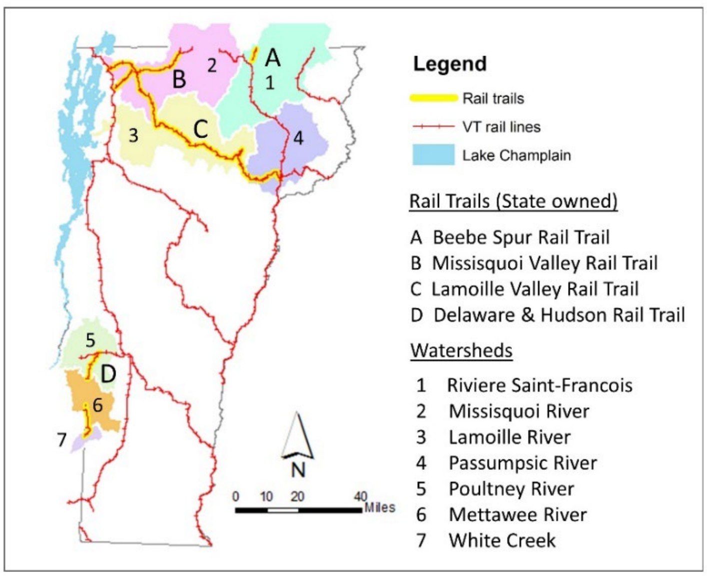


Figure 1. Location of state-owned rail trail segments in Vermont.

VTrans' experience at recently reconnected floodplain sites has suggested the need for a more comprehensive analysis at proposed sites that will consider the multiple functions and uses of floodplains and river corridors alongside the transportation corridors that traverse them. Future floodplain reconnection projects should consider potential impacts to adjacent roads and culvert/bridge crossings, as well as to existing homes and commercial buildings and agricultural uses within the downstream floodplain. A demonstration project illustrating hydraulic modeling

[1] As defined by Rails-to-Trails Conservancy, https://www.railstotrails.org/build-trails/trail-building-toolbox/acquisition/railbanking/

to evaluate reconnection alternatives would be beneficial to VTrans operations statewide, where many additional opportunities exist to address multi-use rail and river corridors.

1.3 Objectives

This research project evaluated effectiveness of floodplain reconnection projects along rail corridors using a variety of approaches to address the following objectives:

1) Development of a screening tool for identifying and prioritizing candidate floodplain reconnection sites based on existing data sets (e.g., topography, river network position, land cover) and informed by potential sediment and nutrient attenuation estimated through field monitoring at selected sites.
2) Analysis of floodplain reconnection alternatives at a specific demonstration site to assess the effectiveness of each alternative for flood-water attenuation and sediment/nutrient storage over a range of design flows and to evaluate potential impacts to adjacent infrastructure and land uses.
3) Dissemination of the resulting tools and research products to VTrans staff, VTANR staff, local and regional stakeholders and participating landowners.

2.0 STUDY AREA

Due to a history of floodplain reconnection projects, both completed and proposed, this study focused on locations along the Lamoille Valley Rail Trail (C in Fig. 1). The 93-mile LVRT connects St. Johnsbury to St. Albans, with more than 33 miles completed as a multi-use recreational trail. Analysis centered, specifically, on a 35-mile section of the LVRT in the Lamoille River valley (watershed 3 in Fig. 1) and a 16-mile section of the LVRT along the Black Creek, tributary to the Missisquoi River (watershed 2 in Fig. 1).

2.1 Regional Context

From 2006 to 2008, twelve segments of the Lamoille Valley Rail Trail (LVRT) were lowered in corridors along the Lamoille River and Black Creek (Fig. 2; Table 1), reconnecting over 200 acres of floodplain along 6 miles of the former rail line (Schiff *et al*., 2008). These floodplain reconnection efforts were conducted under an agreement between VTrans and the VT Agency of Natural Resources (App. A), which ensured that these segments would be returned to their prior status should the property be returned to active rail status under federal rail-banking requirements. Limited one-dimensional hydraulic modeling completed for a Black Creek site indicated that berm removals could reduce in-channel velocities (Schiff *et al*., 2008). Monitoring of three LVRT sites in 2008 and 2009 (Bakersfield 1, Fairfield 3-1, Fairfield 4-1) confirmed that berm removal led to floodplain deposition of more than 950 cubic yards of fine-grained sediment and 1 ton of phosphorus (Schiff *et al*., 2008). However, the performance of nine remaining sites was unclear – including how often and to what extent the restored floodplains were inundated, and their associated capacity for sediment and phosphorus storage. At some reconnection sites, rail trail maintenance concerns have been noted in the years since these projects were completed. Lowered rail sections can remain saturated for extended periods of time after flooding events, leading to muddy and rutted conditions. Ice-jam flooding that impacts lowered sections can lead to icing and render the trail temporarily impassable. Periodically, substantial costs are incurred by the leaseholder (Vermont Association of Snowmobile Travelers, VAST) to remove accumulated fine sediment and flood debris. Beaver activity can also block drainage through cross culverts under the rail trail, requiring periodic maintenance.

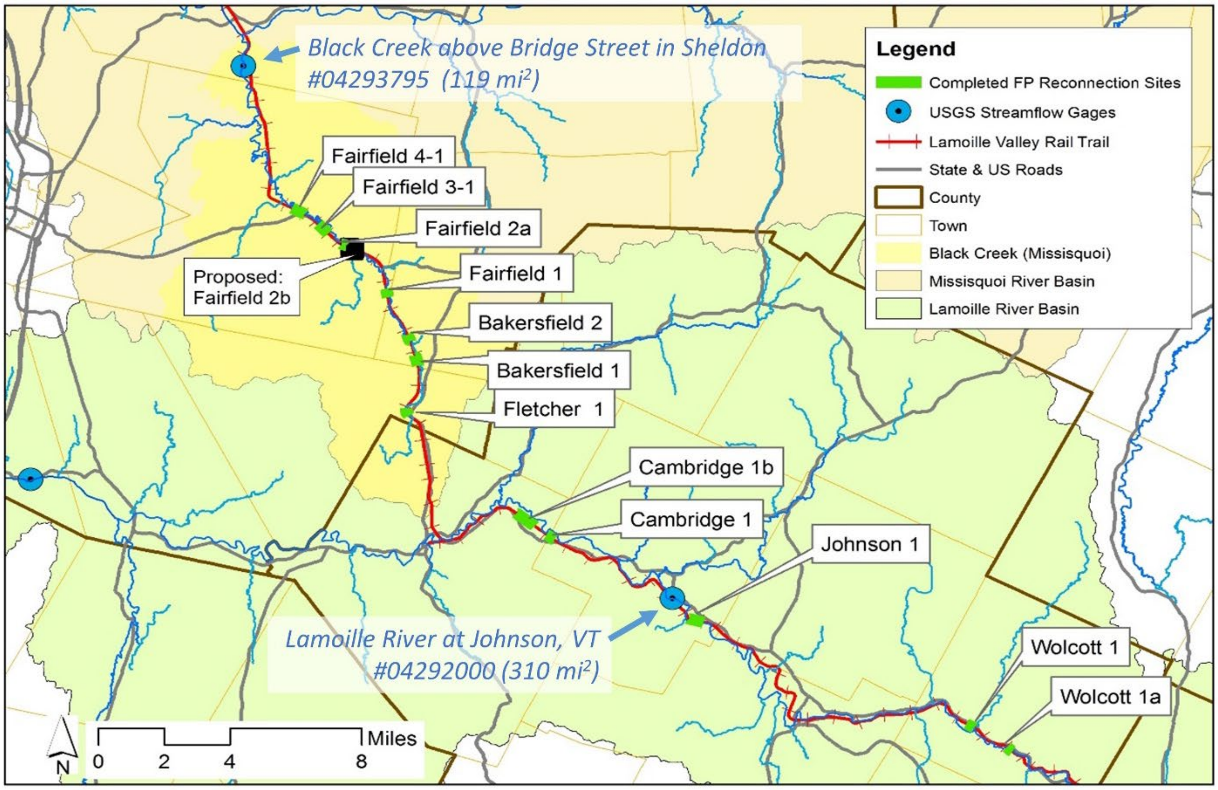


Figure 2. Location of LVRT Floodplain Reconnection Sites along Lamoille River and Black Creek.

Table 1. Completed Floodplain Reconnection Sites along the Lamoille Valley Rail Trail

Site	River	Adjacent Road Corridor	Length Berm Lowered (ft)	Year Completed
Wolcott 1a	Lamoille River		1110	2006
Wolcott 1	Lamoille River		1330	2007
Johnson 1	Lamoille River	VT Route 15	2370	2007
Cambridge 1	Lamoille River	VT Route 15	1600	2007
Cambridge 1b	Lamoille River	VT Route 15	3700	2007
Fletcher 1	Black Creek		1420	2007
Bakersfield 1	Black Creek	VT Rt 108 S	1740	2008
Bakersfield 2	Black Creek		1100	2008
Fairfield 1	Black Creek		1560	2008
Fairfield 2a	Black Creek	VT Route 36	805	2008
Fairfield 3-1	Black Creek	VT Route 36	2330	2007
Fairfield 4-1	Black Creek	VT Route 36	2350	2007

2.2 Demonstration Site

To demonstrate a more holistic planning process involving hydraulic modeling to quantify potential benefits and impacts of floodplain reconnection projects, the TAC chose a proposed reconnection site along the LVRT in the Black Creek valley in the town of Fairfield: site "Fairfield 2b". This project would reconnect the Black Creek to its historic floodplain by modifying up to 1,300 feet of rail embankment. This site also includes adjacent infrastructure of state and local highways, crossing structures for these highways and the rail line, as well as adjacent agricultural and rural residential land uses, and therefore represents many of the multiple uses of river and rail corridors that warrant a more holistic design. This site is also located adjacent to the *Howe Trout Stream and Wetlands Restoration* project that is in the planning stages by the US Fish & Wildlife Service and USDA Natural Resources Conservation Service in coordination with the landowners.

2.2.1 Geologic and Geomorphic Setting

The Fairfield 2b site is located at the mid-point of the Black Creek watershed near the VT Route 36 junction with Elm Brook Road approximately 1 mile downstream of the village of East Fairfield, VT (Fig. 3, Fig. 4). The study area is located within the Northern Green Mountain biogeophysical province (Stewart 1974). Underlying bedrock consists generally of highly metamorphosed greywacke, schists and phyllites (Stewart, 1974; Dennis, 1964). Surficial deposits at the study area are composed of post-glacial lacustrine clays and silts overlain by recent alluvium (Connally, 1968). Streambank materials are comprised of sands over cohesive silty-sands and silts (Johnson Co., 2009).

In a river geomorphic context, the Fairfield 2b site is located between 12 and 15 river miles upstream from the Black Creek confluence with the Missisquoi River (Figure 3) and just downstream of prominent bedrock falls (at Mill Street and Bridge Street) that serve as the foundation for two historic dams, now partially breached. These falls serve as bedrock grade controls for upstream reaches, while the Black Creek in the study area exhibits a very low gradient until the next downstream bedrock knickpoint at Sheldon Falls near the Bridge Street crossing in the town of Sheldon. According to a stream geomorphic assessment completed in 2008 (Johnson Co., 2009), the Black Creek in this modeled study area is classified as a sinuous, sand-dominated channel with dune-ripple bedforms (Rosgen stream type E5-D/R) that has good connection to the adjacent floodplain (incision ratios ≤ 1.4).

2.2.2 Hydrologic Setting and Hydraulic Study Area

The Black Creek drains 120 square miles (mi^2) of rural lands from southeast to northwest, emptying into the Missisquoi River just north of Sheldon, Vermont. The focal area for hydraulic modeling is outlined in black on Figure 4, and extends from the bedrock falls below Bridge Street in East Fairfield village approximately 3 miles downstream (northwest) to the

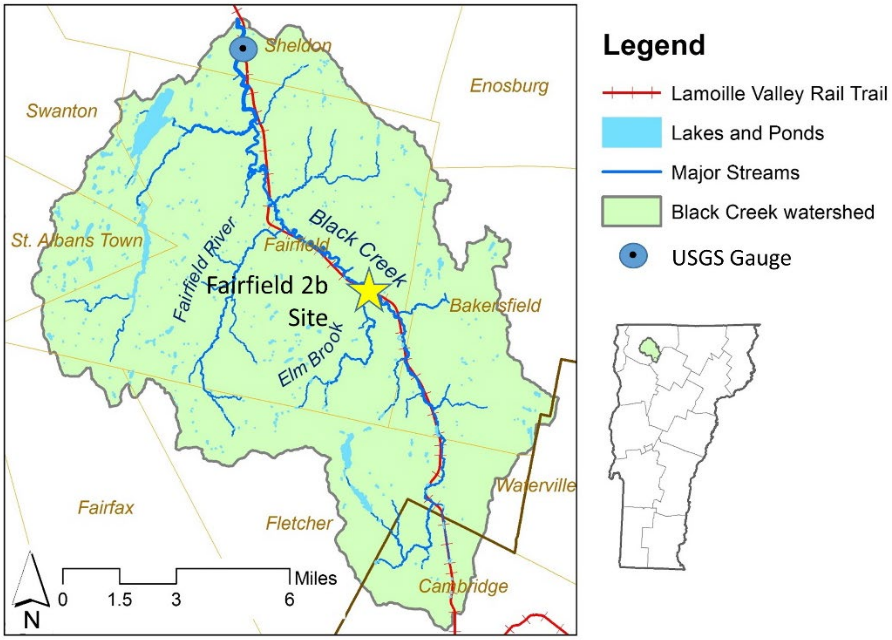


Figure 3. Location of the Fairfield 2b floodplain reconnection site in Fairfield, Black Creek tributary watershed of the Missisquoi River basin, northwestern Vermont.

