Flood Analysis of Bridge-Stream Interactions Using Two-Dimensional Models

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16 Abstract

The northeastern United States is experiencing more frequent precipitation events of longer duration (i.e., extreme events). Infrastructure therefore must be able to withstand more frequent flood events of greater magnitude. It is not feasible to analyze and retrofit each structure for the rigorous hydraulic demands of extreme flood events; so prioritizing limited resources to locations at greatest risk in order to minimize flood damage is critical. Current state of practice is often limited in scope to steady-state analysis in the immediate vicinity of a specific structure or feature, and the far-reaching impacts up- and downstream the river are often not understood and considered in decision making. To better understand the interactions among rivers, hydraulic structures and surrounding hydrogeological features, a two-dimensional (2D) transient HEC-RAS (Hydraulic Engineering Center's River Analysis System) model of a section of Mad River, Vermont was constructed and calibrated. Available 2D HEC-RAS models of two additional Vermont rivers (sections of Black Creek and Otter Creek) supplemented the study allowing comparisons across a range of river gradients. All three river study sections have nearby USGS (U.S. Geological Survey) gauges and a number of bridges (3 to 16), and therefore make suitable study sites. The analyses considered the 2011 Tropical Storm Irene, as well as flood events that have annual exceedance probabilities of 50%, 4%, 2% and 1%, to analyze hydraulic impacts and interactions surrounding transportation infrastructure. A screening framework, that uses the 2D hydraulic modeling results, was developed to identify bridges and sites best suited for hydraulic intervention such as floodplain lowering and reconnection and addition of culverts for mitigating the impacts of extreme flood events along the bridge-river network. These interventions were then simulated in the developed 2D HEC-RAS models of the three study sites.

The results of the baseline and intervention models indicate that the developed screening framework that combines geomorphic and hydraulic characteristics can identify suitable bridges and other locations along a river for flood mitigation intervention. The screening framework is comparatively more applicable to moderate to high gradient rivers, but may still be applied to lower gradient rivers with supplementary data from prior flood damage reports and inspection records. The results demonstrate that the interventions have cascading effects up and downstream of the intervention locations. Interventions simulated on a moderate or high gradient river have farther-reaching effects that are often less intuitive up and downstream compared to a low gradient river highlighting the importance of a transient, 2D hydraulic analysis. Overall, the results suggest that bridge flood mitigation projects in similar geographic and climate settings should consider the up and downstream geomorphic and hydraulic characteristics to better understand the potential impact the intervention will have on the bridge-river network.

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Abstract

The northeastern United States is experiencing more frequent precipitation events of longer duration (i.e., extreme events). Infrastructure therefore must be able to withstand more frequent flood events of greater magnitude. It is not feasible to analyze and retrofit each structure for the rigorous hydraulic demands of extreme flood events; so prioritizing limited resources to locations at greatest risk in order to minimize flood damage is critical. Current state of practice is often limited in scope to steady-state analysis in the immediate vicinity of a specific structure or feature, and the far-reaching impacts up- and downstream the river are often not understood and considered in decision making. To better understand the interactions among rivers, hydraulic structures and surrounding hydrogeological features, a two-dimensional (2D) transient HEC-RAS (Hydraulic Engineering Center's River Analysis System) model of a section of Mad River, Vermont was constructed and calibrated. Available 2D HEC-RAS models of two additional Vermont rivers (sections of Black Creek and Otter Creek) supplemented the study allowing comparisons across a range of river gradients. All three river study sections have nearby USGS (U.S. Geological Survey) gauges and a number of bridges (3 to 16), and therefore make suitable study sites. The analyses considered the 2011 Tropical Storm Irene, as well as flood events that have annual exceedance probabilities of 50%, 4%, 2% and 1%, to analyze hydraulic impacts and interactions surrounding transportation infrastructure. A screening framework, that uses the 2D hydraulic modeling results, was developed to identify bridges and sites best suited for hydraulic intervention such as floodplain lowering and reconnection and addition of culverts for mitigating the impacts of extreme flood events along the bridge-river network. These interventions were then simulated in the developed 2D HEC-RAS models of the three study sites.

The results of the baseline and intervention models indicate that the developed screening framework that combines geomorphic and hydraulic characteristics can identify suitable bridges and other locations along a river for flood mitigation intervention. The screening framework is comparatively more applicable to moderate to high gradient rivers, but may still be applied to lower gradient rivers with supplementary data from prior flood damage reports and inspection records. The results demonstrate that the interventions have cascading effects up and downstream of the intervention locations. Interventions simulated on a moderate or high gradient river have farther-reaching effects that are often less intuitive up and downstream compared to a low gradient river highlighting the importance of a transient, 2D hydraulic analysis. Overall, the results suggest that bridge flood mitigation projects in similar geographic and climate settings should consider the up and downstream geomorphic and hydraulic characteristics to better understand the potential impact the intervention will have on the bridge-river network.

Chapter 1: Introduction

This chapter presents the research motivation, overarching and specific objectives of this research, and organization of this report.

1.1 Motivation

The interactions between rivers, their surrounding hydrogeological features (e.g., land use), hydraulic structures such as bridges, and other infrastructure such as roads and culverts are not well-established or understood at the bridge-river network scale, especially under transient flow conditions. Recent extreme flood events have brought to light the vulnerability of transportation infrastructure nationwide. For example, in 2009 Georgia experienced a week-long rain event from March 27th to April 3rd that deposited up to 14 inches of rain in some areas. This resulted in over $60 million in public infrastructure damage to roads, culverts, bridges and a water treatment facility (McKinney, 2009). Hurricane Harvey in 2017 caused damage or collapse of 13 bridges and over 500 roadways (Sharp et al., 2018).

In late August 2011, Tropical Storm Irene moved along the Connecticut River Valley depositing on average 3-5 inches of rain with some areas of Vermont receiving 8 inches (Medalie et al., 2013). The flooding that resulted from this tropical storm left infrastructure damage, including failure of or damage to over 300 bridges, and damage to or closure of more than 500 miles of state highway as well as 200 miles of state-owned rail (Anderson et al., 2017a) (Figure 1.1).

The frequency and intensity of precipitation events are increasing across the United States (Tockner and Stanford, 2002; Guilbert et al., 2015). The southeastern United States is experiencing more intense precipitation from non-tropical storms (Bishop et al., 2019). The northeastern United States is experiencing an increase of precipitation magnitude and persistence, leading to more frequent extreme events; these trends are expected to continue in the future (Horton et al., 2014; Melillo et al., 2014; Guilbert et al., 2015).

(a) Bridge collapse in Rochester, VT (b) VT Route 107

Figure 1.1 Examples of damage to Vermont bridges and roads in 2011 Tropical Storm Irene (source: Pealer, 2012)

As a result, infrastructure will have to withstand more extreme flood events. However, adapting and modifying every structure will be expensive and impractical. With thousands of bridges and other structures in existence, it is unlikely that each one will be assessed and retrofitted or replaced to withstand the anticipated extreme flood events.

Remediation methods such as bridge replacement or relocation and the addition of culverts can potentially reduce negative hydraulic effects that propagate up- and downstream. However, these interventions are not as well studied on a river scale. Floodplain reconnection has been well documented to reduce negative hydraulic impacts on a river reach scale (Booth et al., 1990; Bernhardt et al., 2007; Guida et al., 2015; McMillan and Noe, 2017; Remo et al., 2017). However, not many studies have considered the reduction of these impacts around transportation infrastructure.

Roads and railways have been built along river networks for over a century (Dunbar, 1915, Schwantes, 1993). The associated encroachment on the floodplain is known to cause localized hydraulic changes (Blanton and Marcus, 2009). For example, in Vermont, hydraulic impacts are very common with almost 75% of assessed waterways experiencing floodplain incision and reduced floodplain connection due to human impact (Kline and Cahoon, 2010). Over the past few decades restoration and rehabilitation efforts have been taking place in Vermont, which accelerated with a large number of projects implemented after the 2011 Tropical Storm Irene (Macbroom, 2012; Mears and McKearnan, 2012). Many projects hope to mitigate flood risks and rehabilitate rivers that have experienced extensive historical human impacts (Schiff et al., 2015). Reducing these effects around bridges and structures that cross river corridors poses a more difficult challenge. Due to their critical importance in transportation, crossing structures cannot be removed or altered as easily as berms or other infrastructure in the floodplain.

In Vermont, bridges along freeways are currently designed for an annual exceedance probability (AEP) of 1% (Wark et al., 2015). Bridges on principal and minor arterial roads and collector roads are designed to withstand an AEP of 2% (Wark et al., 2015). Bridges on local roads and streets are designed to withstand flood events with an AEP of 4% (Wark et al., 2015). Railroads are designed for an AEP of 2% and limited access roads are designed at the discretion of design engineers (Wark et al., 2015). These modern structures are designed for bankfull width or greater to mitigate dangerous hydraulic impacts such as constriction or scour at the bridge (Wark et al., 2015). Unlike historic bridges, this design allows for more frequent flood stages and unrestricted passage of Q1.5 - Q2.33 flow events, without significant localized hydraulic impacts (Wark et al., 2015). Significant hydraulic impacts would be more heavily dependent on other factors such as bridge-stream intersection and the river’s ability to access its floodplain in flood stage.

The varying localized impacts of floodplain encroachment and bridge constriction on extreme flood events are well-known (e.g., Johnson et al., 2002; Lagasse et al. 2009, 2012; Anderson et al., 2017a, 2017b). The effects of channel incision due to human impacts is also well studied (Tockner, 2002). However, analyses are generally limited in scope to the immediate vicinity of the relevant structure, feature, or specified project area. A river’s ability to access its floodplain is known to reduce downstream hydraulic hazards, by attenuating the flood wave and reducing specific stream power (Tockner, 2000).

Old bridges, particularly bridges that are on a historic bridge registry, were often built with shorter spans founded on encroaching abutments owing to cost limitations and availability of materials, and often with minimal theoretical basis for engineering design (Gumbel, 1941). As a consequence, historic bridges are more susceptible to hazardous hydraulic impacts such as approach, foundation scour or channel flanking, backwater flooding, and roadway overtopping. Modern bridges with newer designs are more compatible with a stable morphological regime in the localized vicinity (Johnson et al., 2002; Johnson 2006; McEnroe, 2006), but can detract from the historical character of a community.

The cascading hydraulic effects of local perturbations up- and downstream of the site of perturbation may have significant, unexpected, and far-reaching consequences, and therefore often cause concern among stakeholders. Bridge rehabilitation or new bridge design is often performed as needed for individual bridges without much consideration for how the hydraulic changes of the new design may cascade up- and downstream (e.g., effects on other bridges, roads, culverts, streambanks, towns, etc.), largely because of the lack of appropriate analysis methods. This uncertainty is often a concern raised by stakeholders and should be considered for all bridge designs, but is quite difficult to answer given the lack of appropriate quantitative methods for assessing transient unsteady streamflow conditions at a river scale.

Adjustments and changes to transportation infrastructure as well as river rehabilitation and connectivity projects should be more frequently considered as localized changes are known to have watershed scale impacts (Blanton et al., 2009).

1.2 Research Goals and Objectives

The overarching goals of this research were to:

1. Understand how infrastructure, particularly bridges, interact with rivers over a range of gradients and other hydrogeologic features at a reach scale.
2. Understand how the effects from interventions cascade up- and downstream in the river reach.
3. Develop and evaluate a framework that combines stream channel gradient and specific stream power to identify transportation infrastructure most sensitive to flood mitigation interventions.

To accomplish these overarching goals, this research examined three river study sections from Vermont. A transient 2D HEC-RAS model of a section of Mad River was developed. Available 2D HEC-RAS models of two additional Vermont river (Otter Creek and Black Creek) sections supplemented the study allowing comparisons across a range of river gradients. All 2D HEC-RAS models were able to simulate the 2011 Tropical Storm Irene or an event of greater exceedance probability. The models were also able to simulate additional storm events including annual exceedance probabilities (AEP) of 50% (Q2), 4% (Q25), 2% (Q50) and 1% (Q100). The modeling results supported development of a screening tool that combines geomorphic, and hydraulic information to identify transportation infrastructure that would benefit most from flood mitigation interventions. This screening framework was applied to all three river study sections. Based on the feedback provided by experts, floodplain lowering and reconnection, and culvert modification were used as primary flood mitigation interventions in the modeling efforts. The Mad River study section intervention model results were compared to baseline conditions on the

Otter Creek and Black Creek study sections. Baseline conditions refers to the 2D HEC-RAS model simulations when floodplain mitigation interventions were not implemented.

This overall methodology had the following specific objectives:

1. Develop a transient, 2D HEC-RAS hydraulic model for a high gradient river section with multiple bridges for a range of design annual exceedance probabilities (50%, 4%, 2%, 1%, 0.08%) corresponding to approximately to Q2, Q25, Q50, Q100 and the 2011 Tropical Storm Irene events.
2. Modify the hydraulic model to simulate terrain alterations in the river corridor to elucidate their respective impacts at the bridge-river scale. Modifications include lowering floodplains and addition of culverts.
3. Observe and evaluate the localized and river scale impacts of flood mitigation interventions simulated in the high gradient river model.
4. Identify structural and hydraulic characteristics of significance within a bridge-river network to develop a screening framework to categorize and rank transportation infrastructure (specifically bridge sites) best suited for flood mitigation interventions.
5. Apply and assess the developed screening framework for all three river study sites.
6. Compare and contrast flood mitigation intervention simulation results and baseline conditions in all three river study sections to determine network level intervention effectivity and applicability of the developed screening framework to multiple rivers.

Chapter 2: Literature Review

This chapter presents background literature on the impacts of flooding on transportation infrastructure and bridge-stream interactions. Additional topics include regional importance, and a review of relevant hydraulic modeling studies from the literature.

2.1 Impacts of Flood Events and Climate Change on Bridges

Due to climate change, storm events are expected to increase in frequency and magnitude in many parts of the world, leaving transportation infrastructure, such as bridges, at a risk of potential damages or even complete failures. Recent extreme storm and flood events have exposed vulnerabilities in transportation infrastructure. Bridges have been damaged or failed from these events throughout the world including the United States and the northeast region of the United States. This has led to many studies documenting, analyzing and forecasting the impacts of flooding on infrastructure such as bridges, culverts and levees (e.g., Setunge et al., 2014; Kocyigit et al., 2016; Anderson et al., 2017a, b).

Flood events have increased in magnitude across the world, putting strain on current bridge infrastructure. In 2010 and 2011 a series of floods swept through Queensland, Australia devastating transportation infrastructure. The floods damaged 9,170 km of road network, 4,748 km of rail network, and 89 bridges or culverts (Setunge et al., 2014). In 2013, the Lackyer Valley region in Australia had additional flood events that damaged 43 out of the 46 bridges in the area. Researchers have linked increases in precipitation to climate which can exacerbate flood events in these areas (Setunge et al., 2014).

A similar study observed bridge damage and collapse in Turkey due to frequent flood events also linked to climate change (Kocyigit et al., 2016). The study analyzed flood events that took place between 2010 and 2014, and found the current bridge infrastructure to be insufficient and at risk of failure (Kocyigit et al., 2016).

In the southern United States, the 2005 Hurricane Katrina severely impacted transportation infrastructure in the Gulf Coast region, and the estimated cost of replacement or repairs to the bridges exceeded $1 billion (Padgett et al., 2006). More recently, Chang et al. (2010) analyzed precipitation trends in Portland, Oregon, and concluded that the increase in precipitation from climate change will dramatically impact transportation infrastructure, including bridges. Wright et al. (2012) studied the increasing trends in precipitation and concluded that more than 100,000 bridges in the United States are deficient and unable to withstand increased river flows; and estimated a cost of up to $250 billion to adapt all vulnerable bridges in the United States to better withstand extreme events.

Evaluating and, if needed, retrofitting every bridge in the U.S is not cost affective or realistic. Bridge damage and failure is occurring in many parts of the world from climate change-induced extreme flood events (Figure 2.1). It is therefore imperative to better understand flood impacts on bridges at a river reach scale to better prepare stakeholders and project managers for more holistic approach to bridge design.