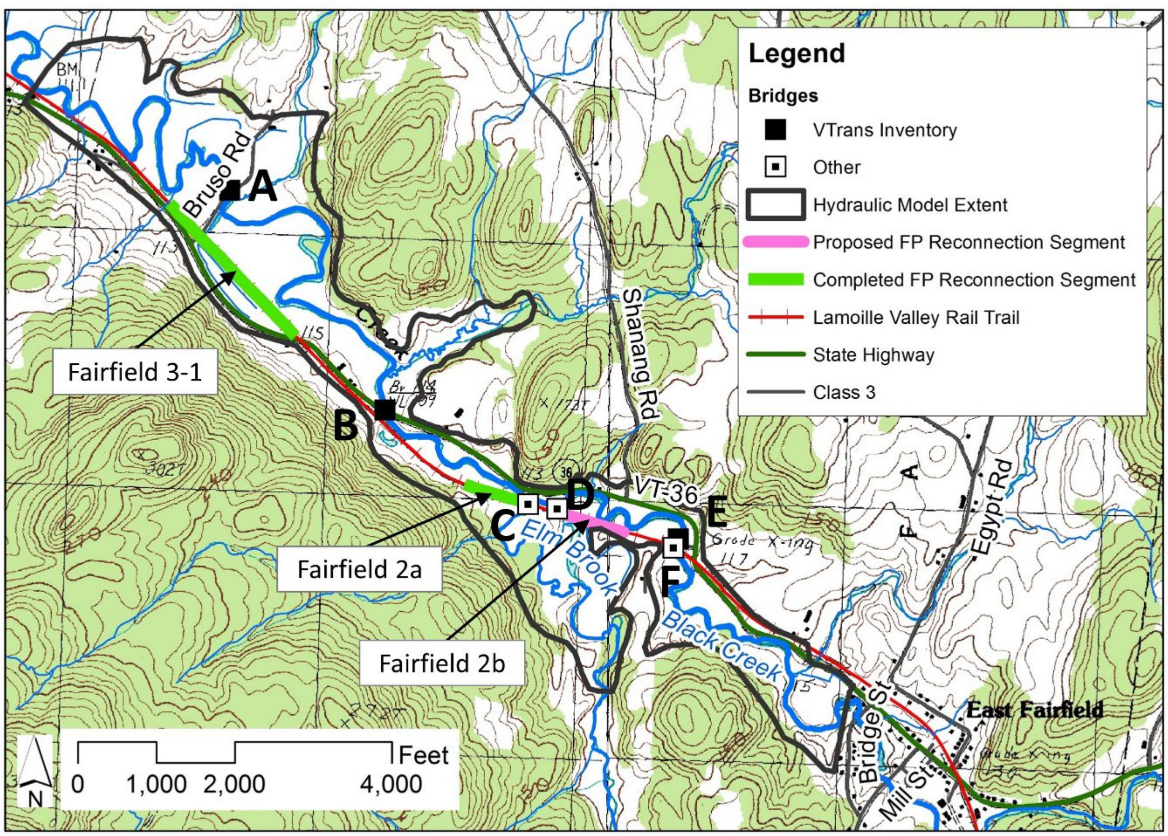


Figure 4. Hydraulic modeling study area spanning Fairfield 2b demonstration site.

vicinity of the Black Creek crossing at Bruso Road. At the downstream end of the study area, the Black Creek drains a land area totaling 53 mi^2, or approximately 44% of the total watershed area. Within the study area, the Black Creek is joined by five tributaries; Elm Brook is the largest of these five (Appendix B, Fig. B-1).

2.2.3 History of Rail Line and Channel/Floodplain Modifications

Substantial modifications of the Black Creek channel were undertaken historically to accommodate the rail line and roads in the vicinity of the Fairfield 2b demonstration site, resulting in significantly reduced meander expression and channel length, consequent loss of lateral floodplain connection, and relocation of the Elm Brook confluence (Appendix C). During construction of the Lamoille Valley Railroad between 1870 and 1877 (Aldrich, 1891, Kendall, 1940), a new channel was blasted through bedrock to re-route the Black Creek (near bridge crossing D in Fig. 5). The blasted rock was then used as foundation under the rail line east of the blasted section toward Elm Brook Road (Rainville, 2019). The confluence of Elm Brook was relocated to the vicinity of a new railroad bridge crossing (C in Fig. 5). The Elm Brook Road crossing of Black Creek (E) was also moved to its present location during railroad construction.

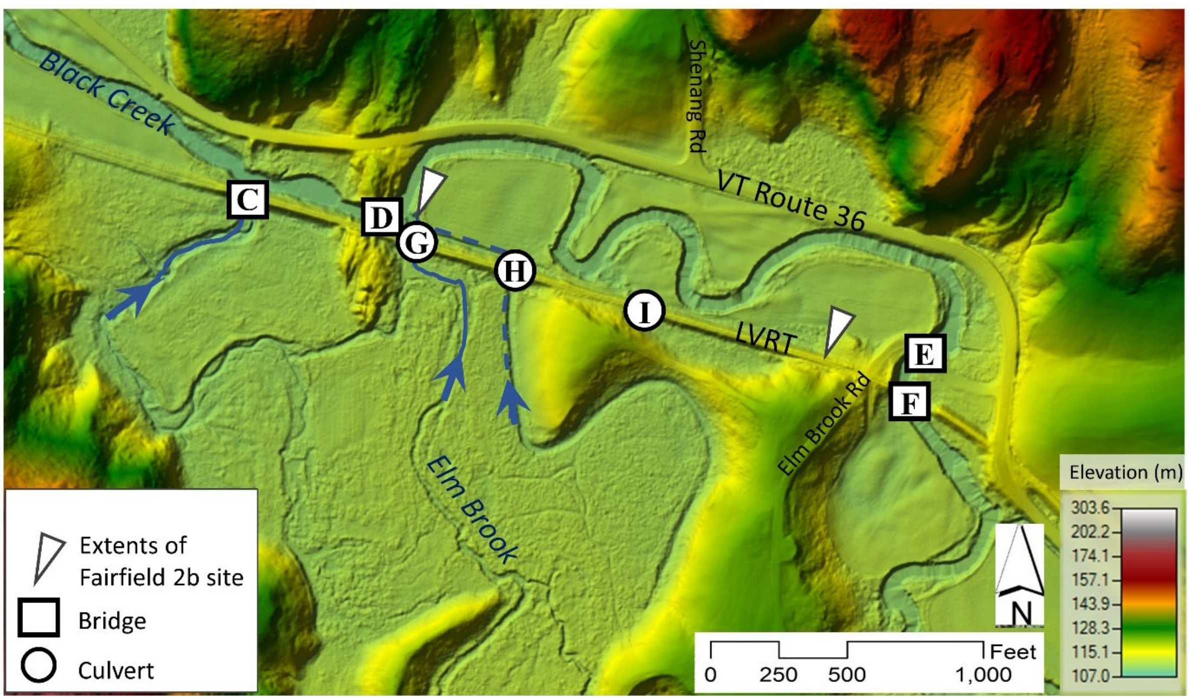


Figure 5. Location of proposed Fairfield 2b site and vicinity crossing structures. Base image is terrain built from lidar-derived Digital Elevation Model sourced in 2017.

The railroad operated until 1997 and was then federally rail-banked and converted to recreational use in 2005 (Schiff et al., 2008). Within the modeled extent, two segments of the rail bed were lowered in 2007 and 2008 to restore floodplain connection: Fairfield 3-1 and Fairfield 2a, respectively (Fig. 4). More recently, the Fairfield 2b segment was proposed for reconnection in conjunction with the *Howe Trout Stream and Wetlands Restoration* project in the Elm Brook floodplain. At present, two cross-culverts under the rail line at this site provide some degree of connection between the Elm Brook floodplain and the Black Creek floodplain. The West and East culverts (G and H in Fig. 5) were replaced by the landowner with slightly larger-diameter structures in 2009 and 2010, respectively (Appendix C). Based on observations in 2019 and 2020 during base-flow conditions, a little more than half of the Elm Brook tributary discharge enters the Black Creek through the West culvert at the upstream end of the bedrock gorge (G). The remainder of Elm Brook discharge (along with contributions from a headwater tributary to the southwest) enters the Black Creek just below bridge C (Fig. 5). A small percentage of flow enters the Black Creek through a ditch network and the East culvert (H in Fig. 5).

2.2.4 Land Use and Water Quality

Land use in the model domain is largely agricultural and rural residential in nature. The Lamoille Valley Rail Trail traverses the site, with a state-owned 66 ft right-of-way through private lands (33 ft on either side of the rail center line). Under an agreement with VTrans, the Vermont Association of Snow Travelers leases the rail corridor for multi-use recreation, and oversees maintenance and construction activities along the rail trail. Vermont Route 36 also traverses the site, running parallel to the rail road (Fig. 4 and 5). Sometime before 1941, the alignment of Route 36 was straightened in vicinity of the Shenang Road intersection (Appendix C). The present road position is set back from Black Creek, and the raised elevation of the former road bed is still evident in the field currently cultivated for hay (Fig. 5).

The Black Creek watershed upstream of the study area is largely agricultural (16%) and forested (76%). Water quality in the Black Creek has been assessed historically by the Missisquoi River Basin Association at a nearby station located at the Ryan Road crossing approximately 1.5 miles downstream of our study area. Total phosphorus measured at this site during 76 separate events in the summers of 2005 through 2014 using grab-sampling methods over varying discharge conditions (from low to high flow) ranged from 18 to 959 µg/L with a mean value of 63 and median of 37 µg/L (Gerhardt, 2015)[2].

3.0 METHODS

Effectiveness of floodplain reconnection sites along the Lamoille Valley Rail Trail was evaluated at various spatial scales using a suite of tools. A screening protocol was developed for application at the watershed and reach scales to identify and prioritize potential floodplain

[2] The phosphorus standard for Class B Warm-Water Medium Gradient streams is not to exceed 27 ug/L at low median monthly flow during June through October in a section of the stream representative of well-mixed flow (VWMD, 2016). It is possible that the Black Creek in the study area would instead be classified as a Slow-Winder stream ecotype; there is no instream phosphorus criterion yet established for the Slow-Winder ecotype.

reconnection sites along rail corridors for further vetting through field inspection. Effectiveness of floodplain reconnection sites for the storage of fine sediment and nutrients was evaluated through limited monitoring at select sites. Reconnection alternatives were evaluated in more detail at a demonstration site relying on a hydraulic model.

3.1 Watershed-Scale Prioritization Model

A tiered screening protocol has been developed and implemented based on various factors influencing the technical feasibility of floodplain reconnection sites along river-rail corridors. (Appendix D). The Black Creek in the Missisquoi River basin and the Lamoille River were used as test watersheds at locations where these rivers share a floodplain with the Lamoille Valley Rail Trail. To facilitate the ranking protocol, first a spatial layer representing the floodplain with an approximate 500-year recurrence interval was generated, using Height Above Nearest Drainage (HAND) algorithms (Nobre et al., 2011; Zheng et al., 2018), leveraging data layers developed under a separate research grant from the Lake Champlain Basin Program (LCBP) (Diehl et al., 2020). For each river valley, the polygon representing the 500-year floodplain was divided into segments of 350-meter river length.

We then attributed these smaller polygons through a spatial join with the current VTANR river corridor layer, to enable reference to stream geomorphic assessment data (where available) from the VTANR Data Management System (https://anrweb.vt.gov/DEC/SGA/Default.aspx). These data, along with other developed metrics (detailed in Appendix D) enabled a Geomorphic Screen for each polygon based on selected parameters including valley confinement, slope, percent wetlands, vertical connectivity of the channel to its adjacent floodplain, and availability of floodplain beyond the rail trail. Six metrics were calculated and scored for each polygon to characterize the potential feasibility of a floodplain reconnection project, and the scores were summed to support a relative ranking of the polygons displayed as a color ramp, with higher-priority floodplain reconnection sites depicted in darker colors.

Additionally, a separate Land Use Screen was performed to calculate agricultural and developed land uses as a percentage by area – both within each floodplain polygon and aggregated to the total upstream floodplain. These layers relied upon 1-meter resolution land cover mapping sourced in 2016 (University of Vermont, 2018), and the developed land use category included roads in addition to buildings and other impervious surfaces. These Land Use Screens were not included in scoring but can be viewed alongside the Geomorphic Screen rankings to infer the land use context for ranked reconnection sites, and to guide selection of sites for further field inspection and landowner outreach. For example, two sites with equal rankings from a Geomorphic Screen might be compared for the percent of developed or agricultural land uses in the aggregate upstream floodplain. The site with greater percentage of either or both of these land uses might be prioritized for project development, assuming that this greater percentage may suggest water quality issues and the potential for attenuating larger amounts of sediment and phosphorus. Of course, this screening layer does not capture the nature and degree of best management practices that may be in place in the river corridor / floodplain to mitigate for water quality impacts of developed and agricultural uses, and this information would become evident during field-verification and landowner outreach phases.

3.2 Retrospective Evaluation of Completed Floodplain Reconnection Sites

A retrospective analysis was completed for rail lowering sites implemented in 2006-2008, by examining screening prioritization results for discrete floodplain polygons that were co-located with these sites. To better understand the extent to which the restored floodplains are inundated and their associated capacity for sediment and phosphorus storage, HAND inundation surfaces for floods with return intervals of 2, 5, 100 and 500 years were developed. These HAND surfaces were generated using Markov Chain Monte Carlo methods to create a probability of inundation (Diehl et al., 2020).

Geographic, geomorphic and floodplain related data were compiled from available data for the twelve floodplain reconnection sites (Table 1). GIS modeling was conducted to estimate floodplain extents under pre- and post-restoration conditions to quantify the percent increase in floodplain, relying on HAND-modeled floodplains for various design storms.

3.3 Floodplain Sediment and Nutrient Monitoring

As an additional measure of floodplain reconnection effectiveness, we evaluated potential storage of floodwater sediments and phosphorus on reconnected floodplain sites in the Black Creek and Lamoille River corridors through floodplain sediment monitoring and analysis. We monitored four floodplain sites within the broader study region: Fairfield 3-1, Fairfield 2b, downstream of Wolcott 1a, and downstream of Wolcott 1 (Fig. 2). These sites were co-located with the separate LCBP study (Diehl et al., 2019). On June 25, 2019, turf mats were deployed at five plots at site Fairfield 3-1: three plots along a transect extending south from a meander bend in the river, and two plots along a transect extending west from the river (Fig. 6a). Additionally, two plots were established at proposed reconnection site Fairfield 2b. Sediment collection was performed following an EPA-approved Quality Assurance Project Plan, and involved trapping of floodwater sediments on four 15x15-cm squares of artificial turf established in orthogonal orientations at 1-meter distance from a central bamboo-pole marker at plots varying in elevation along a transect perpendicular to the river channel (Fig. 6b). Each site has between 3 and 4 plots, each composed of four turf pads. The turf serves as a marker layer defining a time horizon above which sediment has accumulated. Turf pads were retrieved and replaced, periodically, following inundation events. Dried and disaggregated sediment samples were analyzed for organic and mineral mass, percent fines, and total phosphorus by block digestion followed by Inductively Coupled Plasma – Atomic Emissions Spectroscopy analysis (EPA 3050b) at the University of Vermont Agricultural and Environmental Testing Laboratory.