Queensland Australia – 2011 Storm (Chanson, 2011)

Vermont, USA - 2011 Tropical Storm Irene (Photo credit: VTrans; National Wildlife Federation, 2016)

Colorado, USA (2013) (Meyer, 2016)

Texas, USA (2017) (Cho et al., 2017)

Italy (2019) (FloodList, 2019)

Turkey (2020) (Daily News, 2020)

Figure 2.1 Images of bridge damages and failures from flood events across the world

2.2 Regional Significance

Due to the mountainous terrain in New England, railway and road transportation networks are often constructed along river banks (Blanton et al., 2009). Many of the hydraulic crossings on the east coast are well over a century old with the earliest rail lines constructed in the 1830's and paved roads constructed in the early 1900's (Blanton et al., 2009). These historic structures lacked the availability of modern analytical tools for bridge design, and were often built with little consideration to river constriction or, increasing water surface elevation.
Due to increased precipitation events expected in the Northeast, there is stakeholder concern about the ability of current and planned bridges to withstand more frequent and extreme flood events, and the need for new evaluation and guidelines for infrastructure has been identified

(Spierre and Wake, 2010). In the Northeast, bridge rehabilitation programs have been established to better protect the high number of historic structures (FHWA, 2002).

Climate data show that Vermont is experiencing more frequent and persistent precipitation events (Guilbert et al., 2015), and that this trend is predicted to continue into the near future. It has been suggested that the eastern United States will experience greater increases in precipitation compared to the west (Neumann et al., 2015). Research shows that flood events with an AEP of 1% are expected to occur more frequently in the northeast region of the United States (Douglas and Fairbank, 2011).

(a) Bridge collapse in Vermont from Tropical Storm Irene (Hewitt, 2016)

(b) *Bridge collapse in New Hampshire from Tropical Storm Irene (HEB Engineers, 2011)*

Figure 2.2 Regional examples of bridge damages from the 2011 Tropical Storm Irene

2.3 River Dynamics

Healthy rivers perform many essential ecological and social functions (Lewin and Ashworth, 2011). These functions include access to clean drinking water, contaminant removal, aiding plant and wildlife biodiversity, flood mitigation services and more (Lewin and Ashworth, 2011). A key factor to maintain a healthy river is to ensure connection to its floodplain. Floodplains can be described as low-lying lands capable of being inundated by lateral overflow from their associated river (Junk and Welcomme 1990). Vegetation in the floodplain can mitigate flood damage through reduction of stream power (dissipation of energy through friction) and bank stabilization (Ward et al., 2002; Noe and Hupp, 2009; Lewin and Ashworth, 2014), and therefore provides valuable ecosystem services (Watson et al., 2016). However, floodplains also tend to be highly developed and impacted. Europe and North America have lost over 90% of river floodplains (Harvey and Gooseff, 2015) through development, channelization and other alterations. Often berms or levees are constructed in the floodplain to protect nearby buildings or land uses (Kline and Cahoon, 2010). Presence of these raised features and road or rail berms along the channel can lead to artificial entrenchment of the channel (Kline and Cahoon, 2010).

Channel incision can also cause loss of connected floodplains. Incision is excessive erosion caused by flowing water that deepens the channel creating a vertical disconnect from the natural floodplain (Booth, 1990). Incision can occur naturally through river erosion, but can be exacerbated by anthropogenic changes such as intentional channelization or dredging in a misguided attempt at flood mitigation (Booth, 1990).

The loss of floodplain connection has resulted in destabilized river channels and increased infrastructure and property damage from flood events (Harvey and Gooseff, 2015). Increased channel entrenchment from incision or floodplain encroachments or both, has been known to cause hydraulic impacts such as increased velocities, specific stream power, and water surface elevations (Booth, 1990, Opperman et al., 2010, Beck et al., 2019). High values of stream power, velocity, and peak discharge have been linked to large sediment transport and bank erosion which can negatively impact bridges through scour and other impacts (Magilligan et al., 2003, Blanton et al., 2009).

Total stream power, **Ω**, is the rate of potential energy exerted against the bed and banks of the channel (Jain et al., 2008). It is a function of the specific weight of water, stream discharge and friction slope (most often estimated as the bed slope), where γ is specific weight of water, Q is discharge, and s is the channel slope. This is slightly different compared to the HEC-RAS calculation of stream power. HEC-RAS calculates stream power as a product of velocity and shear stress.

Equation 1.1 Total stream power equation

$$\boxed{\Omega = \gamma Q s}$$

This estimation is the driving determinants of sediment transport and geomorphic changes (Gartner et al., 2015). Specific stream power, ω, is total stream power per unit width, in this case bankfull width of the stream or river:

Equation 1.2 Specific stream power equation

$$\boxed{\omega = \frac{\Omega}{w}}$$

where **Ω** is total stream power, and w is the channel width (Gartner et al., 2015).

As a combination of discharge and slope, an increase to either one of these will increase the specific stream power, potentially increasing the risk of channel erosion. Two specific stream power thresholds have been proposed as indicators to identify the stability of channel reaches. Specific stream power exceeding 300 Watts per square meter (W/m^2) has a very high potential for channel-altering erosion (Magilligan, 1992). In an alluvial channel with non-cohesive boundaries, this threshold, known as the Magilligan threshold, defines a highly unstable channel and may be associated with the transport and deposition of coarse gain sizes, stripped floodplain surfaces, channel avulsions, and other impacts (Magilligan, 1992). However, if the channel is bounded by erosion-resistant bedrock boulders, values above this threshold will not be as susceptible to the previously mentioned associations.

The lower threshold of 35 W/m^2 under many circumstances defines a stable channel (Magilligan, 1992). Channels with specific stream power below the 35 W/m^2 threshold tend to be dominated by depositional processes and have a lower potential of large sediment transport, channel avulsions or other negative hydraulic impacts. Channels with specific stream power values that fall between 35 and 300 W/m^2 are categorized as critically unstable and erosion-dominated, but have a lower possibility of major channel disruption than values above the Magilligan, (1992) threshold.

However, these two thresholds do not necessarily identify stability or critical instability for every channel. Every type of sediment has a critical threshold, which is largely dependent on sediment size, that determines large sediment transport or bank erosion (Bull, 1979). For example, due the large grain size of bedrock it is more likely that the critical threshold for a bedrock stream will be well above the Magilligan's threshold previously described (Bull, 1979). Where other sediments such as alluvial sediment have much smaller grain size and are easily moved under lower values of specific stream power (Bull, 1979).

Due to the increased availability of detailed landscape imagery, and river channel measurements, studies are able to use hydraulic models to observe and calculate specific stream power (Bizzi and Lerner, 2015). The ability to relatively easily assess this metric has led to specific stream power becoming a more frequently used indicator and predictive measure of future channel degradation (Bizzi and Lerner, 2015). In combination with specific stream power, changes in channel reach slope are used to identify reach segments with high potential for sediment transport. Bizzi and Lerner (2015) use a combination of specific stream power and the slope difference between reach segments to identify river reaches that are either erosion-dominated or deposition-dominated. The study describes how large changes in slope between river reaches can be due to bedrock, pinch points or other geologic features (Bizzi and Lerner, 2015). As specific stream power has become a more widely employed tool for stream assessments; change in channel reach slope is also becoming a powerful indicator for potential channel disruption.

2.4 Flood Mitigation Strategies

A variety of remediation strategies have been studied and implemented to help improve transportation infrastructure durability and longevity. Strategies such as floodplain reconnection, lengthening bridges, raising bridge deck elevations, and culvert additions and modifications can be considered to reduce potential damage from floods.

Floodplain reconnection and its effects on rivers have been well studied and documented. Studies have shown that floodplain reconnection through excavation, berm removal and levee removal have reduced negative hydraulic impacts such as erosion, scour and increased water surface elevation (Bernhardt et al., 2007; Dierauer et al., 2012; Guida et al., 2015). These studies further document how floodplain reconnection can also be costly and not always applicable due to human encroachment on natural floodplains (Dierauer et al., 2012, Guida et al., 2015). However, when floodplain reconnection is modeled it is often one of the most impactful strategies, having the greatest reduction of negative impacts on surrounding infrastructure (Dierauer et al., 2012, Remo et al., 2012, Guida et al., 2015).

Current Vermont guidelines dictate that hydraulic crossings must have a minimum freeboard distance of 1 foot (30 cm) to the maximum water surface elevation (Vermont Agency of Transportation, 2015). It has been stated previously that many historic bridges were likely constructed without this design consideration. Negative hydraulic impacts such as overtopping and damage from debris can be avoided by elevating bridge decks (Vermont Agency of Transportation, 2015). Programs have been developed to preserve historic bridges and often use bridge deck elevation as a preservation strategy (USDOT, 2017). However, this can be a difficult and costly modification. If floodplain reconnection at a nearby location can decrease peak flood elevations at structures, these mitigation techniques also come with additional ecological and water quality benefits, that may result in a high benefit-cost ratio for a reconnection project.

The addition of culverts has also been implemented at project locations to reduce negative flood impacts in the surrounding area. These culverts are installed under or through road or rail embankments that may encroach in the floodplain to provide a measure of floodplain reconnection. As humans continue to encroach on natural floodplains, property damage is to be expected during flood events. Culverts are often used in urban design to divert flow and reduce damages (Vermont Agency of Transportation, 2015). When culverts are redesigned to mitigate negative hydraulic impacts, additional negative effects can be reduced to nearby bridges (Douglas et al., 2017).

2.5 Hydraulic Modeling

The United States Army Corps of Engineers released a 2D modeling option in the Hydraulic Engineers Center's River Analysis System (HEC-RAS) software in 2016. The 1D model is primarily used to simulate flow when river flow is restricted between the channel banks (USACE HEC, 2016 a,b,c). A 2D model is better able to estimate flow when it expands onto topographically complex floodplains (USACE HEC, 2016c). If a 1D model was used for these complex flows it would fail to capture floodplain dynamics and would underestimate flood attributes such as frictional losses and inundation extents (USACE HEC, 2016c).

Steady state analyses using HEC-RAS modeling are currently more common due to faster computational times of 1D modeling (USACE HEC, 2016c). Given the computational demands of 2D models and additional data collection requirements (e.g., bathymetry), many studies are limited to 1D models (USACE HEC, 2016c). However, as bathymetric data and geospatial data become more widely available, and powerful computers are more accessible, 2D HEC-RAS studies are becoming more widely used (Trueheart, 2019; Gourevitch et al., 2020; Guida et al., 2016). Two-dimensional HEC-RAS models are preferred in many studies because of their powerful visualization features and ability to observe transient conditions at moments in time within the study domain (USACE HEC, 2016c). The discharge in 2D models is not constant along the entire study area due to the attenuation of the flood wave, and values of discharge and other statistics such as specific stream power, velocity, and water surface elevation are able to be observed at specific points or moments in time, unlike the 1D modeling. Two-dimensional models are also preferred during extreme flood events when flow is to be modeled outside of the main channel for greater accuracy and resolution, along with easily available and informative graphics (Wu, 2008).

2.6 Analysis of Bridge-River Networks

Multiple studies document localized flood impacts to bridges and infrastructure along a river (e.g., Johnson et al., 2002; Lagasse et al. 2009, 2012; Anderson et al., 2017a, 2017b). Natural processes such as channel widening, lateral migration, and bed degradation that occur over time can cause infrastructure destabilization (Guida et al., 2015). These processes can also be anthropogenic and can exacerbate destabilization in much shorter time periods (Guida et al., 2015). Inadequately sized channel crossings (e.g. historic bridges) are at an even higher risk for other hazards such as scour, which can quickly result in structural failure during storm or flood events (Lagasse et al., 2009, 2012). Increased flood inundation from localized backwater can lead to increased shear stress and specific stream power due to deeper flows and channel incision (Johnson, 2002; Johnson et al., 2002, 2006; McEnroe, 2006). These bridges are often replaced by newer designs that improve channel connectivity and ultimately channel stability.

To avoid costly repairs or replacement of these structures, various strategies and interventions are often employed to mitigate the previously mentioned detrimental flow effects. Examples of interventions and strategies include bank armoring, culvert addition, floodplain reconnection, cross-vanes, and other techniques (Gumiero et al., 2013; Consoer and Milman, 2018; Van Appledorn et al., 2019). Bank armoring can be effective to maintain channel stabilization at the installation site, but excess energy can be redistributed up- and downstream leading to unforeseen negative effects such as bank undercutting and failure, and increased hazard of flanking flow. Culvert addition to redirect flow into low-lying areas can also mitigate flooding (Kosicki, 2001). However, obtaining permits and landowner permission can be difficult, and flood mitigation can be limited to specific design storms and the localized area. Ideally, floodplain reconnection is implemented to establish stable conditions in a natural river setting, but can be extremely costly due to excavation expenses and land acquisitions (Magilligan et al., 2015).

A river channel can be dynamic, and geomorphological processes are continuously altering flow dynamics throughout the river network. As our knowledge on the value of natural flow regimes in rivers expands, design guidance has slowly evolved for helping to minimize alterations to the natural flow of rivers. Due to human expansion into natural river floodplains and the encroachment of bridge abutments on flow, many rivers are no longer in a natural state (Tockner et al., 2002). These human impacts can result in increased scour and inundation. These adverse flood impacts can be evaluated using physics-based computational models.

The localized impacts of bridges and infrastructure on river networks have been well documented and studied. For example, Blanton (2009) advocated for studying the impacts to bridges on a river-reach scale. The few studies that have investigated these interactions focus on a single river, or only one intervention (Guida et al., 2016, Trueheart, 2019, Van Appledorn et al., 2019, Gourevitch et al., 2020). Without studying multiple locations or interventions it is difficult to determine how meaningful changes or impacts can alter bridge-stream relationships along the entire river section of interest.

The few studies that investigated river-scale impacts show that changes to infrastructure can impact the entire river. A study of the bridge-river network on the Otter Creek in Vermont shows how the simulated removal of road and rail bridges can affect hydraulic variables such as velocity and water surface elevation at bridge locations up and downstream (Trueheart, 2020). Often the removal of road bridges is not a practical option. However, this modeling approach shows the importance of assessing hydraulic changes at bridges to understand the cascading up and downstream effects. Changes in velocity at bridge locations along a river can indicate potential changes in stream power, which could increase the potential of scour and erosion at these locations (Arneson et al., 2012).

Trueheart et al., (2019) modeled the impacts of bridge removal at the river scale using 2D HEC-RAS. Bridge removal showed changes in water surface elevation at hydraulic crossings up and downstream the low gradient river that were dependent on the specific bridge removed (Trueheart et al., 2019). The buildup of water behind hydraulic structures, also known as backwater, is commonly seen at dams, and may also occur at bridges when abutments narrow the channel flow restricting the water flow just upstream of the bridge (Gartner et al., 2015). Backwater effects can be seen throughout the entire river study section, and bridge removal can change the downstream flow profiles which can lead to increased water surface elevation at other hydraulic crossings (Trueheart et al., 2019).

Positive impacts can also be seen on a river following alterations, such as reduction of stream power at a critical location. In some cases, the removal of a bridge or similar alteration can reduce specific stream power in the river (Trueheart, 2019). When these structures are removed, the bottleneck effect that can increase specific stream power is also removed. In addition, removing these structures may increase natural water storage, slowing down velocity and lowering specific stream power along the river channel. Model scenarios also show water surface elevation and peak discharge reduction (Trueheart, 2019). It is often difficult to identify which structures will have a large river- network-scale impact and whether this impact will be positive or negative (Trueheart, 2019).

The potential cascading up- and downstream impacts from perturbations made in the river or at other structures must be considered. Beck et al. (2019) studied the Walnut Creek, located in Iowa, using a 2D HEC-RAS model to understand the relationship between connectivity and multiple hydraulic characteristics. Blanton et al. (2009) recorded the disconnection of rivers from their floodplains due to roads, railways, and hydraulic crossing, and found an increase in river incision in reaches around these structures. However, additional studies are needed to better understand the consequences of bridge-stream interactions on a river network scale, in order to design more effective interventions for mitigating flood damage and preserving structure longevity.