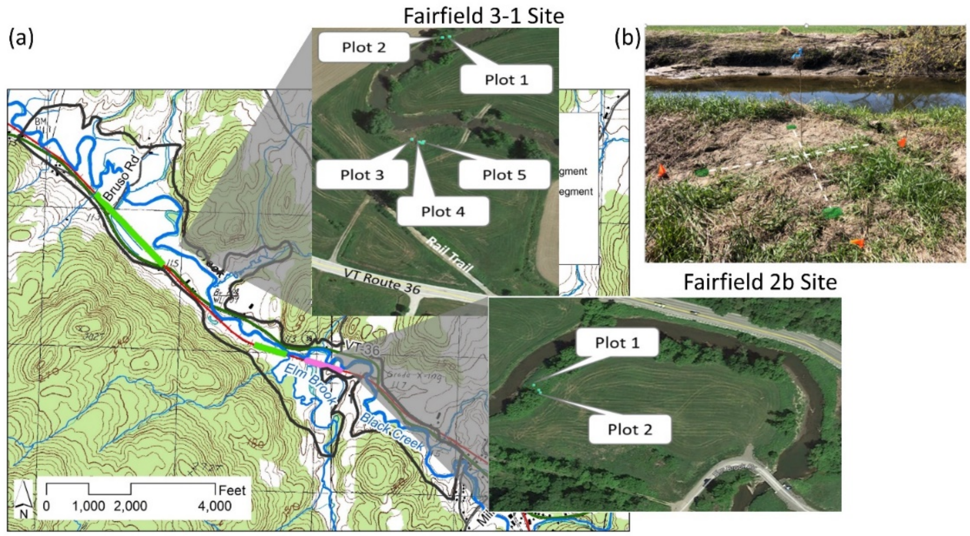


Figure 6. (a) Location map for astroturf plots at Fairfield 3-1 and 2b sites (b) Example astro-turf plot layout at Fairfield 2b site, Plot 1.

To support future monitoring of floodplain sediment accumulation by stakeholders (e.g., citizen scientists, watershed groups, Conservation Districts, VAST), we also developed a field monitoring procedure that uses recreation-grade GPS and simple tools (e.g., augurs, cameras). (Appendix E). We shared the provisional floodplain sediment sampling protocol with VTANR, the Vermont chapter of The Nature Conservancy, and other UVM researchers involved in floodplain studies to test and refine the protocol during April and May of 2019 following wide-spread flooding.

3.4 Demonstration-Site Hydrologic and Hydraulic Modeling

To analyze various alternatives for floodplain reconnection, a hydrologic and hydraulic analysis was completed for a three-mile section of the Black Creek spanning the Fairfield 2b demonstration site (Fig. 4). Analysis included development of a two-dimensional (2D) hydraulic model using the U. S. Army Corps of Engineers' Hydraulic Engineering Center's River Analysis System (HEC-RAS) software (v. 5.0.7; USACE, 2019).

3.4.1 Topographic data

The terrain model underlying the hydraulic model was constructed from three sources of data: (1) 2017 Hydro-flattened Digital Elevation Model (DEM) data sets (0.7m resolution) derived from Light Detection and Ranging (lidar) data acquired in 2017; (2) river channel cross-section surveys, and (3) elevation surveys to determine current position, slope and construction specifications of culvert and bridge crossing structures along the Black Creek and LVRT.

DEM tiles spanning the study area were downloaded from the Vermont Open Geodata Portal and stitched together using the RAS Mapper tool in HEC-RAS. These lidar data sets are classified as Quality Level 2, have a nominal vertical resolution of 9.25 cm (0.3 ft) corresponding to an equivalent contour interval of 1 ft, and were acquired between 5 and 21 November 2017. Based on reference to a flow duration curve for a nearby USGS streamflow gauge (see section 3.4.2), moderate to high flow conditions were encountered on the Black Creek during these November dates. The near-infrared laser of the airborne lidar system does not effectively penetrate the water surface to capture stream channel bathymetry. Resulting “drop-outs” in the 3D point cloud generated from lidar cause river water surfaces to be poorly represented, because the triangular irregular network (TIN) algorithms used to interpolate surface elevations sometimes default to elevations of nearby land-based pixels. Consequently, the water surface in a river channel on the pure DEM is represented by an irregular, triangular-faceted surface. To remove these “tinning” artifacts, a hydro-flattening process is often performed to create a pseudo-representation of the water surface (Heidemann, 2018). Elevations are fixed to an elevation below that of the surrounding land surface and flattened from bank to bank. Then, water-surface elevations are forced to decrease monotonically in a downstream direction, following the valley-floor gradients of the surrounding landscape. While the 2017 lidar coverage for the study area is described as a “hydro-flattened” product, hydro-flattening was not performed on streams smaller in width than 100 feet according to the metadata (Heidemann, 2018). Since the width of the Black Creek channel in our study is nominally 45 feet, the process of hydro-flattening was ***not*** performed. Therefore, the UVM Spatial Analysis Lab was contracted to post-process the 2017 lidar-derived DEM to create a water surface elevation along (i.e., “hydro-flatten”) the 3-mile Black Creek study reach. The hydro-flattened surface was subsequently incorporated into the terrain model for the study site.

To better represent the topography of the river channel bottom, and minimize errors in channel storage and conveyance estimated by the hydraulic model, we completed topographic surveys at 147 channel cross sections along the 3-mile modeling extent in the summer of 2019. Survey data were collected using Emlid™ real-time kinematic (RTK) global navigation satellite system (GNSS) receivers: one operated as a base station and wifi hotspot, the other as a roving unit. Elevation data were post-processed to remove observations where resolution was insufficient to achieve a positional fix. Also, a web-based calculator was used to compute the geoid height at each observation point to convert the Emlid™ GNSS derived NAD83 ellipsoidal height into the NAVD88 official orthometric height (https://beta.ngs.noaa.gov/GEOID/xGEOID18/computation.shtml). Channel bathymetry data interpolated from these 147 surveyed cross sections were then merged with the 2017 lidar-derived DEM for the 3-mile study area. Incorporation of channel bathymetry added approximately 11,490 m^3 of volume (9.3 acre-feet) to the channel. This bathymetry-updated terrain constituted the “Existing Conditions” for our alternatives analysis (see Section 3.5).

Structural data for bridges and culverts within the hydraulic model domain (Fig. 4, 5; Appendix D) were compiled from existing databases maintained by VTrans and VTANR, as well as field-based surveys in 2019 and 2020. 2D modeling in the present version of HEC-RAS does not allow for direct modeling of bridge structures, and post-processing (i.e., hydro-enforcement) of lidar data sets typically results in removal of bridge decks. Modeling of discharge through bridges is relatively straightforward for those crossing structures where the low-chord is elevated sufficiently above the modeled flood stages, and no piers are present. However, two bridges in the Black Creek domain had low-elevation decks that were intersected/overtopped by floodwaters (i.e., Elm Brook Road bridge and Bruso Road bridge). These bridges were therefore simulated in HEC-RAS as box culvert structures with span and rise values very closely approximating the average width and height values for the bridge openings.

3.4.2 Hydrologic data

Hydrologic data for the hydraulic model were developed by reference to a streamflow gauge from a nearby river. A USGS streamflow gauging station was previously active on the Black Creek, located 7.5 miles downstream of the Fairfield 2b site, just above the Bridge Street crossing at Sheldon Falls (Station #04293795, upstream drainage area of 119 mi^2). However, the available record of instantaneous and mean daily discharge data was limited to a two-year period between 25 July 2009 and 30 September 2011. To acquire a discharge time series of sufficient length and reflecting more current conditions in the watershed, we extended the Black Creek time series by examining nearby, active USGS gauges with longer records. For the 2009 – 2011 time period, the Lamoille River at Johnson gauge (#04292000) and the Missisquoi River at East Berkshire gauge (#04293500) each tracked reasonably closely the high flow events recorded at the Black Creek gauge. Black Creek discharge was regressed on discharge for each of these gauges, and the East Berkshire gauge exhibited a better model fit (App B, Fig. B-4). Therefore, the East Berkshire record was used to extend the discharge time series for the Black Creek gauge.

For the period from 2011 through 2019, a time series of daily mean flow (DMF) for the Black Creek at Sheldon was estimated by this regression relationship to DMF recorded at the nearby Missisquoi River at East Berkshire gauge (#04293500). A DMF record for each of the downstream and upstream modeling extents of the study area was then calculated by applying a drainage-area ratio correction. The same method was applied to estimate lateral inputs to the modeled study area for five major tributaries (Section 3.4.4). Design storm magnitudes for hydraulic modeling were estimated for the study area, including contributing tributaries, using the USGS Streamstats tool (Olson, 2014). Three design storms were defined for simulations equating to Annual Exceedance Probability (AEP) of 50% (Q2), 20% (Q5), and 4% (Q25).

3.4.3 Geometry and Computational Domain

The 2D model domain is approximately 1.7 km^2 (0.66 mi^2) and extends 4.8 river kilometers (3 river miles) from the Bridge Street crossing in East Fairfield village downstream to the vicinity of the Bruso Road crossing. Grid elements of the computational mesh range from 2 m to 20 m, with greater resolution (smaller cells) in the area of the channel and various flow-impeding structures (e.g., berms, roads, bridges, and culverts). The channel itself is nominally defined by a minimum of three cells in cross section. Larger cells were selected in the broad floodplains and more remote areas of the 2D flow area, leading to lesser resolution. A balance between coarseand fine-resolution mesh cells was sought to minimize numeric instabilities and achieve reasonable model run times. The present model to simulate existing conditions has 21,568 computational cells.

Mesh break lines (or "no-flow boundaries") were established along roads, driveways, the rail berm, channel berms and other structures to prevent modeled "flow through". Break lines were also established along the channel banks to define points where flow would be constrained to the channel during lower discharges. Quality of the grid was then examined prior to attempting simulations to ensure that the topographic surface was well represented, and to ensure minimal computational errors during simulations. A manual grid-correction process replaced cells with very small interior angles, or nodes with more than eight adjacent cell faces.

3.4.4 Boundary conditions

Upstream, downstream and lateral boundary conditions were established in the hydraulic model. We defined the upstream boundary condition as a hydrograph of hourly discharge, relying on both recorded and extended streamflow records for the Black Creek gauge at Sheldon, and applying a drainage-area ratio, as follows:

$$Q_u = Q_g * \left[{}^{A_u}\!/_{A_g}\right]^b$$

where Q_u is the discharge at the ungauged location, Q_g is discharge at the gauged location, A is the drainage area of the ungauged (u) and gauged (g) location, and b represents the exponent on drainage area derived from the multiple linear regression equations of Olson (2014).

The actual historic streamflow record for the Black Creek gauge (July 25, 2009 through September 30, 2011) was used to identify hydrographs for storms with a magnitude similar to a 2-year and 5-year event defined by USGS regression equations (Olson, 2014; Table A-1). To select hydrographs for a 25-year event, we relied on the extended Black Creek gauging record that was constructed using a linear regression on streamflow from the longer-term USGS gauge on the Missisquoi River at East Berkshire (Section 3.4.2). In each case, continuous (15-min) streamflow discharge data were aggregated to an hourly interval, and an hourly hydrograph was generated for both the upstream and downstream ends of the model domain by adjusting for drainage-area. A similar approach was used to define lateral boundary inputs for five major tributaries that join the model domain (App B, Fig. B-1).

The downstream hydrograph was not used as a model boundary condition. Instead, a normal-depth boundary condition was chosen for the downstream boundary condition and the downstream hydrograph was retained for model calibration.

3.4.5 Numerical Scheme and Computational Parameters

Two methods for unsteady flow simulation are possible within HEC-RAS, employing either the full shallow-water equations of St. Venant or the diffusion-wave equations (USACE, 2016).

After comparing both approaches, we chose to run the model using the diffusion wave equations. Some observed localized instability for Scenario 5-3b was considered to be inconsequential: (a) given the substantially long computational times required for the full shallow-water equations approach, and (b) given that our modeling purpose is a sensitivity analysis to evaluate the incremental changes from baseline on flow conditions induced by various restoration alternatives.

The model uses an adjustable time step of $0.63 \leq s\ \Delta t \leq 40\ s$ that is controlled by satisfaction of a threshold Courant number, c = 3.0. Courant numbers range from 0 to 2 with the stream channel varying between c=1 and c=2. The streambanks have Courant numbers closer to 0. There are a few outliers in the channel with larger spikes over 2. Further reduction of the computation interval would address these elevated Courant numbers, but at the expense of computation run times. The HEC-RAS solver applying diffusion wave approximation of the shallow water equations can accommodate Courant numbers of up to c=5.0 without leading to model instability (Courant et al., 1928; USACE, 2016). One thousand warm-up steps of simulated time are required to pass the storm hydrograph through the downstream boundary of the domain; data are written every 1 hour.

3.4.6 Calibration

We used a storm of 5-year recurrence interval to calibrate the model, because observations during a similar-magnitude flood that occurred in December 2018 allowed us to use high-water marks to evaluate the model. Manning's roughness values for the Black Creek channel were based on field observations and pebble counts performed for a previous stream geomorphic assessment (Johnson Co., 2009). Manning's roughness values for the floodplain were applied based on land cover types identified by the 30m-resolution, circa-2001 Generalized Land Use/ Land Cover data for the Lake Champlain Basin (LCB) (Troy et al., 2007). This land cover source was chosen because it aggregates cover types into broader categories than the National Land Cover Database, which can aid in model convergence and calibration. A review of historic aerial photographs indicated that land cover / land use has remained much the same in the study area over the twenty years since the LCB land cover data was sourced. Typical literature values for Manning's roughness were initially used (Acrement and Schneider 1987, 1989; Chow 1959). We then slightly adjusted Manning's n values until the simulated peak discharge from the Q5 event closely matched the peak of the Q5 hydrograph estimated from a drainage-area ratio applied to the recorded discharge at the USGS gauge at Sheldon. Table 2 displays the calibrated roughness values assigned to land cover / land use categories.