Hermoso et al. (2015) and Van Appledorn et al. (2019) show some of the positive effects of river restoration projects throughout a river network. These studies model how reconnection to floodplains and revegetation projects can lower specific stream power, increase flora and fauna, and reduce negative flood effects.

Studies have shown how specific stream power and change in river slope can be effective tools for stream assessments, to identify channel stability and health (e.g. Bizzi and Lerner, 2015; Parker et al., 2019). It is reasonable to assume that if a channel is unstable and has high specific stream power, nearby infrastructure will be at increased risk of scour, potential failure, and other damages (Lagasse 2009, 2012; Magilligan, 2015). In order to use these tools efficiently, computational models can be used to identify structures at higher risk of negative flow effects. Additional screening frameworks have been developed to identify unstable channels (Buraas et al., 2014; Bizzi and Lerner, 2015); however, these frameworks do not consider transportation infrastructure. Other frameworks that focus on infrastructure use more complex numerical models that are not easily applied to multiple river networks (Deng and Cai, 2009; Koçyiğit et al., 2016).

Current state regulations and reports help regulate projects that cross river channels, and provide guidance on how to adjust structural design to mitigate negative flood effects (Vermont Agency of Transportation, 2015). However, these regulations focus largely on localized effects and generally do not consider up- or downstream impacts in the river network (Vermont Agency of Transportation, 2015).

2.7 Summary and Gaps in the State-of-the-Art

The above literature review indicates that:

1) Transportation infrastructure is vulnerable to floods worldwide including the United States and the northeast region of the United States. Hundreds of bridges have been damaged or failed during previous storm and flood events throughout the world.
2) Climate change is expected to increase the magnitude, duration and frequency of extreme flood events in many parts of the world and particularly in the northeast region of United States.
3) Stakeholder concerns regarding the impacts of bridge damage or failure, or planned retrofits on properties, infrastructure and overall river are difficult to address because of the limited number of tools available to quantify the impacts that occur up- and downstream of these structures.
4) Specific stream power in combination with channel slope have been used as metrics to identify channel stability. Because increases in stream power can lead to significant erosion and sediment transport which may result in bridge scour, these same metrics may be useful for assessing bridge-stream interactions.
5) It is well known that floodplain reconnection and culvert additions have potential for mitigating flood impacts on a river. However, only a few studies have assessed how these interventions impact infrastructure.
6) 2D HEC-RAS modeling is a powerful tool for studying and visualizing the impacts of flood events on bridges across a river. Unlike the 1D HEC-RAS model, the transient 2D version allows users to retrieve values of location-specific metrics that occur at user-defined instances within the study time period.

This research attempts to address the following gaps in the state-of-the-art:

1) Bridge rehabilitation and new bridge designs are often done in isolation with little to no consideration for the up- or downstream impacts to bridges or nearby property.
2) Only a few studies have attempted to quantify or observe bridge-stream interactions at the river scale. As far as the authors are aware, no studies exist on how these interactions differ among rivers with a range of gradients.
3) While the impacts of flood mitigation interventions at the river scale have been well studied, there is limited knowledge as to how these interventions impact bridges up- and downstream of a given project location.
4) It is not cost effective or practical to reassess and/or modify every bridge to better withstand extreme flood events. As a result, a river scale screening tool for identifying bridge conditions and locations that are most vulnerable, as well as the most effective locations for interventions would be useful. Currently, no such screening tool is available.

Chapter 3: River Study Sections and Setting

Three Vermont rivers were selected for this study: Otter Creek, Black Creek and the Mad River (Figure 3.1), to represent low, moderate and high river gradients, respectively. Channel gradient classification is defined by the system used in the National Hydrography Dataset (NHD), which are then organized and grouped by the National Aquatic Habitat System developed by the United States Environmental Protection Agency (USEPA, 2017), and the United States Geological Survey (USGS) (Table 3.1) (USEPA, 2017). Figure 3.2 shows classification of each of the three river study sections from upstream to downstream.

All three river study sections have nearby USGS (U.S. Geological Survey) gauges and a number of bridges (3 to 16), and therefore make suitable study sites. The accessibility of USGS stream gauges vary with each river study section. The Otter Creek study section has two active stream gauges that captured the 2011 Tropical Storm Irene (USGS, 2018a, 2018b). The Mad River study section has one active gauge downstream that also captured the 2011 Tropical Storm Irene (USGS, 2021). The Black Creek study section has a USGS stream gauge found downstream of the study area that is no longer active and captured the 2011 Tropical Storm Irene as an annual exceedance probability of 50% (USGS, 2020). Since the Black Creek stream gauge is outside of the study section, a regression relationship was developed between an active, nearby gauge at the Missisquoi River in East Berkshire and the Black Creek Sheldon Gauge (Underwood et al., 2020). Table 3.2 summarizes gauge availability, reach length, gradient and number of bridges for each of the three river study sections.

Vermont experienced multiple glaciated periods with the last of the ice receding around 14,000 years ago (Stewart and MacClintock, 1969). Glaciers left behind glacial till and glaciofluvial and glaciolacustrine sediments which Vermont's rivers now flow through and rework (Barg and Blazewicz, 2003; Field Geology Services, 2007; Addison County RPC, 2006). Bedrock outcrops are commonly found in Vermont and channel-spanning sections are found in multiple rivers including the Mad River, Black Creek and Otter Creek (Barg and Blazewicz, 2003; Field Geology Services , 2007; Trueheart et al., 2020; Underwood et al., 2020). Deforestation in the headwaters during the 1800s led to accelerated accumulation of sediment in downstream valleys (McGrory-Klyza and Trombulak, 1999). These historical impacts have shaped Vermont's rivers today.

New England's changing climate is expected to impact Vermont and some impacts have already been seen (Marshall and Randhir, 2008; Betts, 2017). Precipitation is expected to increase throughout the New England area, but with a reduction of snowfall (Guilbert et al., 2015). Studies expect more rain during winter months and annual exceedance probabilities of 0.1% to increase in frequency (Douglas and Fairbank, 2011). These increased precipitation events have the potential to result in high flows and increased flood frequency for rivers in the New England area (Collins, 2009).

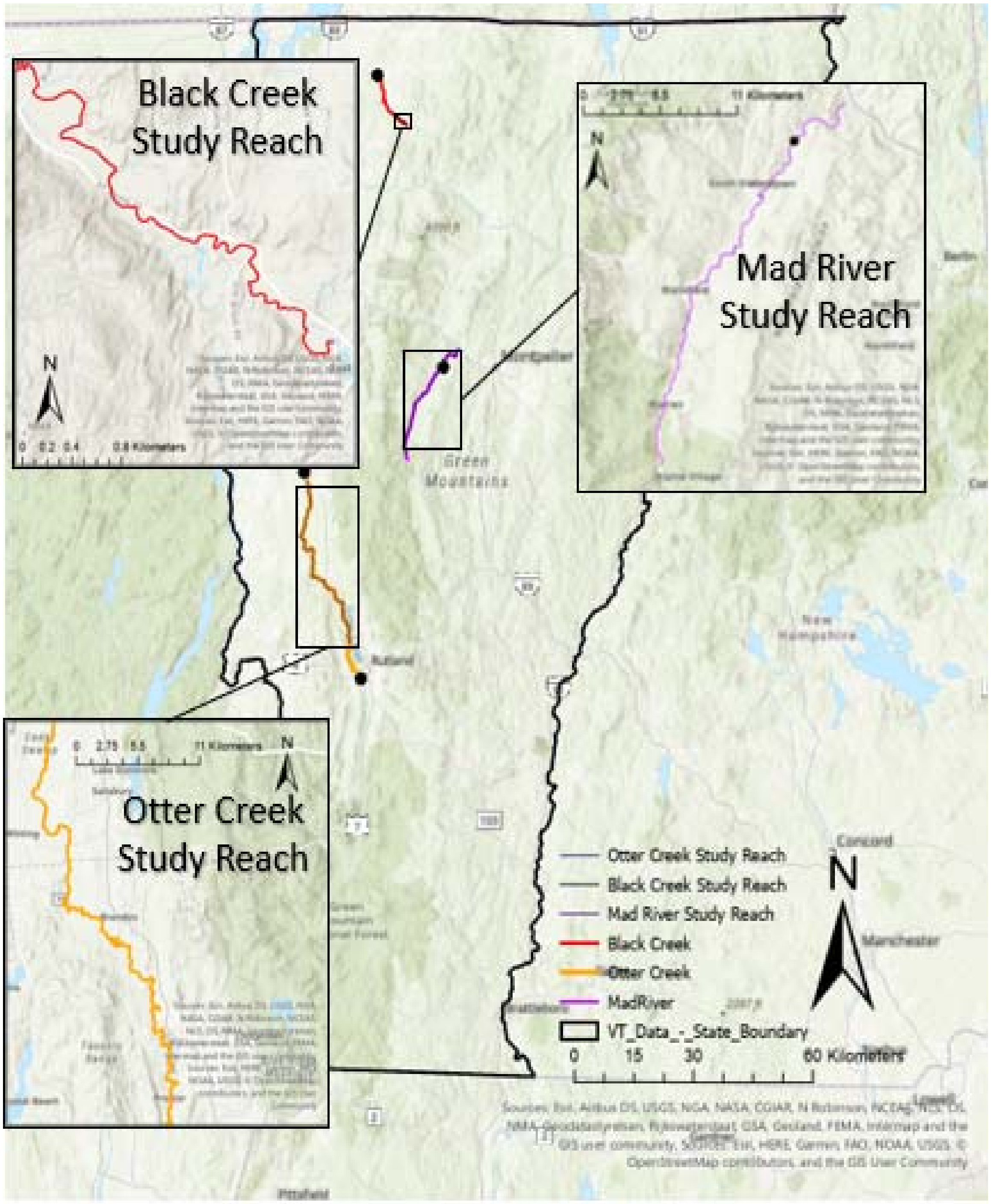


Figure 3.3 Map of Vermont showing all three river study sections with corresponding USGS stream gauges (black dot)

Table 0.1 National Aquatic Habitat (NAH) stream gradient classification developed by the U.S. Environmental Protection Agency (USEPA) and the U.S. Geological Survey (USGS) (USEPA et al., 2017)

Channel Gradient Classification	Channel Gradient Range
Very Low	< 0.02%
Low	≥ 0.02% – 0.1%
Low – Moderate	≥ 0.1% – 0.5%
Moderate – High	≥ 0.5% – 2%
High	≥ 2% – 5%
Very High	≥ 5%

Table 0.2 Overall statistics for the selected river study sections

River	Number of Available Gauges	Study Section Length (km)	Gradient	Road Bridges	Rail Bridges
Otter Creek	2 Active	74.0	< 0.02% - 0.1%	9	5
Black Creek	1 Inactive	4.8	0.1% - 0.5%	3	0
Mad River	1 Active	41.8	0.1% - 5%	16	0

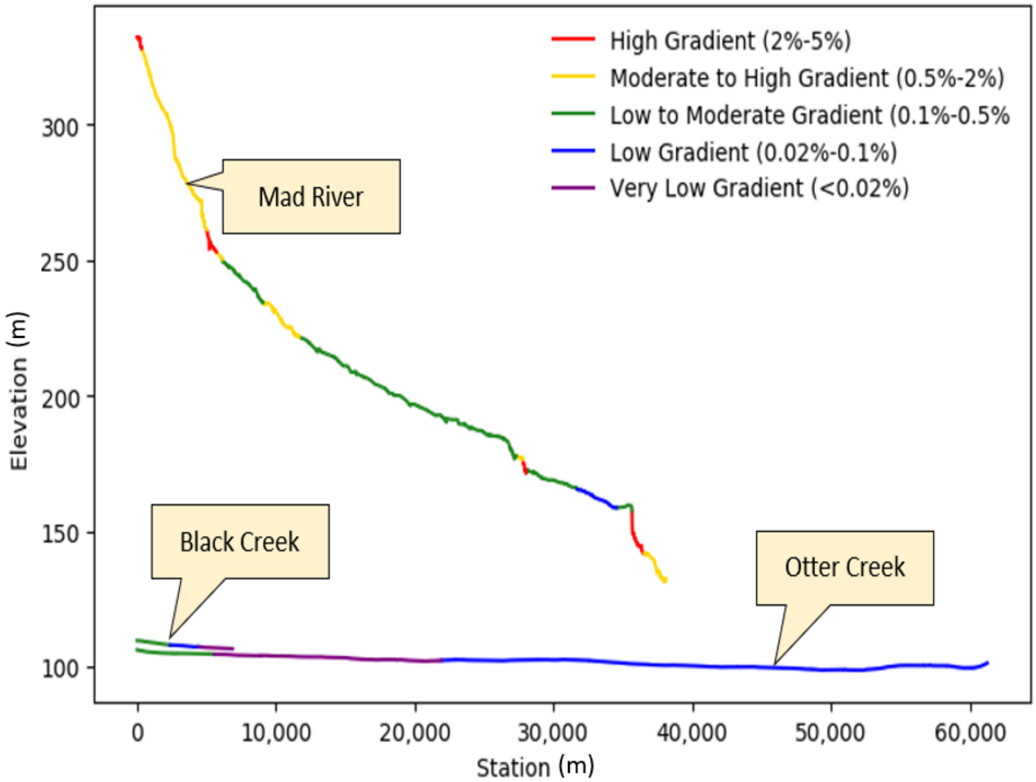


Figure 3.4 River study section elevation and channel gradient classification from upstream to downstream

3.1 Mad River Study Section

The Mad River is roughly 58 km (36 miles) long, and the study section, depicted in Figure 3.3, is approximately 41.8 km (26 miles) starting in Warren flowing northward to Moretown near the confluence with the Winooski River. This river has one active USGS stream gauge in Moretown, and is used as the downstream boundary condition for this study. The study reach includes 16 road bridges, two of which are active historic covered bridges. The B2 bridge has reported damage from the flood that resulted from the 2011 Tropical Storm Irene and has since been replaced; but this study uses the original bridge configuration for modeling purposes. There are no railways in the Mad River study area, so the research focuses on the road bridges that span the river corridor. The majority of these structures are in good or satisfactory condition with only a few categorized as fair with suggested repairs per the recommendation of bridge inspections done in 2020 and 2021 by the Vermont Agency of Transportation as summarized in Table 3.3 (Vermont Agency of Transportation, 2021). Most of the bridges with suggested repairs are town-owned, while the bridges in good condition are state-owned.

The Mad River has an average gradient of moderate to high with about 0.3% gradient in most sections, but some small sections have gradients above 2% as seen in Figure 3.4 (USEPA et al., 2017). The upstream corridor of the Mad River has limited floodplain extent due to confinement from valley walls. The mid and lower portion of the river have established floodplain, with some channel encroachment from anthropogenic impact. Common sections of bedrock develop high velocity flows creating entrenchment. Following previous flood events, berms have been placed along sections of the river to reduce potential flooding in recreation, agricultural and developed areas (Field Geology Services, 2007; Fitzgerald Environmental Associates, 2008). The Mad River is the primary study location for this research. A large portion of this research is dedicated to developing and calibrating a two-dimensional hydraulic model of the Mad River study section. The calibrated model is then used to examine a variety of flood mitigation interventions.

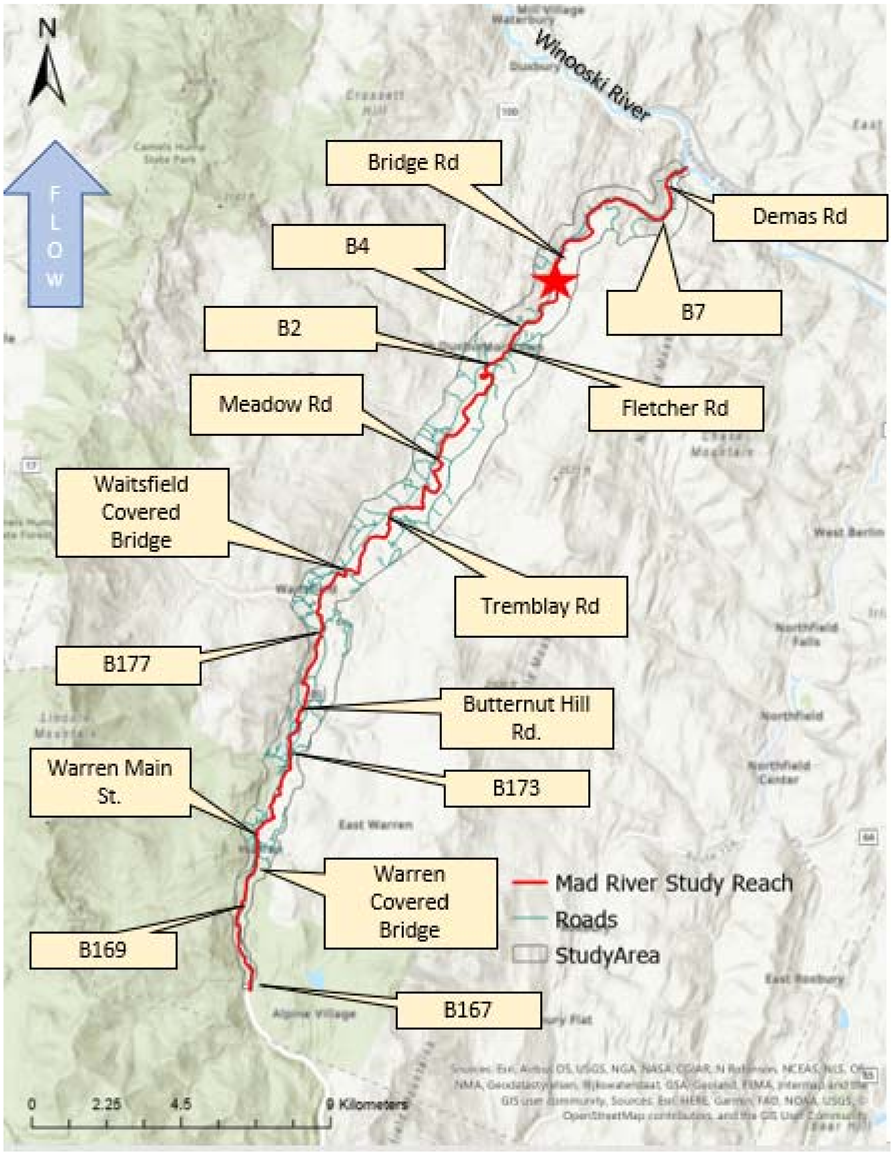


Figure 3.5 Locations of 16 bridges in the Mad River study area showing the Moretown USGS gauge (red star) and the Winooski River.\

Table 0.3 Bridge summary statistics in the Mad River study section

Road/Bridge	Year Built	Owner	Overall Condition	Total Span (m)	Design	Material	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Bridge 167	1957	State	Satisfactory	25.3	Rolled Beam	Steel	44.0806	-72.858906
Bridge 169	1954	State	Satisfactory	24.7	Rolled Beam	Steel	44.106285	-72.859817
Warren Covered Bridge⁺	1879	Town	Fair	14.3	Queen Post Covered Bridge	Timber	44.111110	-72.856996
Warren Main St. Bridge	1929	Town	Satisfactory	15.8	Concrete T-Bream	Concrete	44.116958	-72.857114
Bridge 173	2013	State	Good	42.4	Galv. Pony Truss	Steel	44.141180	-72.844695
Butternut Hill Rd	1999	Town	Good	17.4	Welded Pony Truss	Steel	44.151391	-72.839867
Bridge 177	2016	State	Good	52.4	Welded Plate Girder	Steel	44.173077	-72.832726
Waitsfield Covered Bridge⁺	1833	Town	Satisfactory	30.2	Multi KG PST/Arch Covered Bridge	Timber	44.189397	-72.823487
Tremblay Rd	1983	Town	Fair	27.4	Cont. Steel Beam	Steel Continuous	44.204223	-72.807088
Meadow Rd	1955	Town	Fair	23.8	Rolled Through Beam	Steel	44.220234	-72.789091
B2	2020	State	Very Good	28	Welded Plate Girder	Steel	44.245435	-72.769547
Fletcher Rd	1920	Town	Fair	29.9	Steel Pony Truss	Steel	44.250776	-72.762139
B4	1994	State	Good	29	Con WLD PLT GIR	Steel	44.256223	-72.757125
Bridge Rd	2013	Town	Good	40.2	Glav Pony Truss	Steel	44.276733	-72.742403
B7	1967	State	Satisfactory	45.7	Welded Girder	Steel	44.286243	-72.703588
Demas Rd*	1928	Town	Poor	22.6	Parker Pony Truss	Steel	44.29667	-72.70167

⁺Historic bridge (Vermont Agency of Commerce and Community Development, 2021)
*Pedestrian only

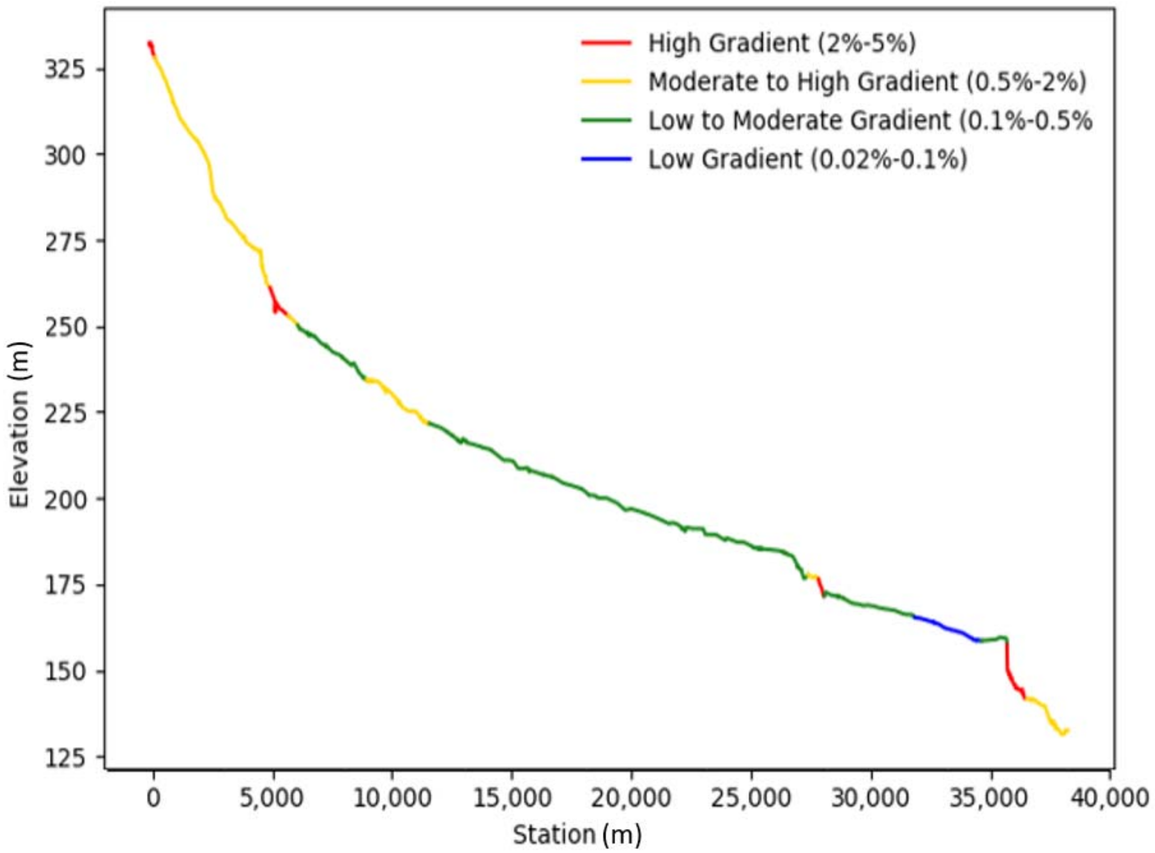


Figure 3.6 Mad River study section elevations and gradients starting upstream in Warren toward downstream to the Winooski River

3.2 Otter Creek Study Section

The Otter Creek is about 186.7 km (116 miles) long in west-central Vermont discharging into Lake Champlain. This study focusses on the 74 km (46 miles) long section of the Otter Creek between the Middlebury and Rutland USGS stream gauges, which contains 14 river crossings (Figure 3.5). These crossings include railway and roadway bridges, three of which are active historic covered bridges (Table 3.4) (Vermont Agency of Transportation, 2021). The majority of the road bridges are town-owned and in good condition. Due to a precipitation event in 2020 that prevented bridge inspections in some locations, the Leicester-Whiting Bridge has no available data for its current condition.

The average gradient for this river reach ranges from very low to low (0.02% to 0.1%). The Otter Creek is also very well connected to its floodplain, providing considerable flood relief to the downstream area (Watson et al., 2015). Due to low valley gradients and the unconfined setting, flow velocity is much slower compared to the Mad River (Addison County RPC, 2006). Trueheart et al. (2020) developed and calibrated a 2D HEC-RAS model for the Otter Creek study section. Their study included AEP's of 4%, 2%, 1% and the 2011 Tropical Storm Irene simulations. Here, an additional storm event is modeled for an AEP of 50%. The model is then re-run and used to compare and contrast against the other two study locations.

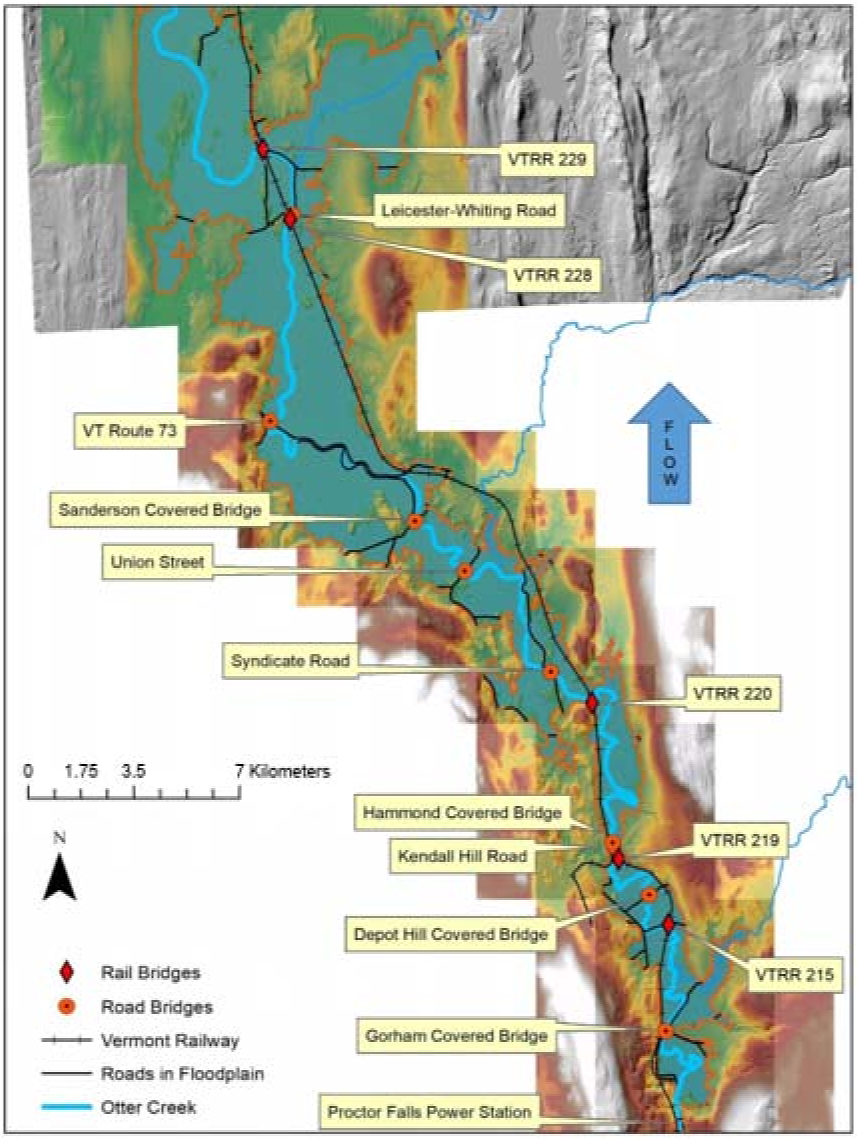


Figure 3.7 Locations of 14 bridges selected for analysis in the Otter Creek study area (Trueheart et al., 2020)

Table 0.4 Bridge summary statistics in the Otter Creek study area

Road/Bridge	Year Built	Owner	Overall Condition	Total Span (m)	Design	Material	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Gorham Bridge[+]	1841	Town	Good	33.2	Town Lattice Covered Bridge	Timber	43.680031	-73.037533
Vermont Railway 215	1899	State	Satisfactory	46.8	Lattice Through Truss	Steel	43.64246	-73.03634
Depot Hill Rd	1840	Town	Satisfactory	32.9	Rolled BM/LAT Covered Bridge	Steel	43.709471	-73.042722
Vermont Railway 219	1900	State	Satisfactory	40.6	Triple-Intersection Lattice Through Truss	Steel	43.71715	-73.05157
Kendall Hill Rd	1960	Town	Satisfactory	21.9	Rolled Beam	Steel	43.720041	-73.053131
Hammond Bridge[+]	1842	Town	Satisfactory	42.0	Town Lattice Trust	Timber	43.72062	-73.05349
Vermont Railway 220	1899	State	Satisfactory	31.3	Pony/ Through Plate Girder	Steel	43.75079	-73.05970
Syndicate Rd/Carver St	1851	Town	Satisfactory	33.2	Steel Pony truss	Steel	43.757323	-73.071714
Union St	1992	Town	Very Good	39.6	Welded Girder	Steel	43.778901	-73.097155
Sanderson Bridge[+]	1838	Town	Good	34.0	Town Lattice Covered Bridge	Timber	43.789575	-73.111662
Vermont Route 73	1952	State	Fair	23.5	Rolled Beam	Steel	43.810868	-73.154053
Vermont Railway 228	1929	State	Satisfactory	47.5	Warren through truss	Steel	43.85455	-73.14899
Leicester-Whiting Rd	1972	Town	NA	7.6	CMPPA/ Buried RC Slab	Steel	43.866114	-73.147847
Vermont Railway 229	1896	State	Satisfactory	47.2	Lattice Through Truss	Steel	43.86956	-73.15693

[+] Historic bridge (Vermont Agency of Commerce and Community Development, 2021)