A Nash-Sutcliffe efficiency rating (Nash and Sutcliffe, 1970) of 0.95 was achieved when comparing the simulated hydrograph to the observed hydrograph at the downstream boundary condition (adjusted by drainage area). Peak flow magnitudes were within 5.02 cms (179 cfs).

Table 2. Calibrated floodplain and roughness values.

Code	Category	Manning's n	Percent Total Land Area (%)
1	Urban	0.05	12
2	Agriculture	0.03	67
3	Brush	0.1	2.5
4	Forest	0.11	16
5	Water	0.035	0.05
6	Wetlands	0.13	1.3
7	Barren	0.04	0.19
8	Urban-Open	0.04	0.65
	Black Creek channel	0.035	

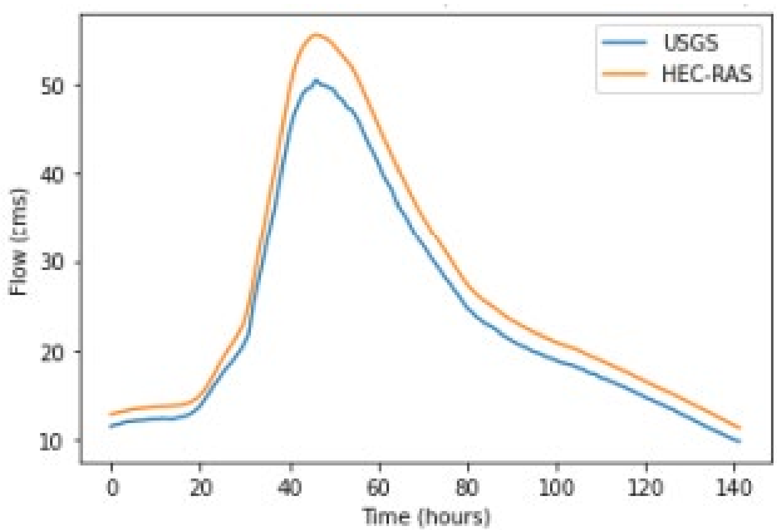


Fig. 7. Comparison of modeled (HEC-RAS) to estimated (USGS) hydrographs at the downstream model extent for the 11 April 2011 flood of 5-year recurrence interval recorded on Black Creek.

3.4.7 Evaluation

The noted difference in modeled and estimated peak discharges in the calibrated models, can be partly accounted for by direct rainfall on the domain. A 24-hour duration, 5-year recurrence interval precipitation event in this region is estimated to yield 2.9 inches (74 mm) of rainfall (https://hdsc.nws.noaa.gov/hdsc/pfds/). This equates to 125,200 m^3 of rainfall over 24 hours, or an average of 1.5 m^3 s^{-1}.

When the 5-year flood was simulated using the terrain model without bathymetric correction, the modeled peak discharge did not change significantly, and the corresponding Nash-Sutcliffe efficiency rating was reduced slightly to 0.94. Thus, in this particular setting, a modest improvement in model performance was gained by using corrected bathymetry from cross-section survey data.

3.5 Demonstration-Site Alternatives Analysis

Once the model was developed and calibrated for the Q5 storm on existing conditions, additional design storms were modeled including storms of AEP 50% (Q2) and 4% (Q25). These simulations for existing conditions served as a baseline for comparison of modeled past and future scenarios.

3.5.1 Modeled Scenarios

Floodplain reconnection scenarios included two prior conditions and nine possible future scenarios (Table 3).

Table 3. Schedule of Modeled Simulations

Modeling Scenario			Simulated Year
1	Existing Conditions *(No Action Alternative)*		2020
2	Simulated Prior Conditions - Railbed intact		2006
3	Simulated Prior Conditions - FF3-1 Removed		2007
4	Simulated Prior Conditions - FF3-1 and FF2a Removed		2008
5	Future Conditions - Modify FF2b-1		2021
I	*Berm Lowering* - Full		
II	*Berm Lowering* - Partial - to Q5 stage		
III	*Bridge*		
	a	33 ft span; >7.2 ft clearance (1.0xW_{bkfl}, 4.0xD_{bkfl})	
	b	66 ft span; >7.2 ft clearance (2.0xW_{bkfl}, 4.0xD_{bkfl})	
IV	*Cross Culverts*		
	a	2 additional culverts - Small - 42-inch round culverts	
	b	2 additional culverts - Large - 12 ft span, 8 ft rise box culverts	
V	*Combo - Partial Berm Lowering/ Cross Culverts*		
	a	Berm to Q5 stage; 2 additional culverts - Small	
	b	Berm to Q5 stage; 2 additional culverts - Large	
6	Future - Modify FF2b-2		2021
I	*Berm Lowering* - Full		

**Note that Scenario 4 – 2008 (Fairfield 3-1 and 2a Removed) – is actually the same as Existing Conditions.*

<u>Prior Conditions</u>

To understand the potential influence of prior rail berm modifications on flood stage and velocities, we simulated flood conditions for the year 2006 prior to implementation of berm-lowering projects implemented by VTDEC in 2007 and 2008 at sites Fairfield 3-1 and Fairfield 2a, respectively. A new modified terrain model was generated by restoring the rail berm elevation at these sites using RAS Mapper. In a similar fashion, separate versions of the terrain model were generated for simulation year 2007 (with FF3-1 removed) and year 2008 (with both

FF3-1 and FF2a removed). In each case, the modified floodplain DEMs were merged with the 2019 channel bathymetry.

Future Conditions

To evaluate various rail berm modification alternatives for achieving greater connection to the historic floodplain at the Fairfield 2b site, we constructed eight separate geometry files for simulating these future-condition scenarios. Notably, the existing topography at this site limits the feasibility of floodplain reconnection to two subsections of the Fairfield 2b site: segment 2b-1 and segment 2b-2 (Fig. 8). At segment 2b-1, two existing culverts convey drainage from the Elm Brook channel toward the Black Creek during low flows, and permit floodwater exchanges between these floodplains at high flows (Fig. 5; App. F). The West (42" diam.) and East (34" diam.) culverts were installed in 2009 and 2010, respectively, and historic research indicates that some degree of cross-connection has existed here through a previous generation of culvert structure(s) since at least the mid-1990s (App. C). Under Scenario 5, seven modification alternatives were specified for segment 2b-1 to achieve a greater degree of connection between the Black Creek and Elm Brook floodplains (Table 3).

Under Scenario 6 one modification alternative was modeled for segment 2b-2 to enhance reconnection to a relatively modest area (5.3 acres) of historically isolated floodplain on the south side of the rail berm. A 38-inch round culvert conveys drainage from this area toward the Black Creek, and a similarly-sized stone box culvert was depicted on the 1916 railroad valuation survey, suggesting that this small floodplain pocket has had some degree of connection for some time. However, during field inspections on 13 May 2020, a partial blockage of this culvert by beaver-chewed woody debris was evident, causing impoundment of the isolated floodplain (App F). For each alternative, the DEM was modified using RAS Mapper to create a unique geometry file that reflected the modification alternative. Each modification alternative was then simulated using the three design storms.

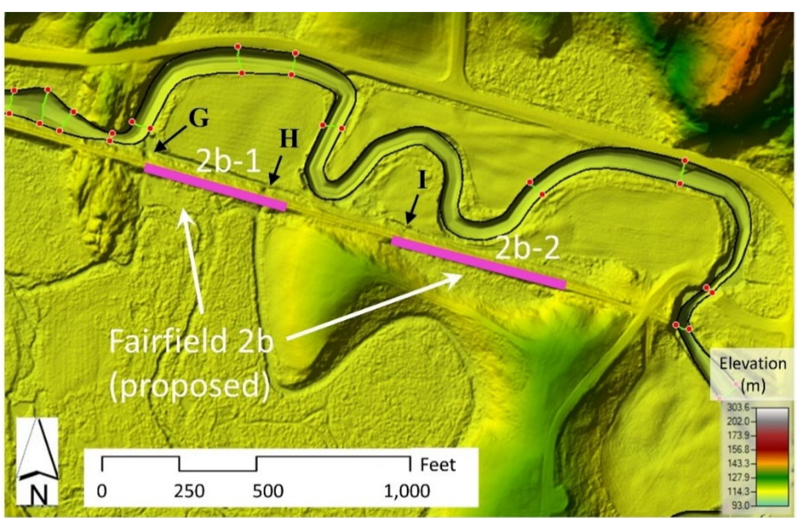


Figure 8. Subsections of proposed reconnection site Fairfield 2b on Howe property and existing cross culverts.

Scenario 5 – Modify Fairfield 2b-1

Alternative 5.1 – Full lowering of the rail berm. The rail berm was lowered entirely to the historic floodplain elevation for a length of 70 meters (230 ft). On transitional slopes, a maximum grade of 5% was maintained in accordance with the Vermont standards for shared-use paths in use by pedestrians as well as bicycles and snow machines (National Center for Bicycling and Walking, 2002).

Alternative 5.2 – Partial lowering of the rail berm to the Q5 stage. The rail berm was lowered to the approximate elevation of the Q5 storm for a length of 86 meters (282 ft), with transitional slopes at a maximum 5% grade.

Alternative 5.3 – Install Bridge to replace West culvert. The existing West culvert at segment 2b-1, that conveys a portion of the Elm Brook flows, was replaced with a bridge structure. Two options were modeled: (a) a bridge span of 33 feet, which approximates one bankfull width for the Elm Brook tributary; and (b) a bridge span of 66 feet, equal to approximately two times the bankfull width.

Alternative 5.4 – Install two culverts to augment two existing culverts. Two new culverts were added to augment two existing culverts to offer greater connection between the Black Creek and Elm Brook floodplains. Two options were modeled: (a) two 42-inch round culverts, in keeping with the size of the existing culverts; and (b) two box culverts, each with a 12-foot span and 4-ft rise to offer greater aquatic organism passage, and to lower velocities through the structures as compared to option (a) above.

Alternative 5.5 – Partial lowering of the berm and addition of two culverts. This combination alternative included lowering of the berm to the approximate elevation of the Q5 storm for a length of 86 meters (282 ft) with transitional slopes at a maximum 5% grade; plus two 42-inch round culverts to enhance floodplain connection at floods of lesser recurrence interval.

Scenario 6 – Modify Fairfield 2b-2

This scenario involved full lowering of the rail bed at segment 2b-2 to more fully reconnect a 5.3-acre pocket of the historic floodplain that has been isolated since construction of the rail road in the 1870s.

3.5.2 Objectives and Target Monitoring Sites

We then visualized and compared model results under each scenario for a suite of design storms with respect to various objectives, including:

- Reduced inundation duration of roads/ trails (for life/safety/health and safe passage; reduced maintenance expenses)
- Reduced scour velocities along infrastructure (for improved flood resiliency)
- Reduced velocities in the channel (reduce sediment erosion, increase channel stability)

- Increased inundation volume and duration of the floodplain where compatible with land uses (for maximum sediment/phosphorus and flood-peak attenuation)
- Decreased inundation volume and duration of the floodplain where incompatible with land uses (for maximum use)

To understand the influence of each modification alternative on flooding parameters, we established standardized observation locations for each scenario (Fig. 9). Target observation points included discrete locations on the floodplain, adjacent roads, rail berms and in the stream channel. We then evaluated each scenario by reviewing model output at these discrete locations within the domain, and compared them to values generated by the model run under Existing Conditions, in terms of a percent increase or decrease.

Evaluated model parameters included flow velocity in meters per second (m/s), inundation depth (m), duration of inundation (hrs), and percent of time inundated (%). For each modeled scenario, a time series of inundation depth and velocity was exported from the results file for each computation cell within the defined area of the model domain. To represent each of the floodplain evaluation areas noted in Fig. 9 (point labels prefixed with the letter A), we constructed a profile approximately parallel to and orthogonal to the down-valley direction of flow. A similar approach has been used for the road and railroad, and stream channel observations points (C1 – C3). We then exported the time-series of depth and velocity for each cell intersected by the profiles; extracted the maximum value of the time series; and computed the average of the maximum values along the profiles.

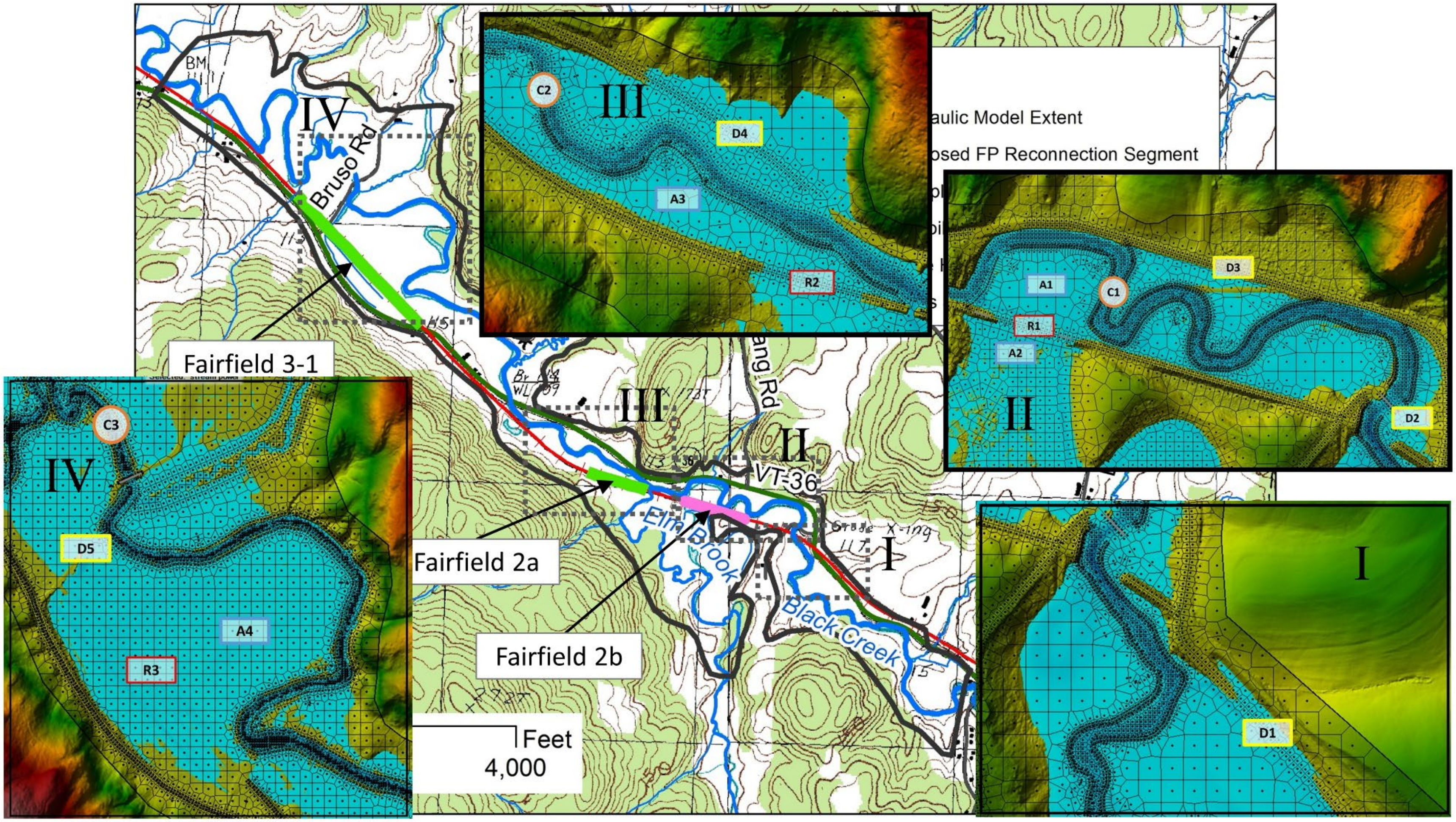


Figure 9. Location of evaluation points within the 2D hydraulic model domain for all modeled alternatives. Locations of inset maps are noted with roman numerals, I through IV. Observation points in floodplains are prefixed with the letter A, river channels with C, roads with D, and rail trails with R.