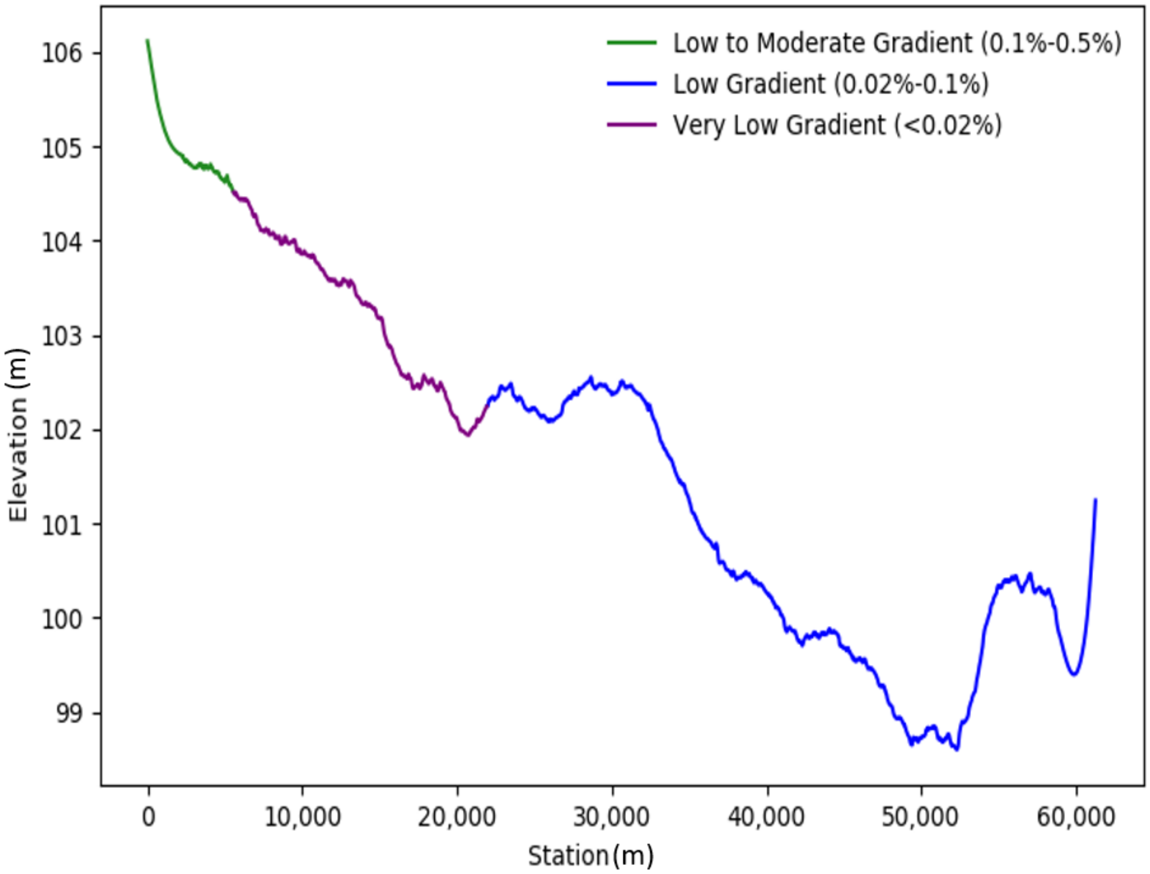
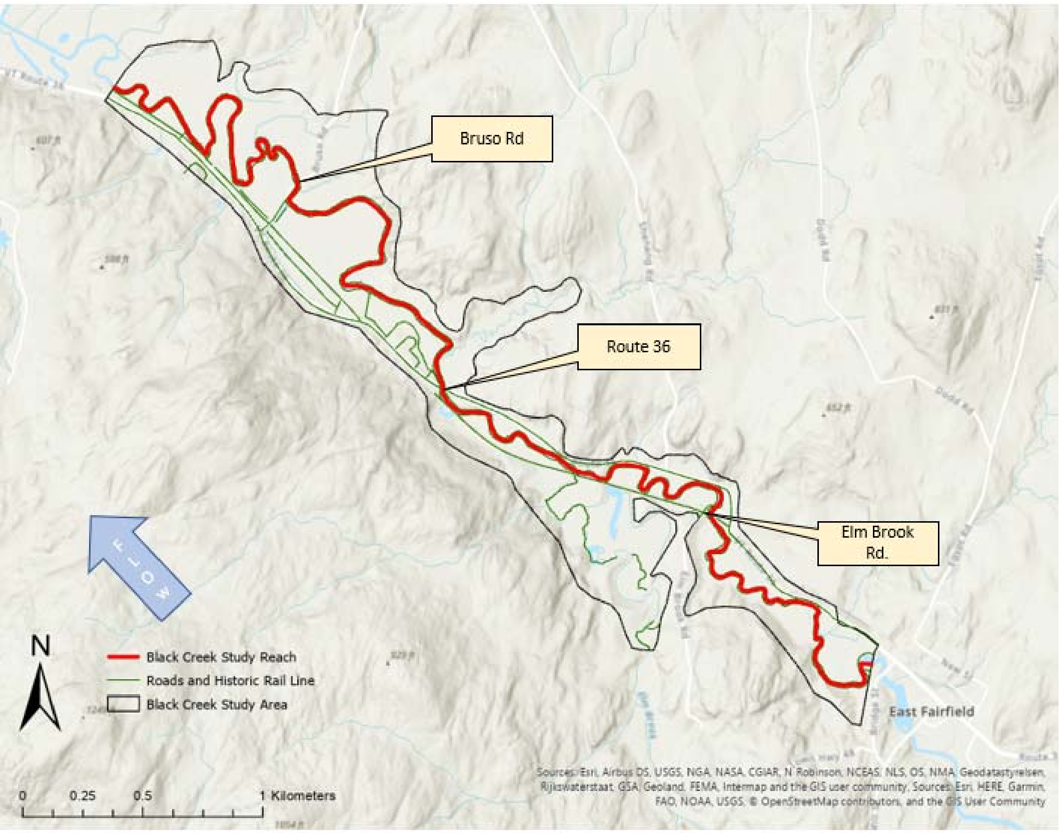


Figure 3.8 Otter Creek study section elevations and gradients starting upstream in Proctor Falls moving downstream into Middlebury

3.3 Black Creek Study Section

The Black Creek study section is west of the center of East Fairfield, Vermont and is the smallest study reach of 4.8 km (3 miles), with three modeled bridges in the study reach (Figure 3.7). A pedestrian and rail bridge just down and upstream of Elm Brook Rd, were not included due to very high clearance of the river. Out of the three modeled bridges two are town-owned and the third bridge is state-owned; all three are in good condition (Table 3.5) (Vermont Agency of Transportation, 2021). This location was selected to simulate additional moderate and very low slopes, similar to the Otter Creek (Figure 3.8). This river reach has similar floodplain accessibility as the Otter Creek. However, the presence of a formerly-active railway (now a recreational trail) is blocking floodplain access. These characteristics make the Black Creek site representative of low- to medium-gradient rivers that may benefit from floodplain reconnection projects.

The Black Creek study section 2D HEC-RAS model simulates annual exceedance probabilities of 50%, 20% and 4%. To compare hydraulic structures at similar storm events across all three river study sections additional hydrographs are constructed for the Black Creek for AEP's of 2%, 1% and 0.2%. Due to only one inactive historical gauge in the study area that did not capture an extreme event, the hydrographs are modified to represent an extreme flow of 0.2% (Q500). This flow is similar to the 2011 Tropical Storm Irene in the Otter Creek, which had areas that experienced flows equivalent to an event with an AEP of 0.2% (Trueheart, 2020). This flow is also only slightly greater than what the Mad River experienced during the 2011 Tropical Storm Irene which is equivalent to an event with an AEP of 0.8%. This allows the Black Creek model observations to be comparable to the Otter Creek and Mad River study section models. This 2D HEC-RAS model was developed and calibrated by Lindsay Worley (Underwood et al., 2020). The model was originally developed for flood events ranging from AEPs of 50% to 4%, and calibrated to a storm of AEP 20%. The AEP 0.2% flood event was additionally developed for this study. The methods used to construct the synthetic hydrographs are further explained in Chapter 4.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 3.9 Location of 3 bridges in the Black Creek study section

Table 0.5 Summary statistics of bridges in the Black Creek study section

Road/Bridge	Year Built	Owner	Overall Condition	Total Span (m)	Design	Material	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
Elm Brook Rd	2015	Town	Very Good	15.5	Prestressed Concrete Slab	Prestressed Concrete	44.792311	-72.871171
Vermont Route 36	1983	State	Good	33.5	Prestress Conc C-BM	Prestressed Concrete	44.804422	-72.893245
Bruso Rd	1978	Town	Very Good	11.3	Prestressed Concrete Slab	Prestressed Concrete	44.804422	-72.893245

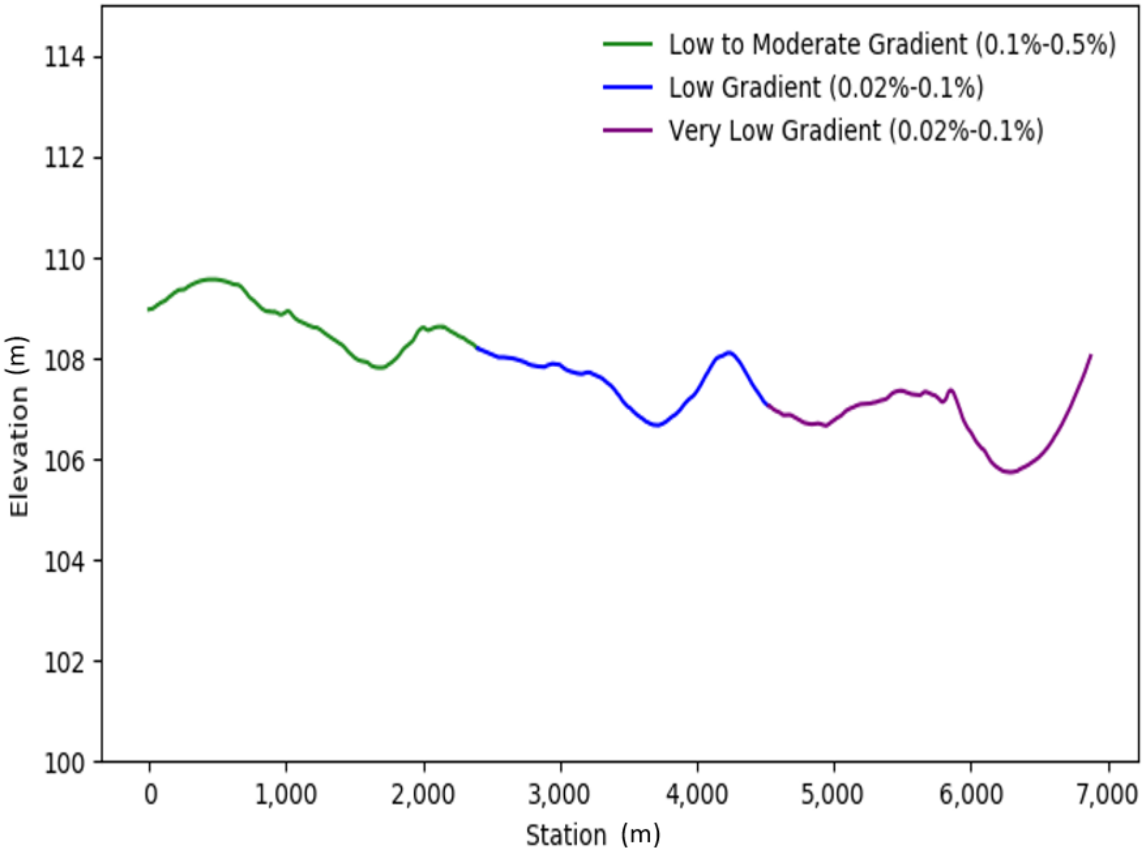


Figure 3.10 Black Creek study section elevations and gradients starting upstream in East Fairfield going downstream

The Black Creek, Otter Creek and Mad River study sections capture river gradients ranging from less than 0.02% to over 2% covering very low and high slopes. Each study section has multiple bridges, and the Otter Creek study section has combinations of road and rail bridges. These reaches have similar attributes not only to rivers found throughout Vermont, but also throughout the Northeast region.

Chapter 4: Two-Dimensional HEC-RAS Model Development for the Mad River Study Section

The development and calibration of the Mad River 2D HEC-RAS model constitutes a major part of this work, which is described in this chapter. The chapter also describes the employed terrain modification process for the proposed flood mitigation interventions at specific bridge locations. The Otter Creek and Black Creek two dimensional HEC-RAS models were constructed and calibrated by Matthew Trueheart and Lindsay Worley, respectively.

4.1 Data and Software

This study uses the Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 5.0.7 to develop a two-dimensional (2D) hydraulic model of the Mad River study reach. Topography and bathymetry data are needed as model inputs. For this study Topography data obtained from the Vermont Center for Geographical Information's hydrologically corrected digital elevation models (2016, 0.7 m post-spacing), Waitsfield (2016, 0.7 m post-spacing), and Warren (2016, 0.7 m post-spacing) were used. Dubois & King, Inc. provided the Mad River bathymetry data collected for a previous 1D HEC-RAS model (Dubois & King Inc., 2017). An additional Vermont georeferenced state boundary file is also incorporated from the Vermont Center for Geographical Information.

Hydrograph data are also required to construct a reliable 2D HEC-RAS model. These data are measured by the USGS stream gauge in Moretown, Vermont, located 7.0 km upstream from the confluence with the Winooski River (Figure 4.1) (U.S. Geological Survey, 2021). The Moretown Mad River USGS gauge has been in operation for over 92 years and is the only gauge within the Mad River study area. The stream gauge recorded major flood events including Tropical Storm Irene in 2011 as well as major flood events in 1998, 1938 and 1927.

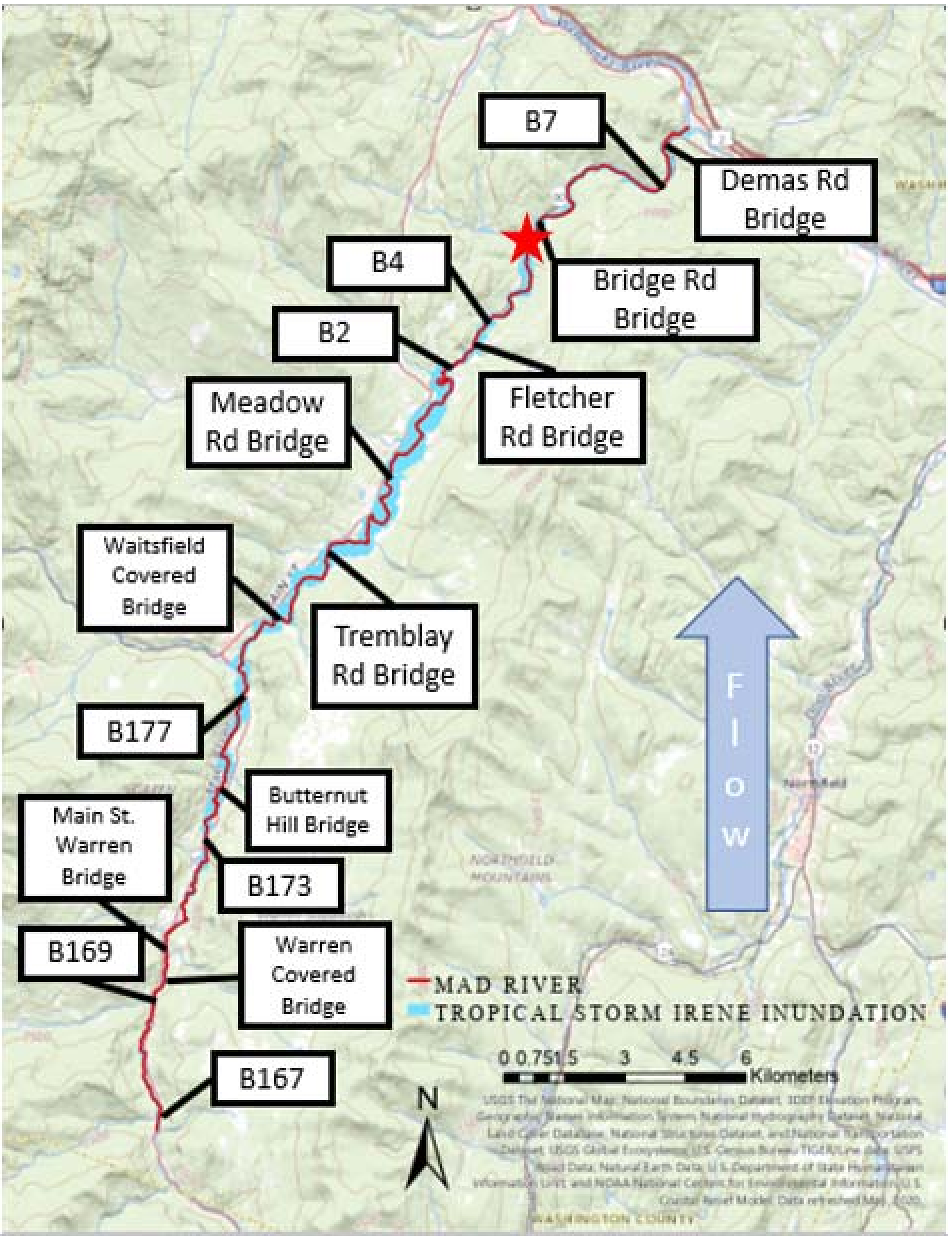


Figure 4.1 Mad River study section showing modeled bridges and the USGS stream gauge in Moretown, VT (red star)

4.2 Terrain Model

In order to build a terrain model for the Mad River study area, the Vermont state boundary is first incorporated into the HEC-RAS model to define the correct projection. Relevant topography tiles are then combined into a digital elevation model (DEM) of the Mad River study area. The DEM defines the high-resolution terrain for the model. Cross section data provided by Dubois & King, Inc. (2017) from the previously mentioned 1D HEC-HAS study are then merged with the created DEM to develop a new terrain. This process interpolates between two consecutive cross sections to determine channel bathymetry (Figure 4.2), and is necessary to develop a 2D model.