4.0 RESULTS AND DISCUSSION

4.1 Watershed-scale prioritization of floodplain reconnection sites

Potential floodplain reconnection sites were prioritized along the Black Creek and Lamoille River valley sections of the LVRT (Fig. 10), following the screening protocol developed for this project. Interactive versions of screening results are available as separate web maps at links available through the report authors.

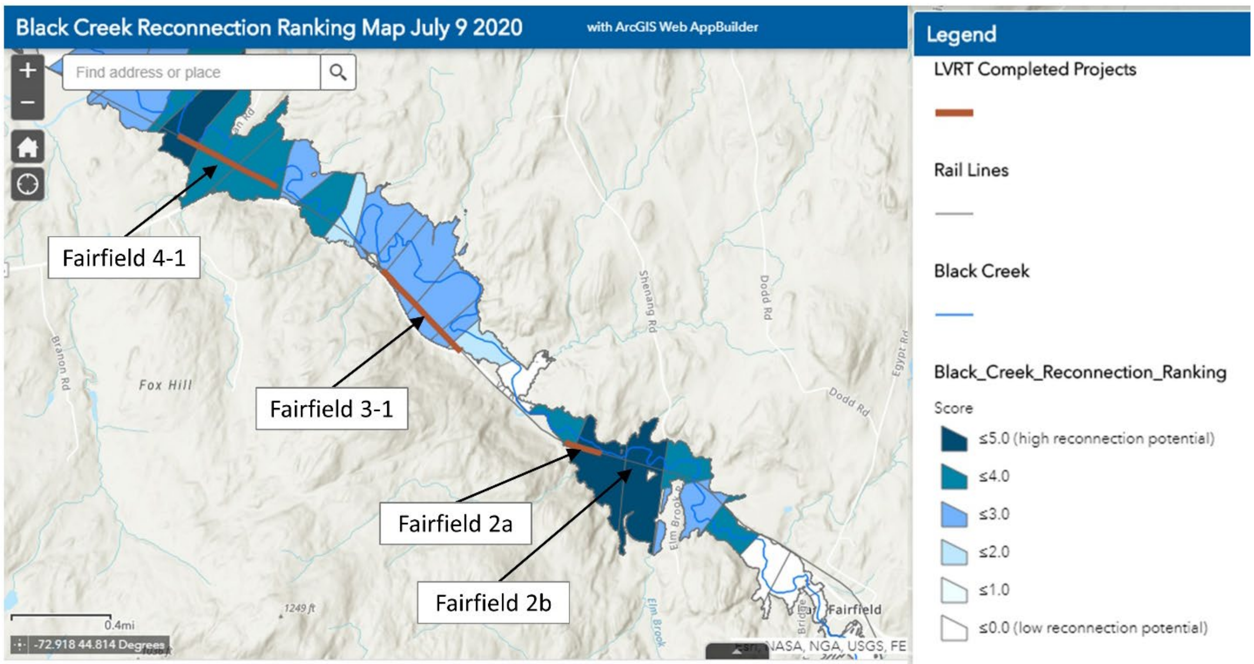


Figure 10. Excerpt from web map of rail trail reconnection ranking map for Black Creek. Darker blue shading indicates higher priority for reconnection. Brown lines indicate position of previously-completed rail bed lowering projects.

Ten of the twelve rail-bed lowering projects completed in 2007 and 2008 (Table 1; Fig. 2) were generally co-located with floodplain polygons of higher rank (≥ 3 out of a possible of 6). The lowest-ranking site (Wolcott 1) was actually completed to meet a different objective – namely, to reduce impacts of Wild Branch flooding at the confluence with Lamoille River and reduce flows directed at an undersized bridge opening (personal communication, S. Pomeroy, August 20, 2020). The Fairfield 3-1 site had a maximum score of 3. Floodplain polygons that intersected this reconnection site showed a relatively modest gain in floodplain area beyond the rail line, and no wetlands were mapped on these prior-converted, cultivated lands. The floodplain polygon containing the completed Fairfield 2a site had a ranking of 4.9 out of 6, and the proposed Fairfield 2b site had a ranking of 5 out of 6. The screening protocol also identified two high-ranking sites that were previously identified but not completed, because the landowners were unwilling (Schiff, personal communication, 4/17/2020). Generally, sites with higher screening ranks had greater increases in modeled floodplain area resulting from the lowered rail bed (Appendix G; Table 4).

Table 4. Retrospective evaluation of floodplain reconnection sites completed along the LVRT in 2007 and 2008.

River	Reconnection Site	Screening Score *	Percent increase in Floodplain Area (%)			
			2-yr RI	5-yr RI	100-yr RI	500-yr RI
Lamoille River	Wolcott 1a	3.9	0	2.7	31.7	33.7
	Wolcott 1	2.0	0	0	0	8.7
	Johnson 1	4.0	34.0	35.0	35.0	36.3
	Cambridge 1	3.9	0	0	28.0	37.0
	Cambridge 1b	2.3	0	0	11.0	13.0
Black Creek	Fletcher 1	5.2	30.2	46.7	39.0	36.3
	Bakersfield 1	4.6	39.6	38.8	36.4	35.5
	Bakersfield 2	4.3	44.1	44.1	44.2	44.3
	Fairfield 1	4.6	50.9	48.8	51.5	51.6
	Fairfield 2a	4.9	44.5	44.8	45.2	45.1
	Fairfield 3-1	3.0	16.0	14.9	13.0	13.0
	Fairfield 4-1	4.3	47.6	41.3	33.3	33.3

RI = Recurrence Interval
** presented score is maximum value if multiple floodplain polygons intersected the reconnection site*

4.2 Event-scale Sediment and Nutrient Monitoring on Floodplains

Two flooding events occurred during the study period that enabled testing of field protocols for event-scale sediment and nutrient storage on floodplains: (1) a flood of approximate 5-year RI on 22 December 2018, and (2) a 27-year RI flood peaking on 1 November 2019. Photodocumentation of flooding conditions is provided in Appendix G.

The field monitoring procedure developed for citizens and stakeholders (App. D) was tested at the Fairfield 3-1 site in the spring of 2019 after spring runoff and following the 5-year flood event of 22 December 2018 (Fig. 11a). Sediment distribution and recovery amounts were very limited, possibly due to the seasonal timing of the flood when senesced vegetation and a degree of frost may have resisted surface soil erosion, thereby yielding lower suspended sediment concentrations in floodwaters. Observed floodplain sedimentation on the reconnected 10 acres of floodplain southwest of the rail line was markedly less than observed in April of 2008 by Milone and MacBroom, Inc. (Fig. 11b).

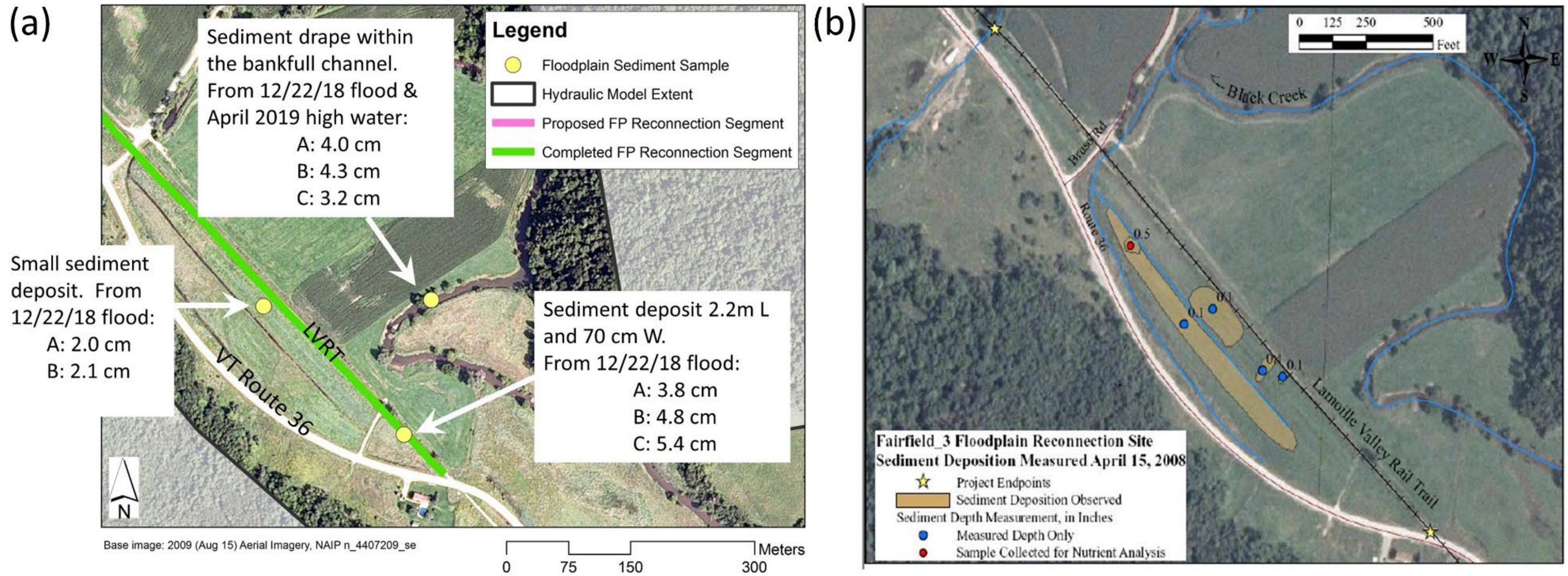


Figure 11. Floodplain monitoring results at Fairfield 3-1 (a) in April 25, 2019 following a December 2018 flood of 5-year recurrence interval and spring 2019 high water (~Q2); and (b) on April 15, 2008 following April 13, 2008 spring runoff flooding with a ~2-year recurrence interval. Map in panel b reproduced from Milone and MacBroom, Inc.

For turf plots deployed in June 2019 at both Fairfield 3-1 and Fairfield 2b, field inspection on October 28, 2019, confirmed that no sediment had accumulated during a flood of approximate 2-year recurrence interval that occurred on October 2, 2019. However, only days later, a flood with a recurrence interval of approximately 27 years inundated the study area floodplains on October 31 and November 1, 2019 – the so-called Halloween storm of 2019 (App. F).

Following a hiatus in field work imposed due to the COVID-19 pandemic, our team secured permission to resume field activities on this project from both VTrans and UVM, and returned to the site on 13 May 2020 to retrieve the turf pads and accumulated sediment. No flooding in excess of a 2-year recurrence interval was recorded in the intervening time period at reference USGS streamflow gages, thus we are confident that the volume of sediment contained on these turf pads was accumulated during the Halloween storm event of 2019. However, due to the interim ice/snow melt and rainfall events, as well as the vegetative growth that occurred during the extended time period between sediment deposition and retrieval, it was not possible to map the aerial extent of sediment deposition across the floodplain. A small amount of sediment could have been lost from the turf plots in that intervening time due to these processes.

Table 5. Accumulations of fine sediment at turf plots established in the 2D model domain during the October 31 – November 1, 2019 storm event and composite phosphorus concentration.

Site	Plot	Average Depth (cm)	Average % Sample > 2mm	Total Phosphorus (mg/kg)	Average Sediment Deposition (kg/m^2)	Equivalent Total Phosphorus Deposition (kg/hectare)
Fairfield 3-1	Pad 1	7.0	1.3%	779	48.7	375
	Pad 2	0.6	5.7%	737	8.5	59
	Pad 3	1.3	0.9%	911	11.7	106
	Pad 4	0.9	1.3%	856	12.1	102
	Pad 5	1.2	1.0%	990	10.5	103
Fairfield 2b	Pad 1	2.5	18.9%	750	12.7	77
	Pad 2	0.04	3.6%	925	2.7	25

Sediment accumulations were generally thinner at pads that were more distant from the stream channel. Phosphorus concentrations tended to be greater in samples that were composed of finer grain sizes. Predictive relationships beyond these generalized observations are not possible given the small sample size (n=7). The range in total phosphorus concentrations in these floodplain sediment deposits was similar to the ranges detected in streambank and floodplain surface soils from other Vermont watersheds (Langendoen et al., 2012; Ishee et al., 2015; Ross et al. 2018; Perillo et al., 2019).

The average sediment and phosphorus deposition values in Table 5 should be interpreted with great caution. These values relate to average conditions at the pad sites themselves measured in one unique flood event, and cannot simply be extrapolated to the full floodplain or applied for flood events of any return interval. Actual sediment and phosphorus accumulation volumes will be a highly complex function of many factors including floodplain microtopography, spatially-varying hydraulics (e.g., eddies), degree of hydraulic connectivity to the channel, variable residence time of floodwaters (affecting settling velocities), and vegetative states on the floodplain. Additionally, the nature of the floodwater event that accesses the floodplain will influence sediment and phosphorus accumulation, including lateral inundation extents, floodwater volume, suspended sediment concentration, phosphorus concentration and forms (dissolved vs particulate), and these factors will vary across years, across seasons, and with the intensity of the flood event itself, as well as with changing upstream land uses.

Despite these complexities, a method for estimating sediment and phosphorus attenuation in floodplains will be needed to characterize the efficiencies of various river restoration and conservation practices, and to support phosphorus-crediting frameworks under TMDLs. Until more rigorous methods are developed, a "back-of-the-envelope" calculation of sediment and phosphorus accumulation can be made for the Fairfield 2b and 3-1 sites by assuming the minimum sediment thickness measured at the sites (0.04 cm - essentially a halo of fine silt/clay), applying the minimum reported phosphorus concentration (737 mg/kg), and considering the full floodplain extent at each site. After applying appropriate dimensional conversions, this simplified approach yields a conservative estimate of 0.07 U.S. tons of phosphorus stored at Fairfield 2b (on 8.5 acres), and 0.41 tons at Fairfield 3-1 (on 48 acres), for a total of almost half a ton of phosphorus at these two sites which are a small percentage of the accessible floodplain over the 3-mile study area.

The floodwater sediment samples collected at these two sites during this project are part of a much larger data set of floodplain deposits being characterized under the LCBP research project (Wemple, et al., 2018; Diehl, et al., 2019) which will develop predictive empirical models to relate sediment deposition and phosphorus content to a range of landscape metrics including distance from the stream channel, slope, elevation, and vegetative cover (expected in early 2021). Additionally, ongoing research under Vermont's Functioning Floodplain Initiative (https://dec.vermont.gov/rivers/ffi) will be developing methods for estimating floodplain storage of sediment and nutrients (2020 – 2022).

4.3 Modeled Scenario Outcomes

Hydraulic modeling results are presented below for the model domain with a focus first on replicating existing conditions, then simulating prior conditions (with the rail bed intact at Fairfield 3-1 and 2a), and finally evaluating several future floodplain modification alternatives at the Fairfield 2b site.

4.3.1 Existing Conditions

Under existing conditions (Scenario 1), Black Creek has access to its floodplain nearly throughout the model domain in all three design storms. A noticeable increase in inundation extent occurs between the Q2 and Q25 flood in the vicinity of the Fairfield 2b demonstration site (Fig. 12). It takes a >Q5 flood to overtop the modified rail bed at site Fairfield 2a (Fig. 12b). However, all three design storms overtop the lowered rail bed at site Fairfield 3-1, with maximum inundation depths ranging from 0.60 to 0.84 m (2 to 2.8 feet) (Fig. 13).

Road evaluation points show variable inundation status across the design storms (Table 6). Modeled overtopping at the noted evaluation points on the Bruso Road, Elm Brook Road, and Vermont Route 36 east of Elm Brook Road is reasonably consistent with conditions observed during the Q5 and Q27 floods that occurred in 2018 and 2020, respectively.

Table 6. Maximum flooding inundation at road observation points under Existing Conditions.

Evaluation Points		Max Inundation at Crown (m)		
Point	Description	Q2	Q5	Q25
D1	Rt. 36 east of Elm Brook Rd	0.0	0.1	0.4
D2	Elm Brook Road, eastern bridge approach	0.36	0.47	0.74
D3	Rt 36 at Shenango Rd, north of Fairfield 2b	0.0	0.0	0.0
D4	Rt 36 north of Fairfield 2a	0.0	0.0	0.0
D5	Bruso Rd between Rt 36 and Black Creek	0.26	0.32	0.48

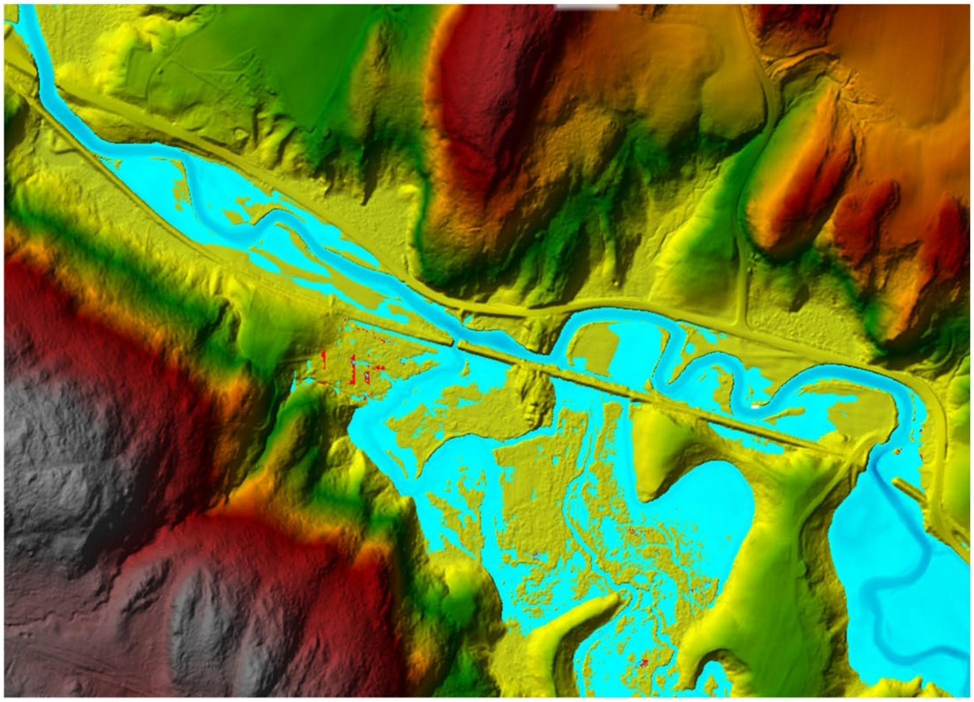
4.3.2 Prior Conditions

In 2006, before rail berms were lowered at Fairfield 2a and 3-1, none of the modeled storms overtopped the rail bed. At Fairfield 3-1, floodwaters from all three design storms intercepted the base materials along the north side of the rail berm with water depths ranging from 8.1 inches (Q2) to 10.6 inches (Q25); but the rail prevented flow-through to the southwest (Fig. 14). The original height of this berm above the historic floodplain was typically 6 feet (MMI, 2007).

Similarly, the intact rail bed at Fairfield 2a was not overtopped during the Q25 flood, and appeared to serve as a barrier to floodwaters from the Elm Brook tributary and a smaller tributary to the southwest. While >Q5 floodwaters can today overtop the rail line at this site to join the Black Creek (Fig. 12b), in previous years floodwaters from Q2 to Q25 storms were forced through the opening at bridge C (Fig. 5).

Modeled conditions during the Q25 flood at site Fairfield 2a changed very little in response to lowering of Fairfield 3-1 in 2007, with a negligible increase in inundation depths at the shoulder of this berm (fraction of an inch), and a very slight increase in flooding duration from 2.7 to 3 hours during the Q25 discharge. Fairfield 3-1 is about 1300 meters (0.8 river mile) downstream of Fairfield 2a.

(a)



(b)

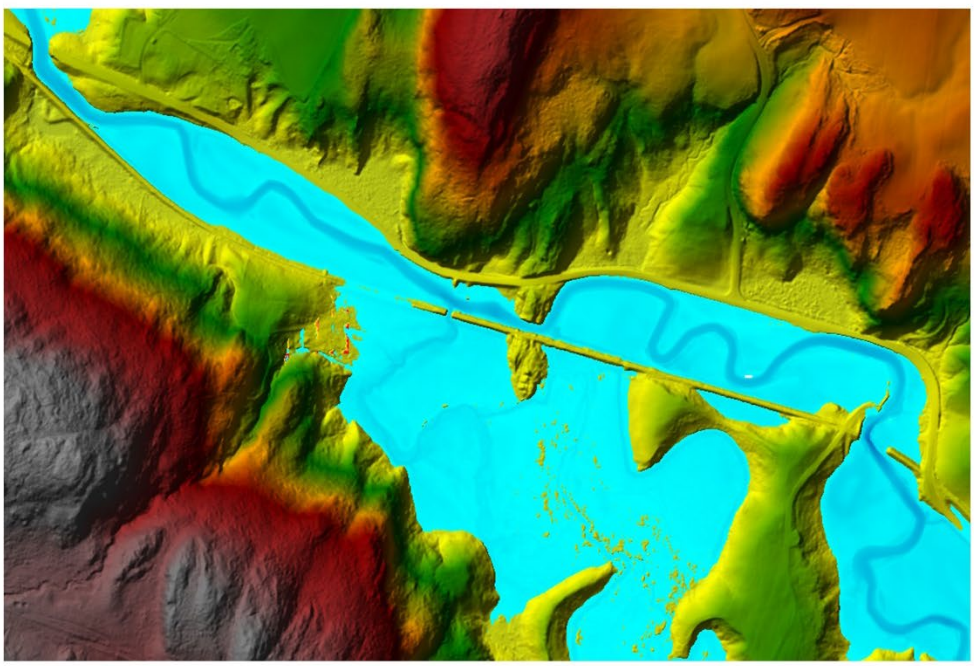


Figure 12. Simulated flooding extents for (a) Q2 and (b) Q25 flood in the vicinity of Fairfield 2a and 2b under existing conditions.

(a)

(b)

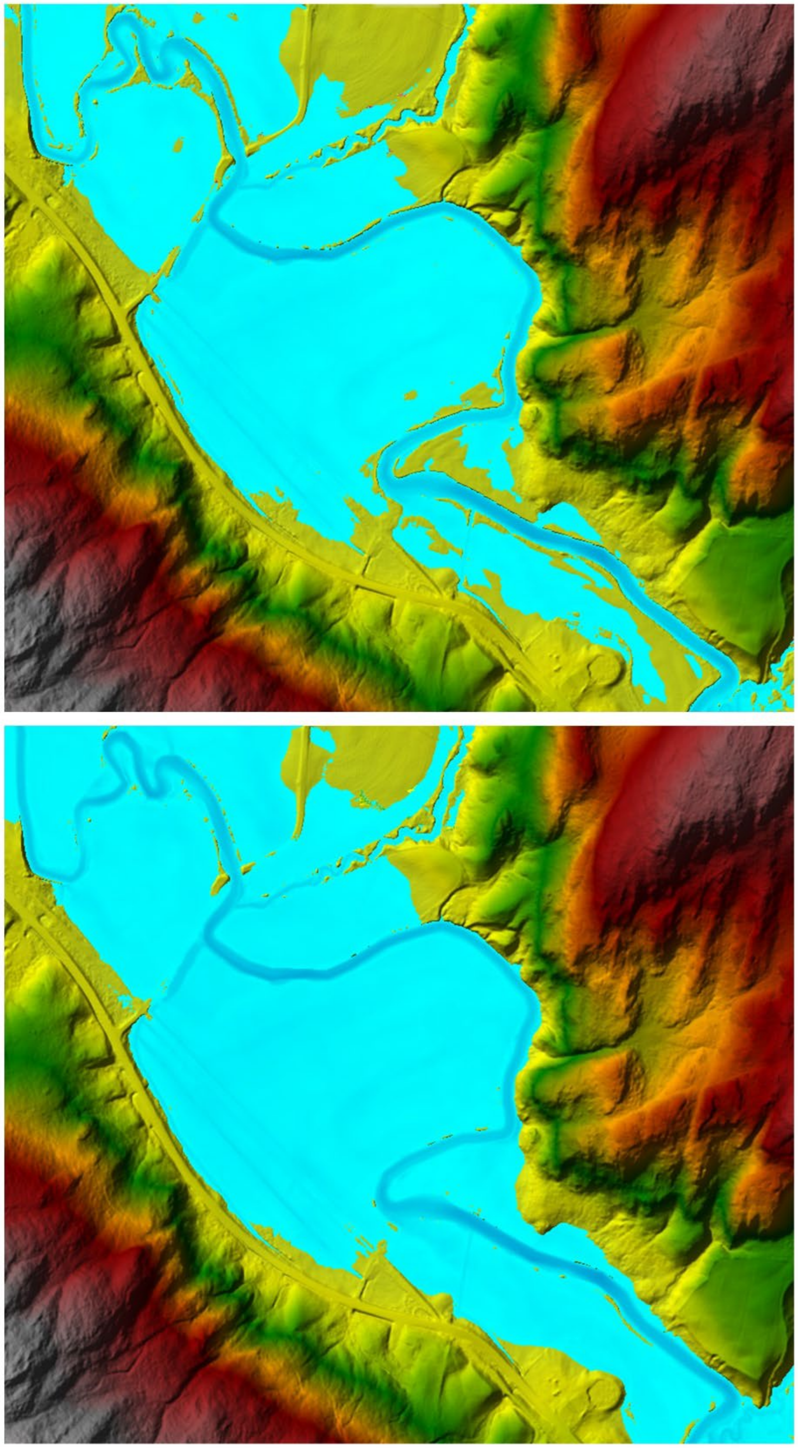


Figure 13. Simulated flooding extents for (a) Q2 and (b) Q25 flood in the vicinity of Fairfield 3-1 under existing conditions.

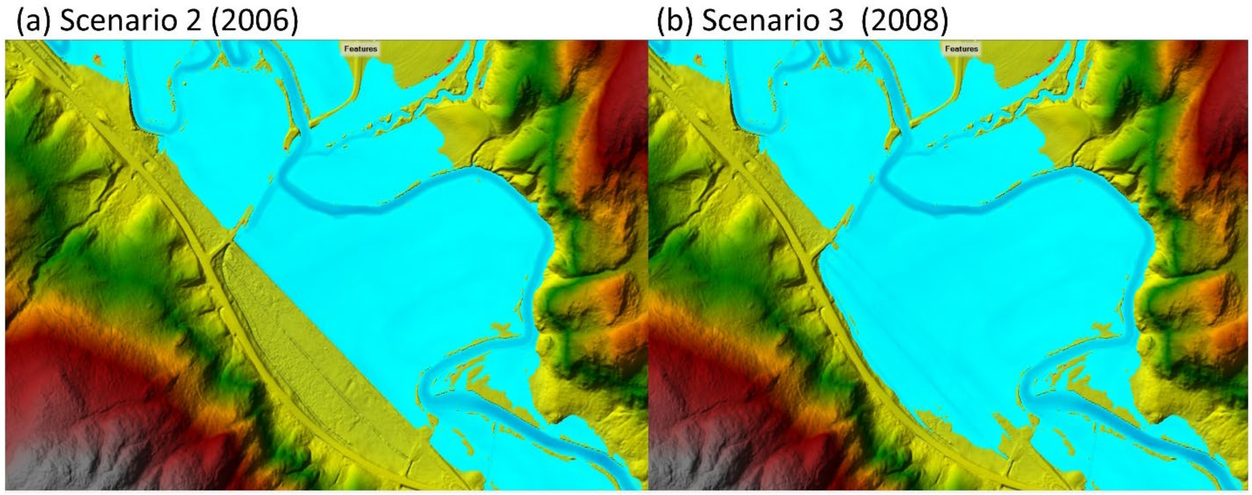


Figure 14. Comparison of flooding extents at Fairfield 3-1 during Q5 flood under (a) prior conditions (rail-trail intact) and (b) existing conditions (rail-trail lowered).