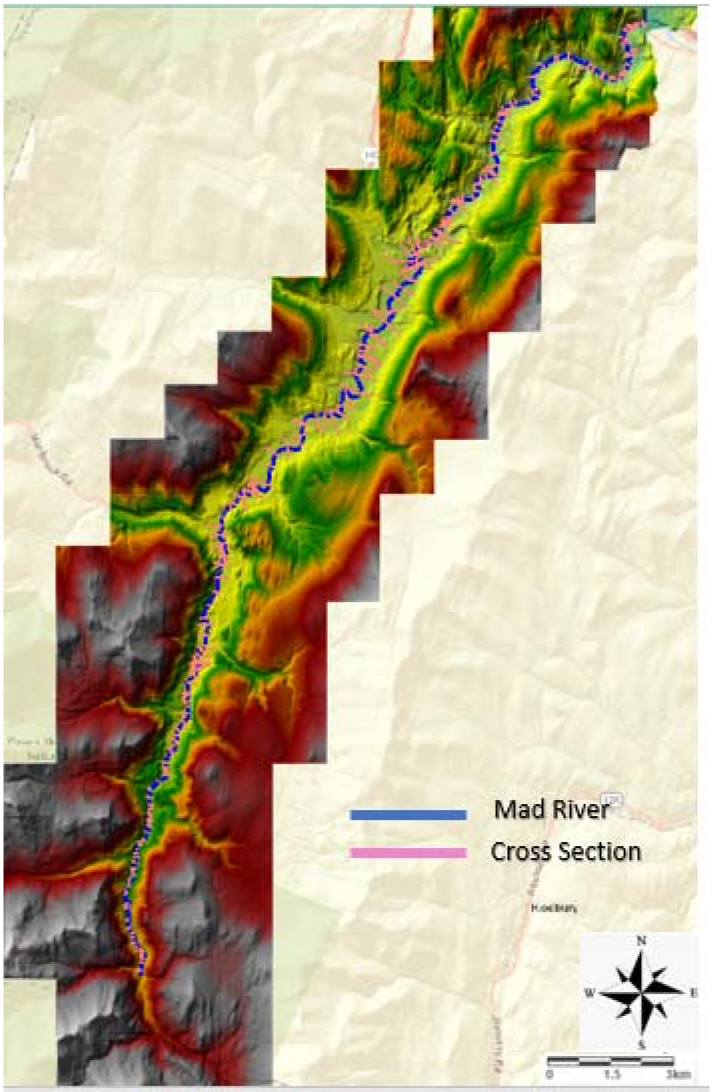


Figure 4.2 DEM and model cross-sections of the Mad River Study section

4.3 Geometry and Computational Domain

Geometry features such as breaklines, banklines, and culverts are added to the terrain to develop a model that resembles real world conditions (Figure 4.3). Breaklines in the model simulate roads and railways. In this version of HEC-RAS bridges cannot be modeled directly. To work around this, the cross sections just up and downstream of each bridge are adjusted to reflect bridge abutments. This simulates channel constriction caused by these structures without modeling a physical bridge.

A 2D mesh is drawn around the Mad River expected flow area, and the upstream and downstream boundaries are defined. The upstream boundary is located in Warren, 42.2 km south of the Winooski River. The downstream boundary is located at the USGS stream gauge in Moretown. The computational boundaries extend past the downstream boundary; however, the 2D model is calibrated to the USGS Moretown gauge.

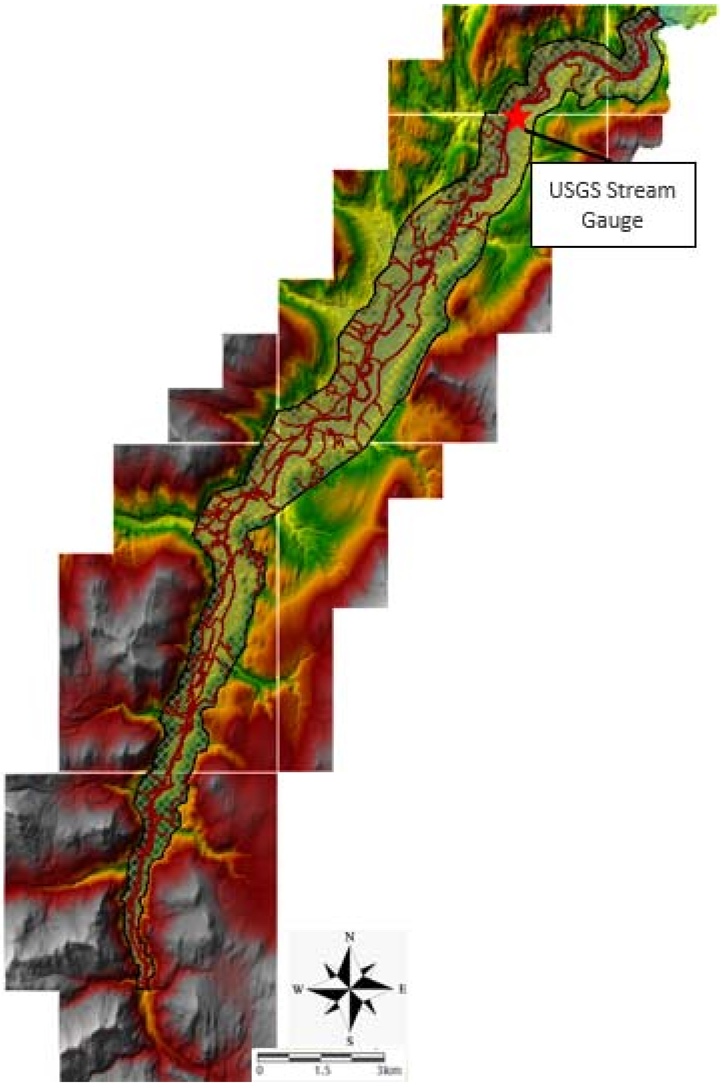


Figure 4.3 Image of Mad River terrain with associated geometry highlighting up- and downstream boundary conditions

In order to minimize computation time, a coarse two-dimensional mesh is initially used to allow reasonable processing time yet produce calibrated results. Nominal node spacing is set to 20 m, with a more refined mesh in the main channel set to 15 m. The refined region is also applied to mesh breaklines that define channel banks, roads, bridges and berms (Figure 4.4).

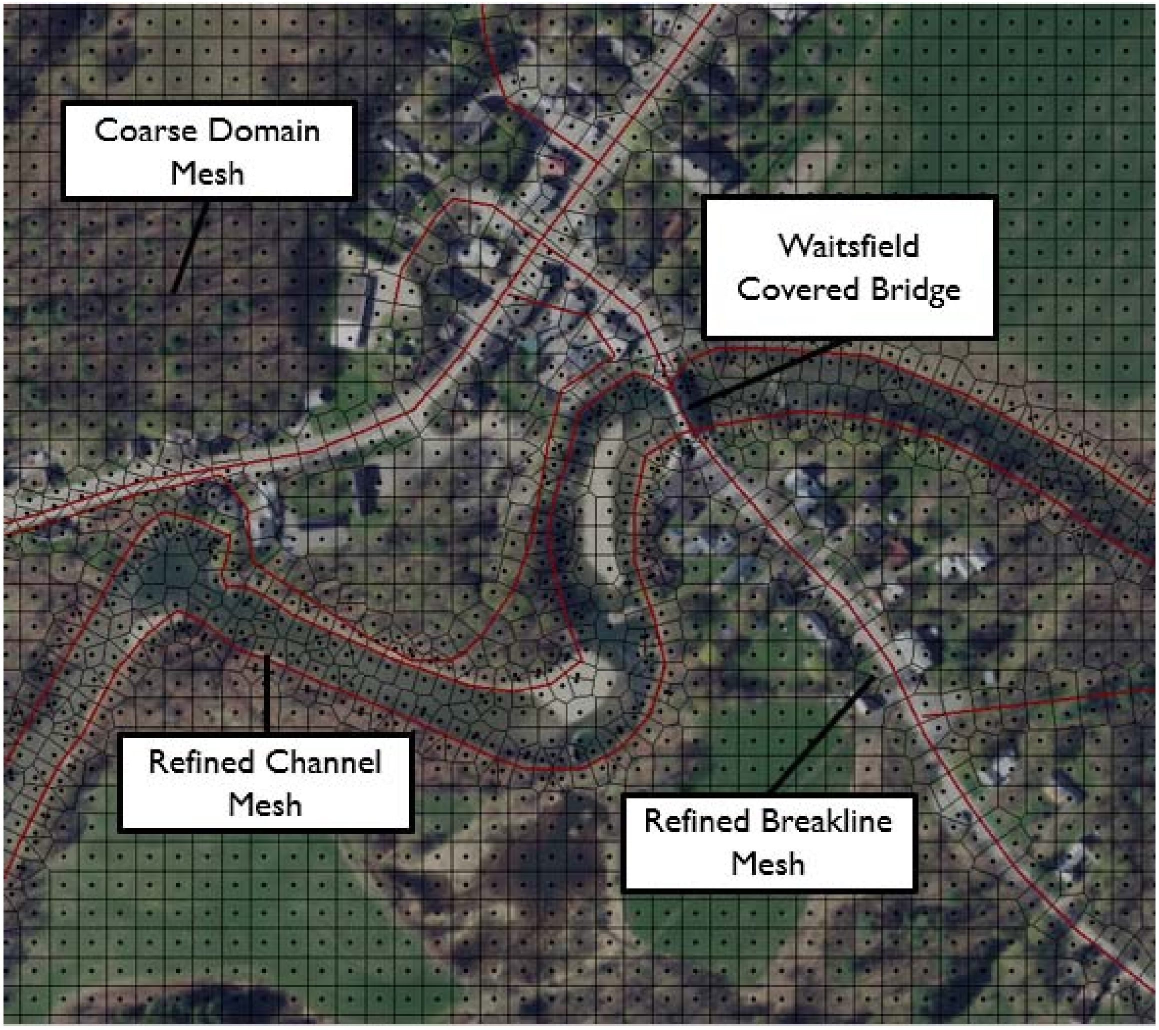


Figure 4.4 Example of mesh size variation at the Waitsfield Covered Bridge. The refined mesh within and surrounding the main channel as well as breaklines are shown, and the less refined mesh for the remaining study area computational domain

4.4 Lateral Hydraulic Inputs

Ten ungauged hydraulic lateral inputs are also applied to the domain. Tropical Storm Irene discharge values measured at 15-minute intervals are scaled and shaped for the tributaries and upstream boundary. The tributaries are as follows: Welder Brook, Dowsville Brook, Shepard Brook, High Bridge Brook, Mill Brook, Folsom Brook, Clay Brook, Bradley Brook, Freeman Brook and Lincoln Brook (Figure 4.5).

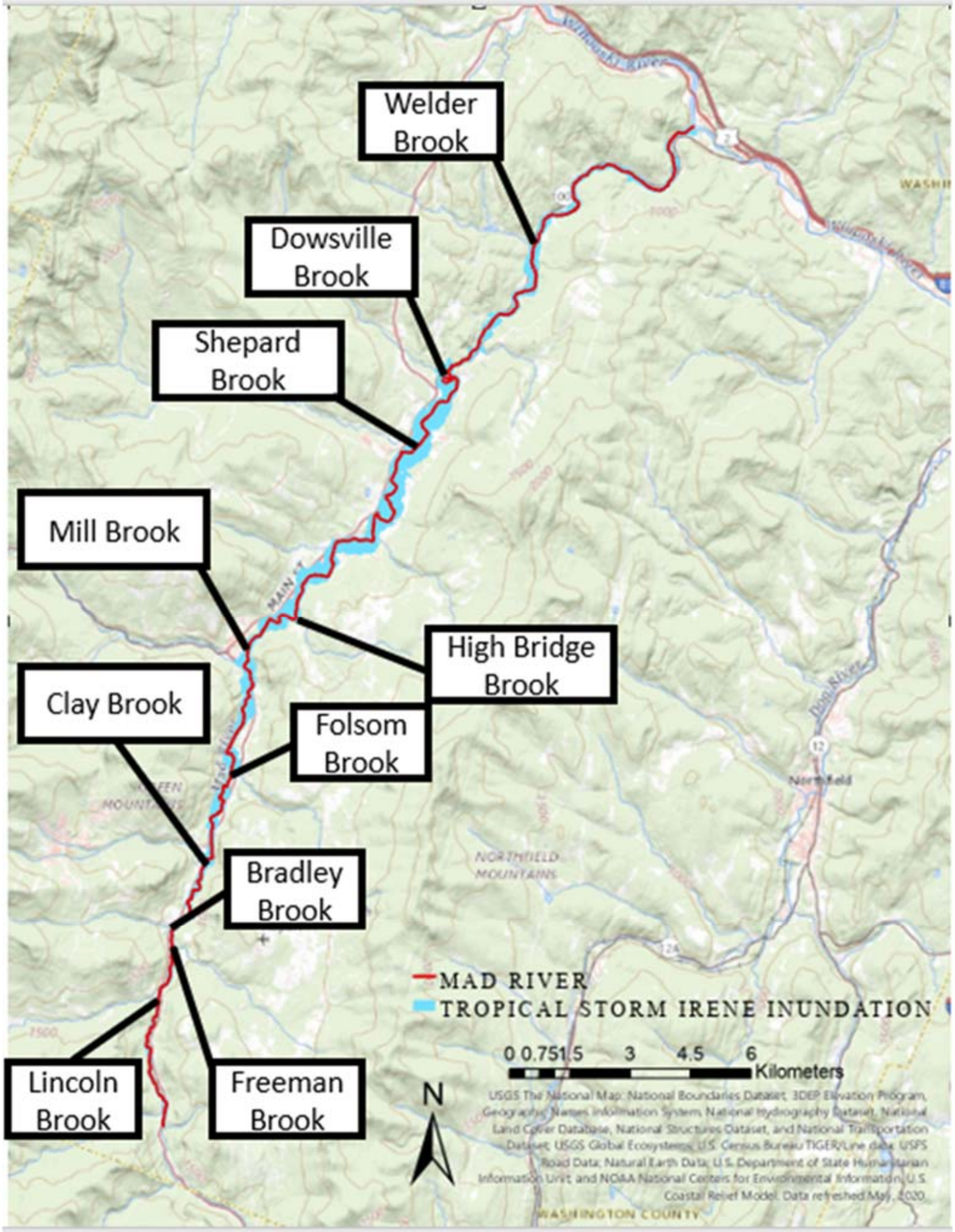


Figure 4.5 Image of the Mad River showing tributaries included in the 2D HEC-RAS model

The inflow hydrographs for the ungauged tributaries are estimated by calculating the proportional tributary watershed area relative to the overall Mad River watershed, and scaling the measured hydrograph accordingly (Figure 4.6). The Mad River study domain is the same as the 1D Mad River model of Dubois & King, Inc. (2017). The upstream boundary condition in Warren, Vermont, is slightly upstream of the B167 bridge. Because the upstream boundary is also ungauged, the proportion of the watershed area at that upstream boundary over the total watershed are at the downstream boundary is used to estimate peak flow, and hydrographs. This is a common practice at ungauged areas (Olson, 2014).

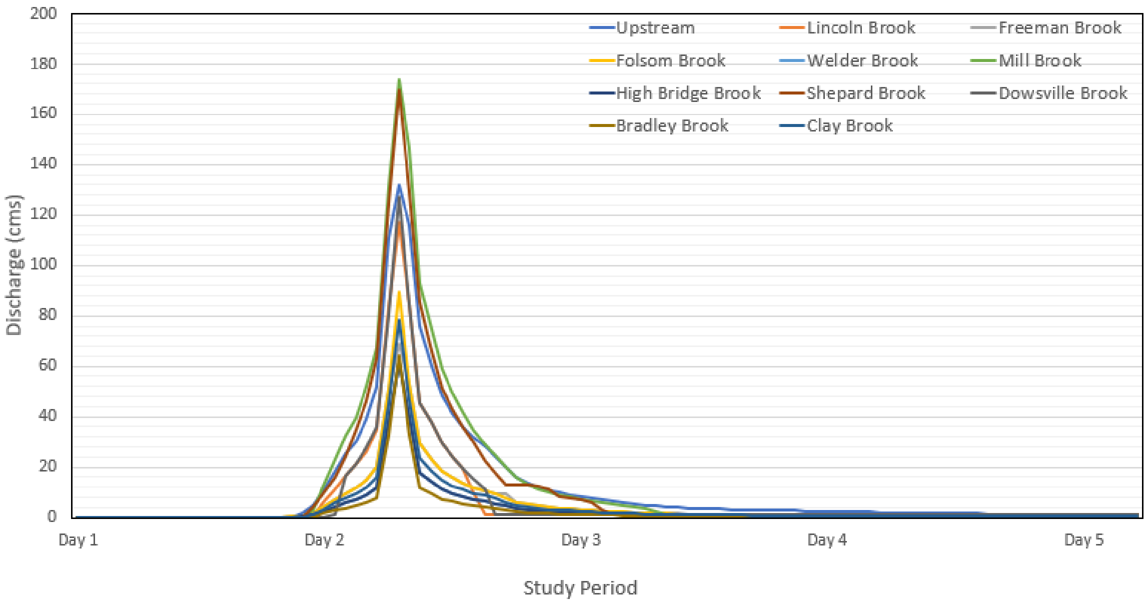


Figure 4.6 Synthetic hydrographs of upstream and lateral inputs for the 2011 Tropical Storm Irene

4.5 Numerical Scheme and Computational Parameters

The HEC-RAS software user can choose to run a steady state or unsteady flow analysis. The unsteady flow analysis has two options: the "full shallow water equations" or the "diffusion wave approximation". This Mad River study uses the diffusion wave approximation, in part to be consistent with the already built 2D HEC-RAS models of the Otter Creek and the Black Creek, but also because the shallow water equations option requires a denser mesh for numerical stability and significantly longer computation time. The 2D HEC-RAS Reference Manual and User's Manual describe the computational advantages and disadvantages in greater detail, and should be consulted when designing any 2D HEC-RAS models (USACE HEC, 2016b, c).

4.6 Synthetic Unit Hydrograph Development

In addition to the Tropical Storm Irene flood, four other floods with varying annual exceedance probabilities (AEP) are simulated in the 2D HEC-RAS model (50%, 4%, 2%, 1% corresponding to 2-year, 25-year, 50-year and 100-year return periods, respectively). To simulate these flow events on the Mad River, synthetic unit hydrographs are developed for the downstream USGS gauge in Moretown. A log-Pearson Type III distribution is fitted and evaluated against USGS Streamstats data for each corresponding storm event (Table 4.1).

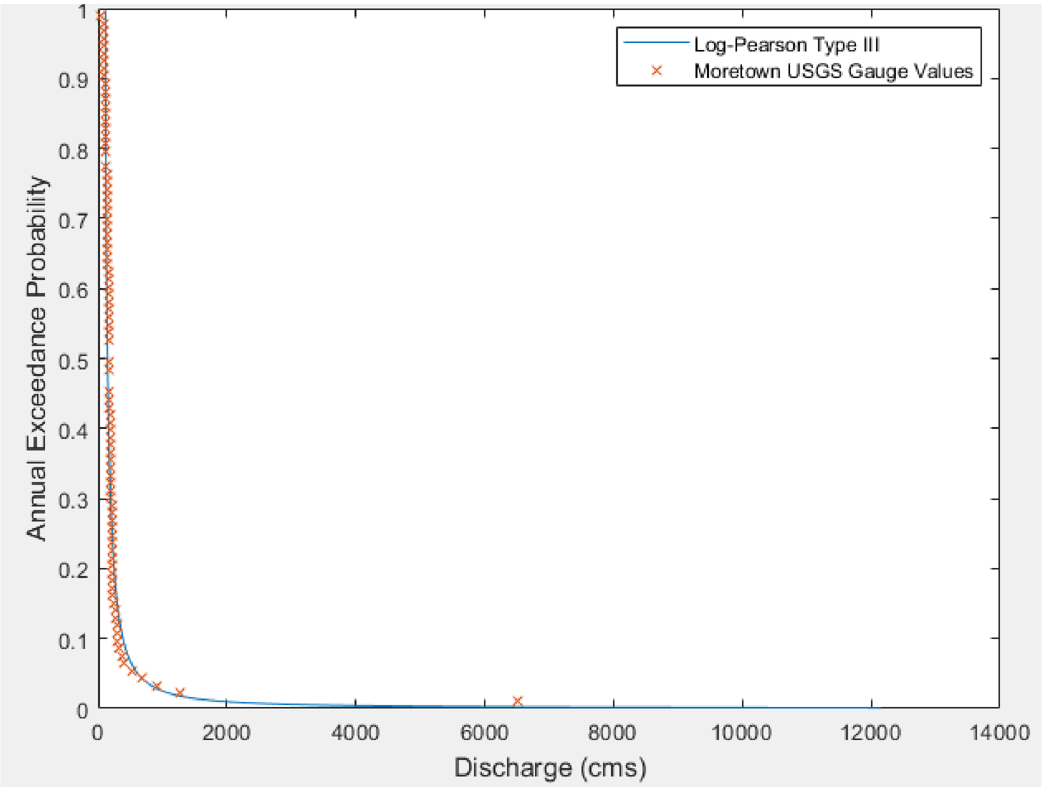


Figure 4.7 Annual exceedance probability graph for the USGS gauge in Moretown on the Mad River for 91 years of available data

Table 0.1 Peak discharge values (cms) for their associated flood events using Log-Pearson Type III analysis

Annual Exceedance Probability (AEP)	Peak Discharge (cms)
Tropical Storm Irene (Q125) / 0.8%	685
Q100 / 1%	467
Q50 / 2%	410
Q25 / 4%	382
Q2 / 50%	153

Tropical Storm Irene has peak flows of 685 cms (24,200 cfs) at the Moretown USGS stream gauge, which has an AEP of 0.8% (Q125). This is slightly higher discharge than an AEP of 1% (Q100). Hydrographs for 1%, 2%, 4% and 50% AEP are developed by rescaling and adjusting the previously developed hydrographs for Tropical Storm Irene (Figure 4.8). Similarly, these hydrographs are scaled to match estimated peak flows calculated from USGS Streamstats for each lateral input (Olson, 2014). Synthetic hydrographs are constructed based on catchment characteristics and observations of an observed storm (Yue et al., 2002). Catchment characteristics include peak flow values, and unit hydrographs are often scaled to reflect these values, which is done for the other simulated storm events as reflected in Figure 4.8.

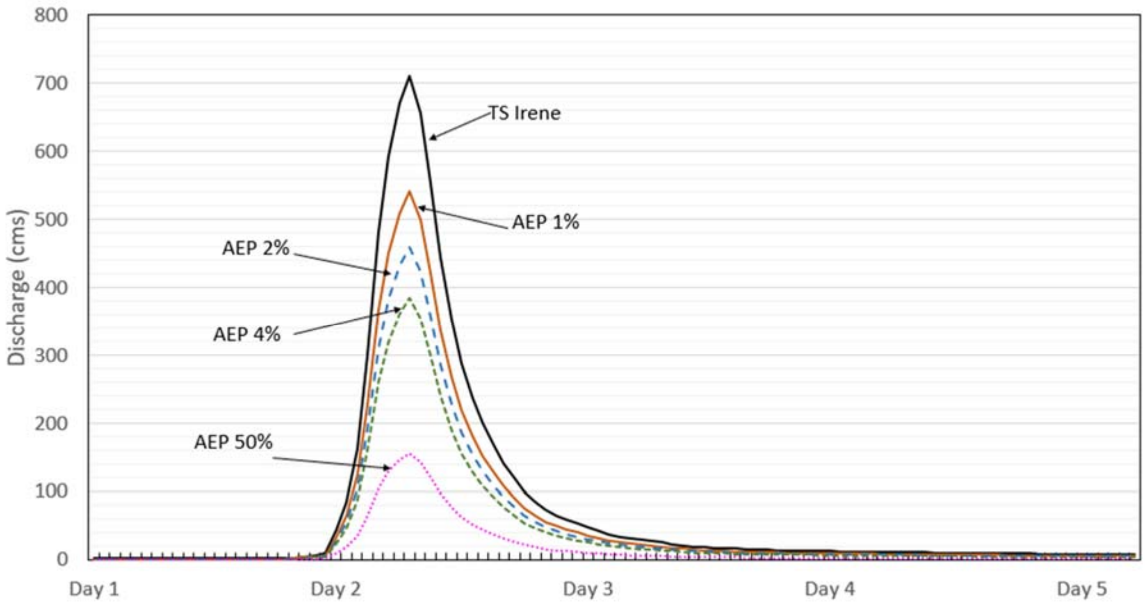


Figure 4.8 Hydrographs of simulated storm events in the Mad River study section at the downstream boundary

4.7 Calibration

Manning's roughness (*n*) is the primary parameter for calibrating the HEC-RAS model. Values are assigned based on land cover types identified by the National Land Cover Database (NLCD) (Homer et al., 2015). Initial values are based on previously built Vermont hydrologic/hydraulic models, as well as available literature (e.g., Chow 1959; Acrement and Schneider 1987, 1989; Trueheart, 2020), and are adjusted based on conditions observed in the field. Calibrated values are summarized in Table 4.2. Relatively high roughness values are used for calibrating to the 2011 Tropical Storm Irene, which occurred in late August, when riparian vegetation is fairly dense and mature cropland is still present.

Once all input hydrographs are scaled and shaped appropriately and Manning's n values are calibrated, the HEC-RAS downstream hydrograph is compared to the observed values from the Moretown USGS gauge, and the fit is quantified using a Nash-Sutcliffe efficiency (NSE). NSE values can range from negative infinity to 1.0. Values above 0.7 may be considered calibrated, with 1.0 representing a perfect fit (Nash and Sutcliffe, 1970). The Mad River model, calibrated to Tropical Storm Irene, achieved a Nash-Sutcliffe efficiency of 0.94 at the downstream gauge/boundary (Figure 4.9).

Table 0.2 Calibrated Manning's n values for the Mad River HEC-RAS model

Cover Type		Manning's *n*	% Total Area
Cultivated Crops		0.035	14%
Deciduous Forest		0.16	7%
Developed	High Intensity	0.1	0.5%
	Medium Intensity	0.08	0.5%
	Low Intensity	0.08	4%
	Open Space	0.04	6%
Emergent Wetlands		0.07	2%
Evergreen Forest		0.16	7%
Grassland		0.035	0.5%
Mixed Forest		0.16	26%
Pasture/hay		0.03	30%
Shrub/scrub		0.1	0.5%
Woody Wetlands		0.12	2%
Mad River Channel		0.04-0.06	

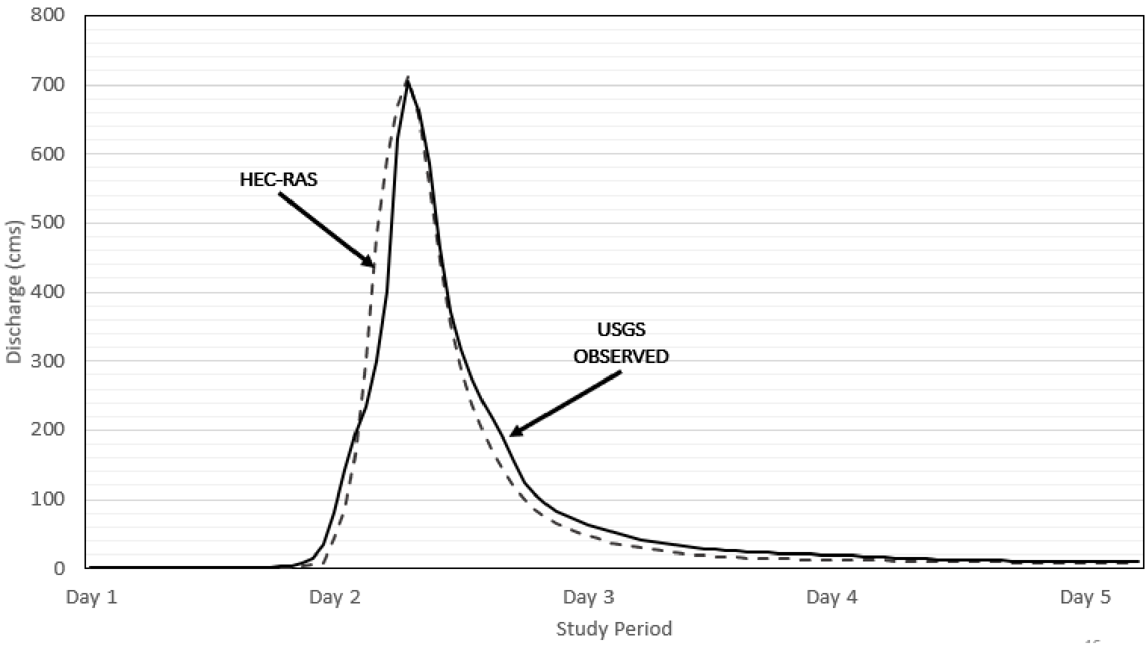


Figure 4.9 Tropical Storm Irene observed hydrograph at the USGS gauge in Moretown compared to the modeled HEC-RAS output hydrograph

4.8 Verification and Validation

To validate the calibrated model against Tropical Storm Irene, water surface elevations predicted by the models are compared to bridge damage reports from Tropical Storm Irene, specifically, at locations that overtopped. A similar process is also used for roadways in the area. It is important to note that not all records are easily accessible and, in some cases, the model predictions may represent those reported during Tropical Storm Irene.

Multiple mesh sizes are tested to ensure that validation is not dependent on model resolution. For the Tropical Storm Irene calibration, uniform node spacing of 20 m, 15 m, and 10 m are simulated in the domain with the associated break lines. Nash-Sutcliffe efficiency values of 0.94, 0.94 and 0.93, are achieved for the node spacing variations, respectively. A 20 m grid with a 15 m refinement region along the main channel provides a good balance between mesh size and computational time.

4.9 Intervention Terrain Modification

Two main types of interventions – floodplain reconnection and addition of culverts are used in the 2D HEC-RAS Mad River model. To model these interventions, the terrain must be modified to reflect the altered conditions. The USACE HEC (2016a, 2016b) user manuals suggest multiple strategies for altering terrain in 2D HEC-RAS.

Depending on the floodplain reconnection goals, different methods of lowering the terrain can be used. Identifying a select region and then lowering or raising the terrain by a constant is most common when working with a 2D model that has no cross-sections (USACE HEC, 2016b). However, the benefit of having cross sections built into the terrain allows for more precise representation of the alteration, which is why this method is used to lower the terrain for floodplain reconnection interventions in this study. Figure 4.10 shows an example of the original terrain that combines the bathymetry and topographic data compared to the lowered terrain at the Waitsfield Covered Bridge project location.

Culvert addition or modification can also assist in flood mitigation. Increased culvert sizes allow flows to be redirected around or underneath infrastructure to increase floodplain access, thereby reducing instream channel velocities and shear stress to avoid erosion and sediment transport, or redirected onto empty fields for better floodplain access without disruption to the roads or other transportation infrastructure (Figure 4.11). In order to model a culvert in HEC-RAS, a weir is represented in the model. This establishes a foundation to construct the culvert, and a center line is defined for the culvert and various parameters such as shape, material, and dimensions are added. When the culvert is initially constructed, the model output for the smallest storm event and largest computational time is recorded in order to quickly and efficiently obtain the minimum water surface elevation at the culvert up- and downstream opening. Once this value is determined, the culvert dimensions are redefined in order to reflect the simulated conditions.