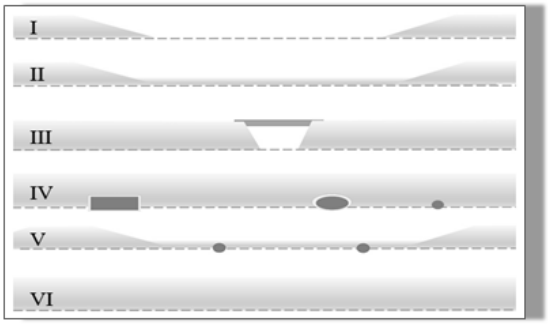
Modeling results indicated that sequential lowering of the rail bed at Fairfield 3-1 (R3) in 2007 and at Fairfield 2a (R2) in 2008, did not appreciably influence flow depths, velocities or durations of inundation at the upstream Fairfield 2b site (R1). Fairfield 2a is approximately 190 meters (620 feet) downstream of Fairfield 2b.

For road and channel observation points, there was no significant difference in velocity and inundation when comparing prior railbed-intact conditions to existing conditions. The floodplain observation points also showed no change between railbed-intact conditions and existing conditions, with two exceptions.

- In the Elm Brook floodplain south of the Fairfield 2b rail site (A2), inundation depths were modestly higher during railbed-intact times under the Q25 flood - 0.01 m (0.4 inch) higher, amounting to a 1.5% difference. As presented earlier, the rail bed constrained flows from the Elm Brook floodplain to pass through the crossing at bridge C.
- Similarly, in the Black Creek floodplain northeast of Fairfield 3-1 (A4), there were modestly greater inundation depths during railbed-intact times as compared to existing conditions – 1.3 to 2.5 % greater depths (up to 0.5 inch), that led to associated increases in velocity (3, 7, and 15 % increases for the Q2, Q5, and Q25 storms, respectively). Stated another way, lowering of the rail bed at Fairfield 3-1 resulted in modestly lower inundation depths and velocities.

4.3.3 Future Floodplain Modification Alternatives at Fairfield 2b Segment 1

From a baseline of existing conditions, new alternatives for rail berm modifications along Segment 1 of Fairfield 2b were simulated under Scenario 5 (Fig. 15). Notable findings for railroad, road, channel and floodplain observation points are presented below.



I. Complete lowering
II. Partial Lowering
III. Bridge (a) small; (b) large
IV. Culverts (a) small; (b) large
V. Combination – II and IVa
VI. No Action

Figure 15. Proposed Rail Trail Berm Modification Alternatives.
See section 3.5.1 for more detailed descriptions.

Railroad observations points:

- As expected, full rail-bed lowering (Alternative I) resulted in greater inundation depths, velocities and durations over the rail bed at site Fairfield 2b-1 (R1). The simulated elevation of the partially-lowered rail bed (Alt. II) is just about at the Q5 stage, and therefore this point is not quite inundated during a Q5. During the modeled Q25 storm inundation depths of 8 inches were present over the top of the partially lowered rail berm (Alt. II and Alt. V).

- At downstream site Fairfield 2a (evaluation point R2), each of the modeled alternatives at 2b-1 resulted in slightly increased flooding depth, velocities and duration during the Q25 storm. The maximum increase was for Alternative I (full berm lowering) which resulted in an inundation rise of 0.015 m (0.6 inch, or 10% increase) and a 25% increase in velocity to 0.75 meters/second (or 2.5 ft/sec). At present, floodwaters from Elm Brook tributary and floodplain are temporarily detained behind the rail berm and must drain through crossings C, G, and H before reaching downstream site 2a. Under a scenario of full lowering of the rail berm to the historic floodplain, these floodwaters would be released more quickly to downstream locations.

- For all modification alternatives implemented at Fairfield 2b-1, there were negligible changes in velocity or inundation at downstream site Fairfield 3-1 (R3) under the range of modeled storms.

Road segments:

- At upstream (D1) and downstream (D4, D5) road observation points, the various modification alternatives implemented at Fairfield 2b-1, resulted in negligible changes to inundation depths and velocities during the three design storms. Notably, at Bruso Road observation point D3, the bridge Alternative IIIb led to a 23% increase in flooding duration for the Q5, and a 54% increase in duration for the Q25 as compared to Existing Conditions. The other alternatives had no quantifiable influence on flooding duration at this downstream road point as compared to Existing Conditions. This outcome may be the result of more rapid draining from the vicinity of Fairfield 2b toward downstream reaches.

- At Elm Brook Road (D2), there was a 21% decrease in velocity for each of the Q2 and Q5 storms for flooding conditions under Alternative V (combination berm lowering to Q5 and addition of two small cross culverts). This alternative may reduce erosional scour on this gravel road approach to the Elm Brook Rd bridge. Other modeled alternatives showed negligible differences in inundation depths, velocity, or duration at this observation point, compared to existing conditions.

Channel:

- At channel evaluation points, there were no significant changes other than a slight decrease in stream power at C1, ranging up to 9 or 10 % decrease for reconnection accomplished through cross bridges in Alternatives IIIa and IIIb, respectively.

Floodplains:

- In the Black Creek floodplain to the north of the rail line (A1), depth of inundation was increased slightly under the Q2 and Q5 floods for most alternatives. The maximum change was for twin, large box culverts (Alt IVb), and modeled inundation depths increased 23% from 0.013 to 0.016 m (0.5 to 0.6 inch). An associated slight increase in flow velocity across the floodplain was estimated for this observation point under these scenarios. A very slight *decrease* in inundation depths was evident for the modeled Q25 storm. This contrasting result for a larger-magnitude flood event, was associated with a reversal of flow direction through the culverts (Fig. 16).

- An opposite pattern for inundation depth was evident in the Elm Brook floodplain to the south of the rail line (A2). Inundation depths *decreased* as the Elm Brook floodplain drained more easily to the north with alternatives that increased the cross connection, until the modeled Q25 storm, when flows reversed through the cross connections (Fig. 16, 17).
- The magnitude of the depth change was greater in the Elm Brook floodplain than it was in the Black Creek floodplain. For example, inundation depth dropped from 9.4 inches average inundation depth at A2 under Existing Conditions to 3.6 inches for Alt. IVb during the Q2 storm.

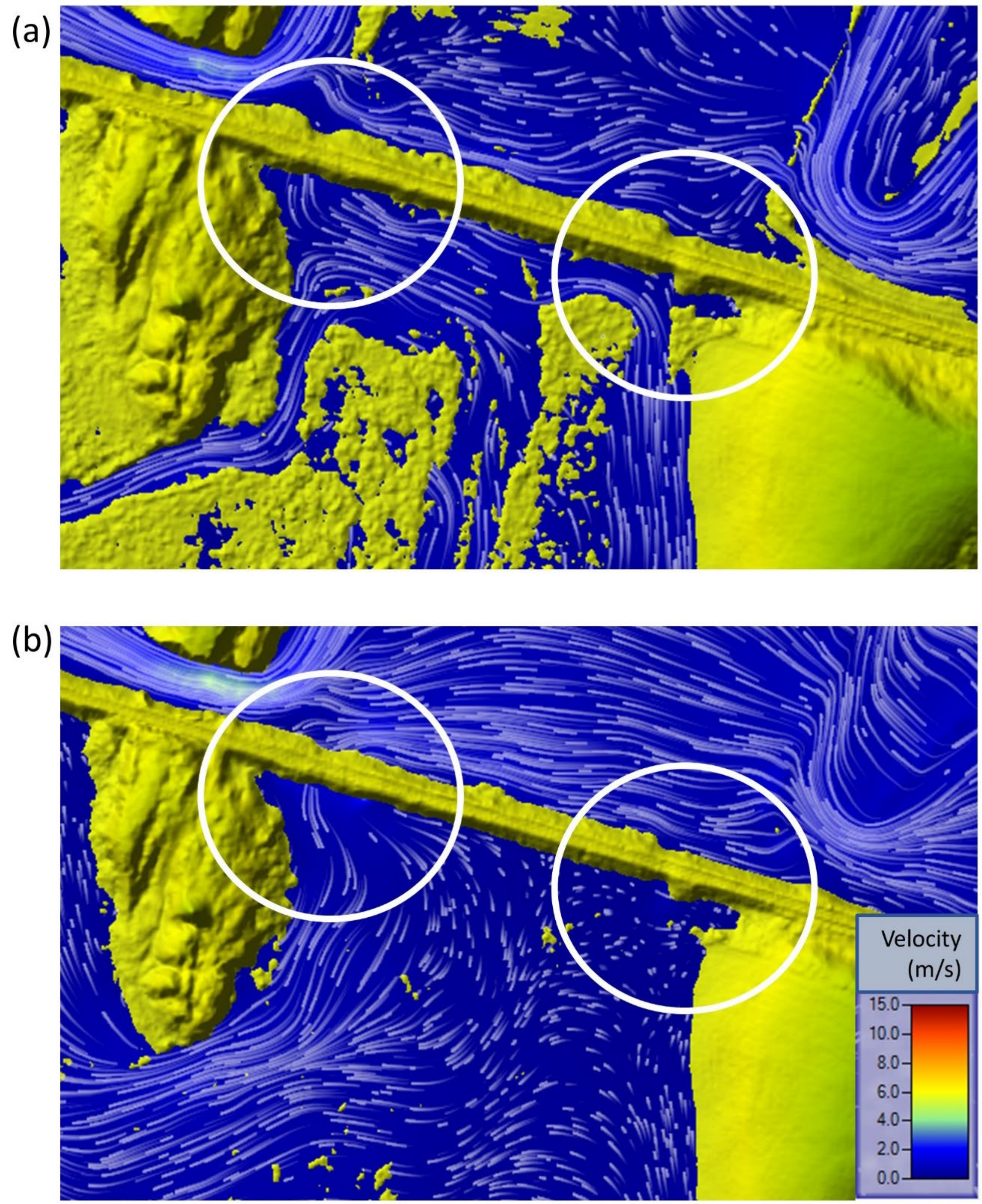


Fig. 16. Flow velocity for peak discharge conditions under Alternative IVb (twin large box culverts) under (a) a Q5 flood and (b) a Q25 flood. Color bar indicates the magnitude of velocity and particle-tracking highlights the relative direction of velocity. Note the reversal of flow direction to the south through the culverts under the Q25 flood.

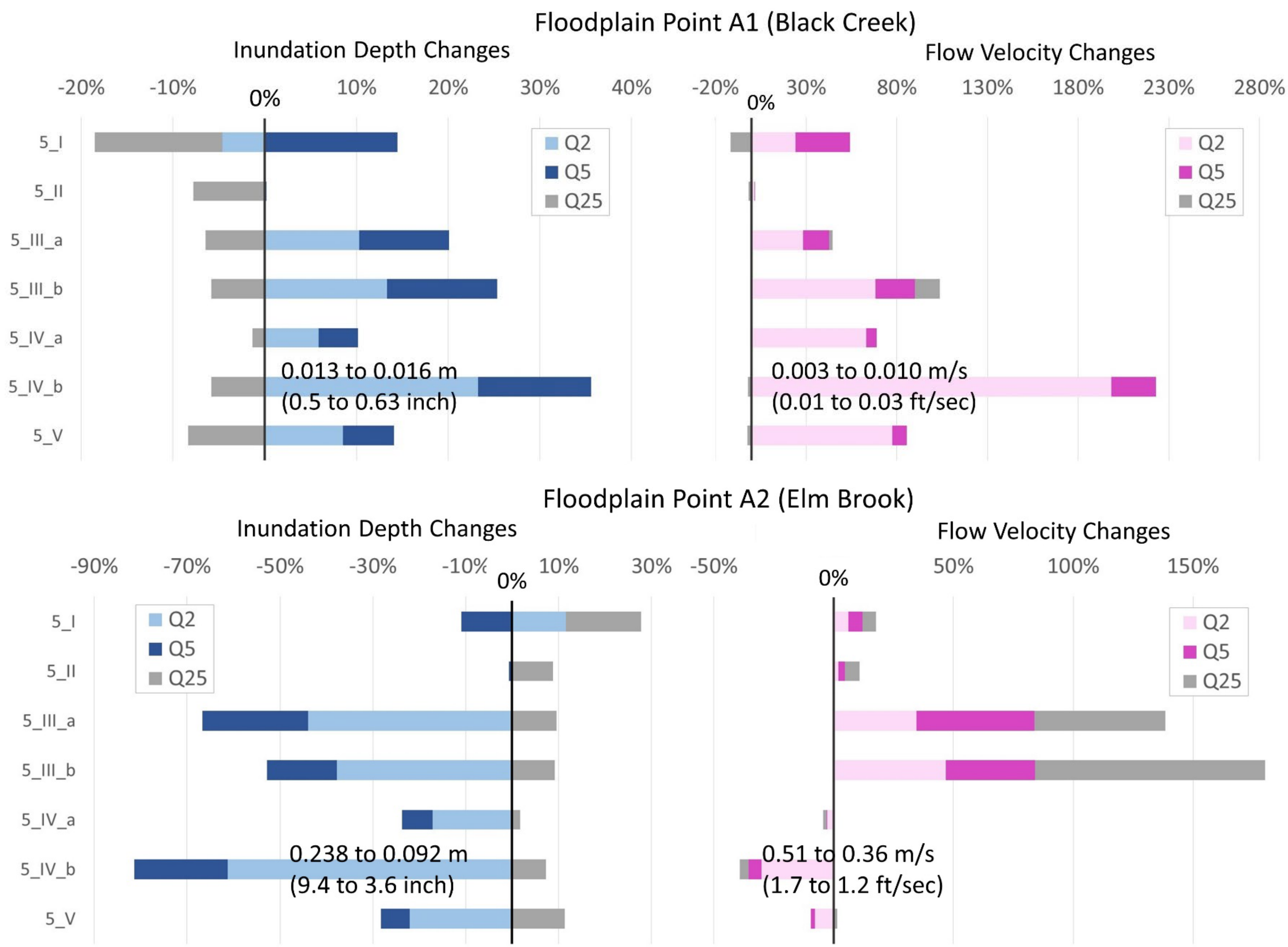


Figure 17. Percent increase in flood parameters for indicated design storms under various alternatives for floodplain reconnection at Fairfield 2b-1, as quantified in the Black Creek floodplain (A1; top) and in the Elm Brook floodplain (A2; bottom).

4.3.4 Floodplain Lowering at Fairfield 2b Segment 2

A full lowering of Fairfield 2b Segment 2 was simulated under Scenario 6 to connect a small floodplain area of 5.3 acres. At all evaluation points in the model domain (railroads, roads, channel, and floodplains) no significant change in flooding depths, velocity or duration were recorded. This result is likely due to the very small floodplain area and modest floodwater storage gained as compared to the total upstream floodwater volumes for each design storm.

4.4 Alternatives Analysis

The various alternatives for modification of Fairfield 2b-1 were considered with respect to objectives expressed by the TAC, ranging from maintaining use of the LVRT for recreation and emergency vehicle access to improving aquatic organism passage in the Elm Brook (Table 7). An important goal of this demonstration project was a more holistic analysis that considered not only the benefits of restored floodplain connection, but also the impacts to existing shared uses within the river/rail corridor. Out of a maximum score of 3, each modification alternative was scored on the basis of whether it improves (+), runs counter to (-), or has no expected effect on (O), the stated objective relative to existing conditions (or the "No Action" Alternative VI). For each alternative, the scores were summed to identify a priority ranging from Very Low (0), Low (1-2), Moderate (3-4), High (5-6), or Very High (>6). Costs in the last column of Table 7 are approximate and provided for reference only; costs were not included in the assignment of priority. This analysis focused on conditions imparted by floods of 2 to 5-year recurrence intervals, and not the more extreme, lower-frequency flood magnitudes.

In terms of restoring the naturalized functions of Black Creek and Elm Brook floodplains, the full or partial lowering alternatives were most favorable, since these floodplain re-connection methods resulted in greater cross-connection (removal of artificial barriers) and less potential for constriction of flows through bridge or culvert openings. However, they would impact more greatly than other alternatives the full recreational and emergency-vehicle use of the LVRT, because of the potential for persistent wet conditions and associated maintenance issues resulting from inundation of the rail trail surface and shoulder materials. Because bridge and culvert alternatives allow for the rail trail surface to be elevated above the floodplain, materials can drain more quickly resulting in greater usability and fewer maintenance expenses. Bridges may also have fewer maintenance issues than the existing round culverts or proposed box culverts associated with blockages created by beaver dams.

As compared to existing conditions, the modeled alternatives resulted in negligible to modest increases in floodwater storage (and inferred sediment and nutrient attenuation) in the Black Creek floodplain under Q2 to Q5 floods. This outcome suggests minimal impacts (above existing conditions) to hay cultivation operations in the Black Creek floodplain. Additionally, inundation and scour velocities along Route 36 were not substantially different from existing conditions under any of the modeled alternatives.

In the Elm Brook floodplain, enhanced floodwater storage to achieve sediment and nutrient attenuation in the Elm Brook floodplain would not conflict with current land uses, because these agricultural lands have been fallow since the mid-1990s. Additionally, the landowners are engaged in discussions and project planning tasks with NRCS and other project partners to enhance trout habitat in the Elm Brook channel and wetlands, and enhanced floodwater storage would be compatible with these goals. However, modeled re-connection alternatives under Q2 and Q5 conditions either had no significant affect or actually decreased floodwater storage in the Elm Brook floodplain. The bridge and culvert alternatives (III through V) caused floodwaters to drain more quickly to the north into the Black Creek floodplain during a Q2 or Q5 event, and therefore are not favored for their ability to achieve floodwater storage in the Elm Brook floodplain. In particular, the enhanced velocities of floodwaters across the Elm Brook floodplain (Fig. 17 bottom, right) under either of the bridge alternatives (III) may run counter to the objective to settle out fine-grained, nutrient-bound sediments.

A bridge alternative would improve fish passage at the Fairfield 2b-1 site. The existing western culvert (G in Fig. 5) is perched and presents a barrier to upstream migration of fish from the Black Creek. However, only a modest improvement in fish passage was assigned to the bridge alternatives, because under existing conditions, fish do have access to upstream reaches of Elm Brook through the LVRT bridge just 500 feet west of the Fairfield 2b-1 site (C in Fig. 5).

In consideration of all the objectives, the modeled alternatives were assigned a Very Low to Low priority. Important limitations apply to this analysis. First, this analysis focused on physical factors that suggested enhanced floodplain connection (e.g., expanded inundation extent), and were relied upon to infer improved floodplain function resulting from this reconnection, such as increased groundwater recharge, sediment and nutrient storage, and attenuation of downstream peak flows. Select flooding parameters simulated by HEC-RAS (e.g., increased inundation depth, decreased velocity) were interpreted to suggest increased floodwater storage. An assumption was made that floodwater storage equated to potential for fine sediment and nutrient attenuation, but no sediment modeling was conducted for this analysis because the current version of HEC-RAS is not able to model sediment erosion and deposition in 2D flow areas (USACE, 2016). It is possible that the modeled alternatives would be associated with varying capacities for sediment attenuation. For example, connection between floodplains achieved by small cross culverts may be less effective at net storage of fine sediments (and associated nutrients) than connections achieved by berm lowering. The task of modeling sediment attenuation at this demonstration site would be quite complicated, because the reconnection floodplain on the south side of the LVRT rail would be receiving floodwaters from Black Creek but also floodwaters from Elm Brook, and each upstream watershed could be sourcing different sediment and nutrient loads under variable storm conditions.

Table 7. Alternatives Analysis for LVRT Rail Berm Modification at Site Fairfield 2b-1, East Fairfield, Vermont.

Scenario 5 Alternative	Naturalize historic floodplain connection	Enhance sediment/nutrient attenuation in the floodplain		Improve Aquatic Organism Passage	Maintain hay cultivation in Black Creek floodplain	Protect VT Route 36 from scour/ inundation	Maintain recreational/ emergency use of rail trail	Priority	Cost / Technical Difficulty
		Black Creek	Elm Brook						
I – Full Lowering	+++	O	O	+	O	O	- - -	1-Low	$ 20K
II – Partial Lowering	++	O	O	O	O	O	- -	0-V. Low	$ 15K
IIIa – Bridge-small	+	+	- -	+	O	O	-	0-V.Low	$350K
IIIb – Bridge-large	+	+	- - -	++	O	O	O	1-Low	$500K
IVa – Culverts (2) - small	O	O	-	+	O	O	O	0-V. Low	$175K
IVb – Culverts (2) - large	O	++	- - -	++	O	O	O	1-Low	$250K
V – Combination Part.Lowering Culverts (2) - small	++	+	-	+	O	O	- -	1-Low	$225K

Out of a maximum score of 3, the indicated modification alternative improves (+) or runs counter to (-) the stated objective relative to Existing Conditions. A "O" symbol indicates no difference relative to the Existing Conditions.

Additionally, effects of groundwater recharge from, or discharge to, the model domain were not simulated and may be important in the vicinity of the demonstration site. The effects of entrained sediment and large woody debris on flow stage, velocity and inundation extent were not explicitly modeled. Based on visual observations and anecdotal accounts, beaver activity in the site vicinity can periodically constrain flows through existing cross culverts and add to maintenance costs of the LVRT for the Vermont Association of Snow Travelers.

Finally, the analysis did not address potential modifications to the floodplains themselves, which in large part are wetlands that have been previously-converted to agricultural uses. As part of the separate wetland and stream restoration project for improved trout habitat, the Elm Brook floodplain and stream channel may be modified in coming years. Typical wetland restoration techniques such as ditch plugs and streambank and floodplain revegetation could significantly influence flow directions, and inundation depths and velocities in the Elm Brook floodplain. In particular, these planned restoration efforts may mitigate for the effects of modeled bridge alternatives for the LVRT (i.e., decreased inundation depths and increased flow velocities). This hydraulic model will be available for stakeholders of the trout habitat restoration project, and could be used to simulate the effects of planned wetland and stream restoration techniques, in combination with LVRT floodplain reconnection alternatives.

5.0 CONCLUSIONS

This research has resulted in a framework for performance assessment of proposed floodplain reconnection sites along rail-banked rail trails that will enable more holistic analysis of the multiple uses and functions of river and rail corridors, potential impacts to adjacent infrastructure and life safety and health, as well as environmental benefits and impacts.

A screening protocol has been developed for stakeholders to identify and prioritize candidate floodplain reconnection sites along river and rail trail corridors in Vermont. This protocol employs low-complexity hydraulic modeling (Height Above Nearest Drainage methods), and leverages stream geomorphic assessment data maintained by VTANR for many state rivers. A retrospective analysis of the Black Creek and Lamoille River valleys indicated that ten out of twelve floodplain reconnection projects completed along the Lamoille Valley Rail Trail in 2006-2008 were predicted as a priority. The screening protocol identified additional candidate sites, including the proposed site, Fairfield 2b. Modeling results confirmed that the completed projects have provided significant increases in the floodplain availability at almost all sites for floods of 2- to 5-year recurrence interval and at all but one site, for the 100- to 500-yr flood. This additional floodplain connection has provided increased capacity for sediment/nutrient attenuation and floodwater storage. At the same time, enhanced flooding of the rail trail at these sites, has led to increased maintenance expenses and challenges for recreational use. Experience at these sites has highlighted a management need for strategies that balance these recreational goals alongside flood resiliency and water quality goals.

A monitoring protocol has been developed for citizen-based evaluation of floodplain storage of sediment and nutrients (Appendix D). Planned field training for stakeholders in the spring of 2020 was canceled due to the COVID-19 pandemic. However, based on spring 2019 trials, we anticipate that this procedure could be useful in the future for stakeholders to monitor the effectiveness of completed floodplain reconnection sites, or to evaluate sediment/nutrient storage on any floodplain of interest. Testing of this protocol at Fairfield 3-1 and 2b sites (and other sites as part of separate project sponsored by the Lake Champlain Basin Program) has revealed that sediment thicknesses are highly variable depending upon surface micro-topography and variable residence times of floodwaters. Sediment tended to be greater in thickness nearer to the channel and in local areas of low elevation (e.g., abandoned channel meanders) where floodwaters have longer residence times. Also, flooding events varied in their suspended sediment content (e.g., seasonally, by storm duration and degree of flashiness), yielding variable thicknesses and extents of floodplain sediment.

Two-dimensional hydraulic modeling (HEC-RAS) has been performed at a demonstration reach of the Black Creek near East Fairfield spanning two completed floodplain reconnection sites and one proposed site to better illustrate the potential benefits and impacts of various floodplain reconnection scenarios on flooding conditions at the rail trail and vicinity roads and floodplains. Modeling results revealed several factors in this specific reach that complicated its role as a demonstration site for floodplain reconnection.

The Black Creek in this reach is vertically well-connected to its floodplain in floods with recurrence intervals equal to or greater than 2 years. Thus, the volume of floodwaters stored in reconnected floodplains is relatively small in comparison to the total volume of floodwaters already able to access the floodplain in the model domain. Consequently, the model indicated little change in inundation depth and duration when these historically-isolated floodplain areas were reconnected. Similarly, little change in velocity of those floodwaters across the plain was evident, given the very low gradient of the river in the site vicinity. Nevertheless, historic reconnection at Fairfield 2a and 3-1 has expanded floodplain areal extents. Substantial volumes of sediment (and phosphorus) can be stored on these sites, as has been documented historically (Schiff et al., 2008), and during field monitoring over this most recent year.

The proposed reconnection site in this reach, Fairfield 2b, is located at the confluence of a major tributary, Elm Brook. Rather than expanding a single floodplain, proposed rail berm modification would be facilitating enhanced cross connection between two adjacent floodplains, and this mixing of floodwaters complicates the evaluation of alternative performance. The nearby site completed in 2008, Fairfield 2a, is similar in that its partial lowering enhanced the exchange of floodwaters for both the Black Creek and a portion of Elm Brook floodplain, as well as a smaller tributary flowing in from the southwest.

Historical documentation compiled for this study also revealed that some degree of cross connection between the Elm Brook and Black Creek floodplains already exists at the Fairfield 2b site. Under baseflow and <Q2 flood stage, a portion of Elm Brook tributary discharge and ditch

drainage pass through two cross-culverts under the rail line that were improved in 2009 and 2010. At higher flood stages, discharge accelerates through these culverts but can also reverse direction and flow from the Black Creek floodplain into the Elm Brook floodplain, depending on relative flood stages on either side of the rail line. Given the existing degree of cross connection between the two floodplains, the influence of proposed berm modification alternatives on flood depths, velocities and durations at observation points in each floodplain was rather modest. Flow may also occur as seepage through blast rock that reportedly forms the base of the rail berm, as was observed by the local farmer historically; however, this transient groundwater flow was not modeled.

Research products have been shared with stakeholders through the research team's ongoing interactions with VTrans and VTANR personnel serving on an interagency technical advisory committee, collaborations with other floodplain researchers, production of webinars, and participation in the annual VTrans research symposiums. The hydraulic modeling products and scenarios developed for this project can be adapted to support analysis and modeling of potential fine-sediment and phosphorus attenuation as VTrans continues to collaborate with VTANR to develop a phosphorus-crediting framework for floodplain reconnection projects.

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Appendices

Appendix A. Memorandum of Agreement Between VTrans and VTANR

Appendix B. Hydrologic Analysis

Appendix C. History of Rail Line and Channel/Floodplain Modifications near Fairfield 2b site, Fairfield, VT.

Appendix D. Screening Protocol for Rail Trail Reconnection Sites

Appendix E. Floodplain Sediment Sampling Protocol

Appendix F. Bridge and Culvert Data

Appendix G. Modeled increase in floodplain area at historic reconnection sites