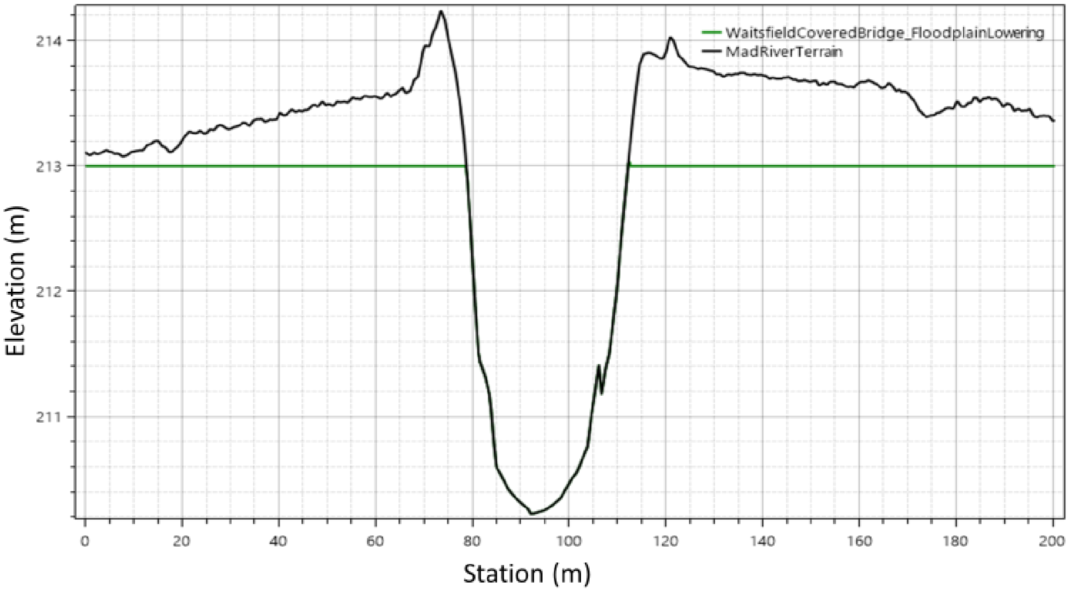


Figure 4.10 Cross-section from the Waitsfield Covered Bridge intervention location showing the original terrain (Mad River Terrain), to the terrain modified for the flood mitigation intervention (Waitsfield Covered Bridge Floodplain Lowering)

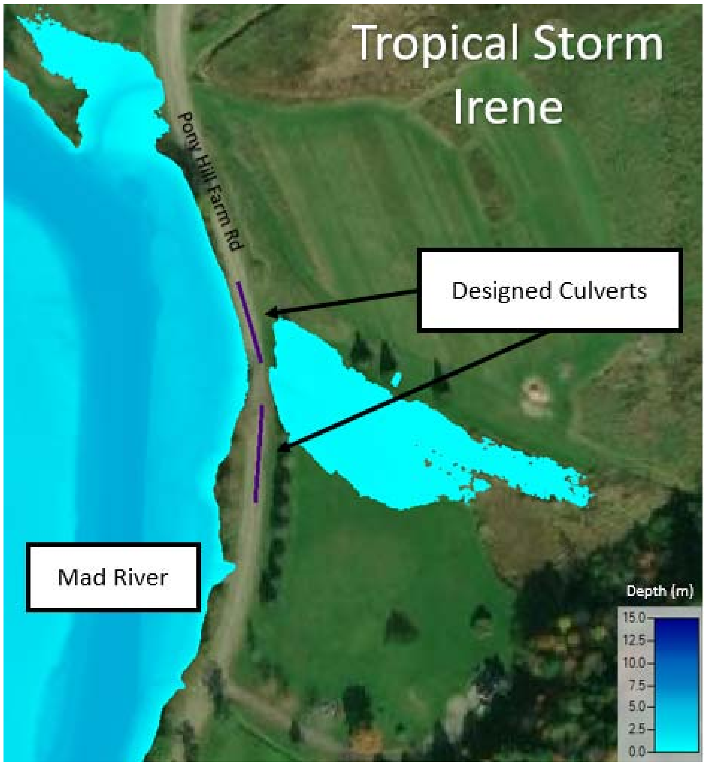


Figure 4.11 Mad River with modified culverts designed to redirect storm flow under Pony Hill Farm Rd and into adjacent field

4.10 Summary

A 2D HEC-RAS model of the Mad River study reach is constructed using current terrain tiles and cross-sectional data provided in the 1D Dubois & King Inc. (2017) model. The 2D model is calibrated using flood hydrographs constructed from the USGS stream gauge in Moretown, Vermont and synthetic hydrographs for tributaries and the upstream boundary. A Nash-Sutcliffe efficiency value of 0.94 is obtained, which is much greater than the minimum recommended value of 0.7, indicating successful calibration. Due to the number of synthetic hydrographs in this study, it is possible to achieve more than one hydrograph output with a Nash-Sutcliffe efficiency value equal or greater than 0.94. Given the enormous number of possible combinations of Manning's n values and synthetic hydrographs, developing alternate combinations of data to produce similar results is very challenging and unlikely.

A final 2D mesh (node spacing of 20 m with refined regions spaced at 15 m) is selected to balance computational time and calibration to the Tropical Storm Irene hydrograph. Extra synthetic hydrographs are constructed to model additional flood events with annual exceedance probabilities of 50%, 4%, 2%, and 1%. We use the calibrated 2D HEC-RAS model to obtain baseline hydraulic performance at the bridges and throughout the modeled river section under various flood events including Tropical Storm Irene, and evaluate how those change when flood mitigation interventions are modeled. Additionally, this model is to be compared and contrasted with 2D HEC-RAS models of the Black Creek and Otter Creek study sections to observe flood events across multiple rivers of varying size and gradients.

Chapter 5: Intervention Evaluation Framework Development and Application

This chapter describes the developed framework to help identify bridges that might benefit most from flood mitigation projects. The framework is applied to the three study reaches and results from the modeled proposed flood mitigation interventions are presented.

5.1 Evaluation Framework Development

Multiple studies identify and predict structures along river networks that have an increased risk to flood damage (Remo et al., 2012; Setunge et al., 2014; Kocyigit et al., 2016). Some studies used only geomorphic and hydraulic attributes to characterize flood damage to the river (e.g., Jain et al., 2008; Parker et al., 2014; Magilligan, 2003, 2015). However, as far as the authors are aware, very few studies have combined geomorphic and hydraulic attributes to evaluate the vulnerability of bridges to flood events.

Trueheart et al. (2020) proposed a flowchart to help identify river or structure network sensitivity from perturbations to structures within the river reach (Figure 5.1). This flowchart can be a useful decision-making tool to determine whether a proposed alteration necessitates a river-scale analysis or whether modeling should include nearby structures (Trueheart et al., 2020). Although this flowchart considers hydraulic characteristics on a local scale, it does not factor in the local geomorphic characteristics nor characteristics on a network level scale, which may affect overall bridge and river sensitivity to alterations within the reach.

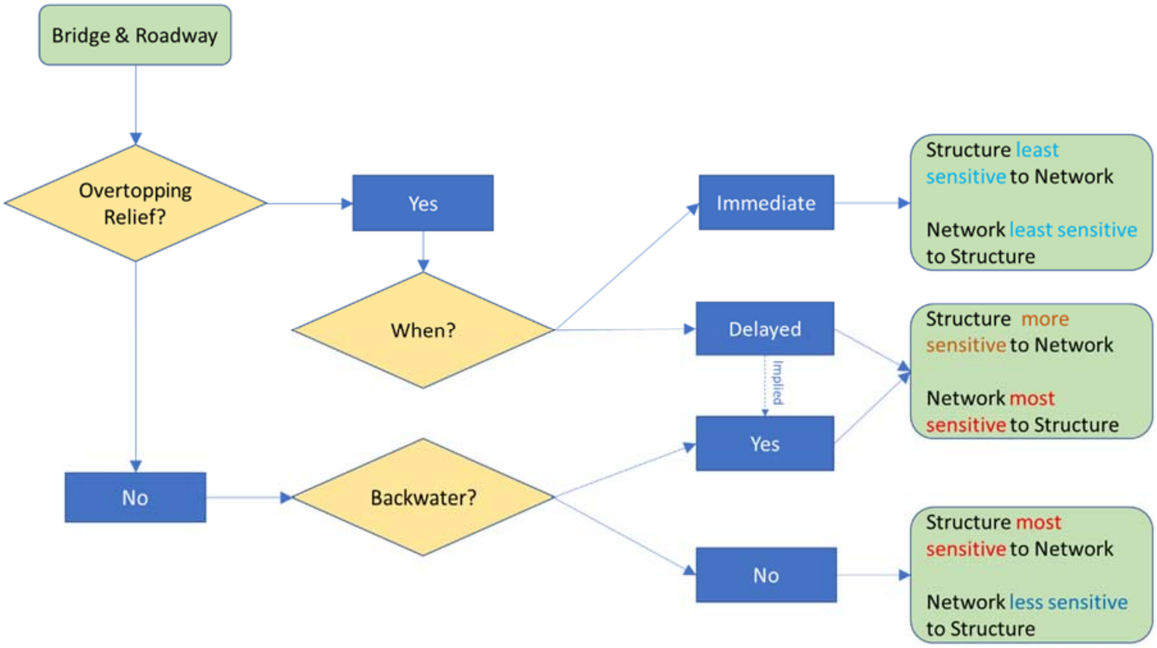


Figure 5.1 Simplistic flow chart identifying potential structure and network sensitivity proposed by Trueheart et al. (2020)

Other studies have used specific stream power and changes in reach slope as indicators for stream stabilization and overall channel health (Magilligan et al., 2003; Bizzi and Lerner, 2015). Specific stream power may be an indicator for channel erosion and sediment transport (Magilligan et al., 2003), and is known to be closely linked to approach scour and infrastructure damage along a river reach (Johnson et al., 2006).

This study proposes a screening framework that considers specific stream power, channel gradient and observed adverse flood impacts to identify what sites are suitable for flood mitigation interventions along the river network (Figure 5.2).

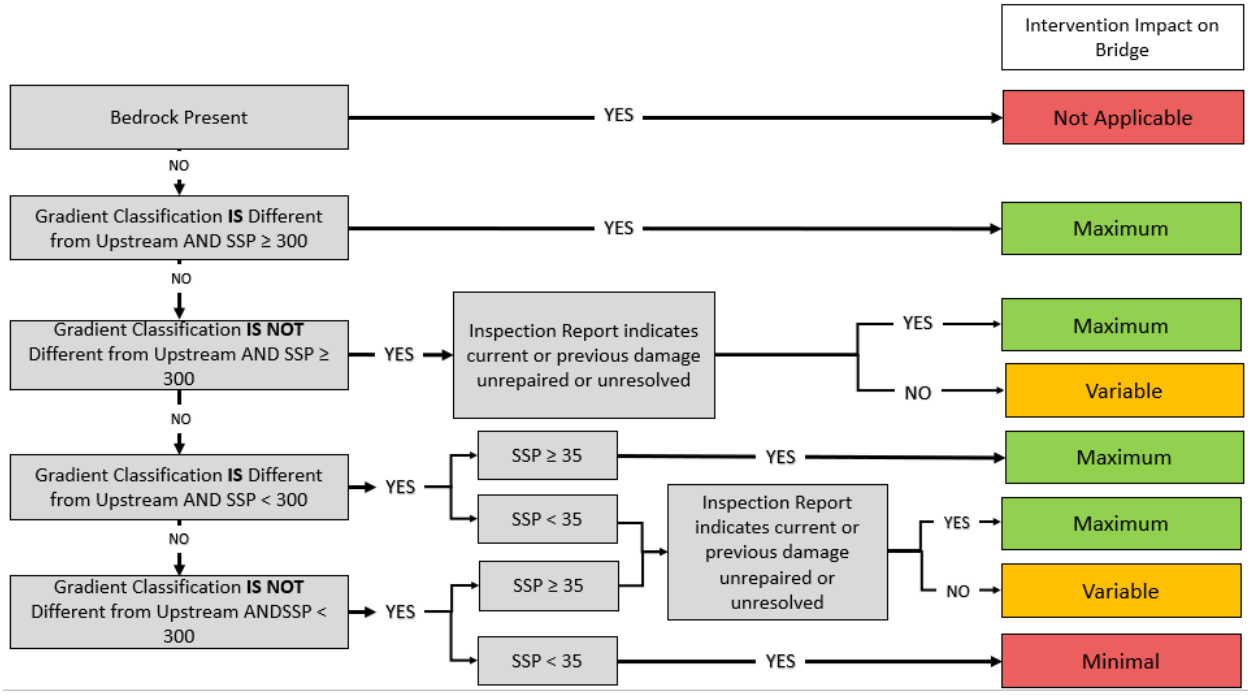


Figure 5.2 Proposed framework to identify structures or locations in a river network that would be best suited for flood mitigation interventions based on specific stream power, channel gradient, and noticed adverse flood impacts

The proposed flowchart in Figure 5.2 is helpful in evaluating whether an alteration to a structure or location in a river would be well suited for reducing the negative flood impacts such as bridge overtopping, scouring, or inundation for example, that have or are predicted to cause bridge damage or failure. This research considers interventions including bridge span increase and floodplain reconnection through floodplain lowering and culvert addition. This screening framework first inquires about the presence/absence of bedrock at the project location in question. High specific stream power values are often associated with bedrock channels, but they are not necessarily linked to increases in channel scour or result in harmful effects to bridge infrastructure due to the high channel-boundary resistance to erosion in these areas. This is why locations with bedrock presence are categorized as *Not Applicable*, due to the low practicality of interventions at these locations.

The framework changes in the channel gradient classification compared to an upstream location. Using the National Aquatic Habitat (NAH) channel gradient classification system, the project's gradient classification is determined using the reach's established categorization. This value is compared to the reach just upstream of the project location (Table 5.1). Reach length is determined by NHD stream data. A decrease or increase in gradient can identify areas that could have large water storage, quick changes in velocity, water surface elevation or other hydrologic attributes, that when altered could have a significant impact on flood mitigation or attenuation in the river (Gartner et al., 2015; Parker et al., 2014).

Table 0.1 National Aquatic Habitat (NAH) stream gradient classification developed by the U.S. Environmental Protection Agency (USEPA) and the U.S. Geological Survey (USGS) (USEPA et al., 2017)

Channel Gradient Classification	Channel Gradient Range
Very Low	$< 0.02\%$
Low	$\geq 0.02\% - 0.1\%$
Low – Moderate	$\geq 0.1\% - 0.5\%$
Moderate – High	$\geq 0.5\% - 2\%$
High	$\geq 2\% - 5\%$
Very High	$\geq 5\%$

Locations that have a significant change in channel gradient classification and have specific stream power greater than 300 W/m^2 are categorized as areas that would have a *Maximum* impact on the location and river reach. Specific stream power values at or above 300 W/m^2, known as the Magilligan's threshold, have been linked to channel instability, large sediment transport, channel bank erosion, approach scour, and infrastructure damage along the river corridor (Magilligan, 2003).

Adverse flood impacts are considered when reach gradient classification does not change or when it does change and values are below the Magilligan's threshold but still above 35 W/m^2. If the structure has seen overtopping, approach scour or other types of damage, flood mitigation interventions might still be considered. When stream gradient classification does not change and the specific stream power is below 35 W/m^2, that location is considered stable and most likely does not need intervention, which is why it is categorized as having a *Minimal* impact to the structure and river reach. This screening framework is meant for evaluation, and current knowledge about the infrastructure and geomorphology is required. Bridge and project locations that require additional information, such as inspection reports, will have a *Variable* impact to the location and river reach.

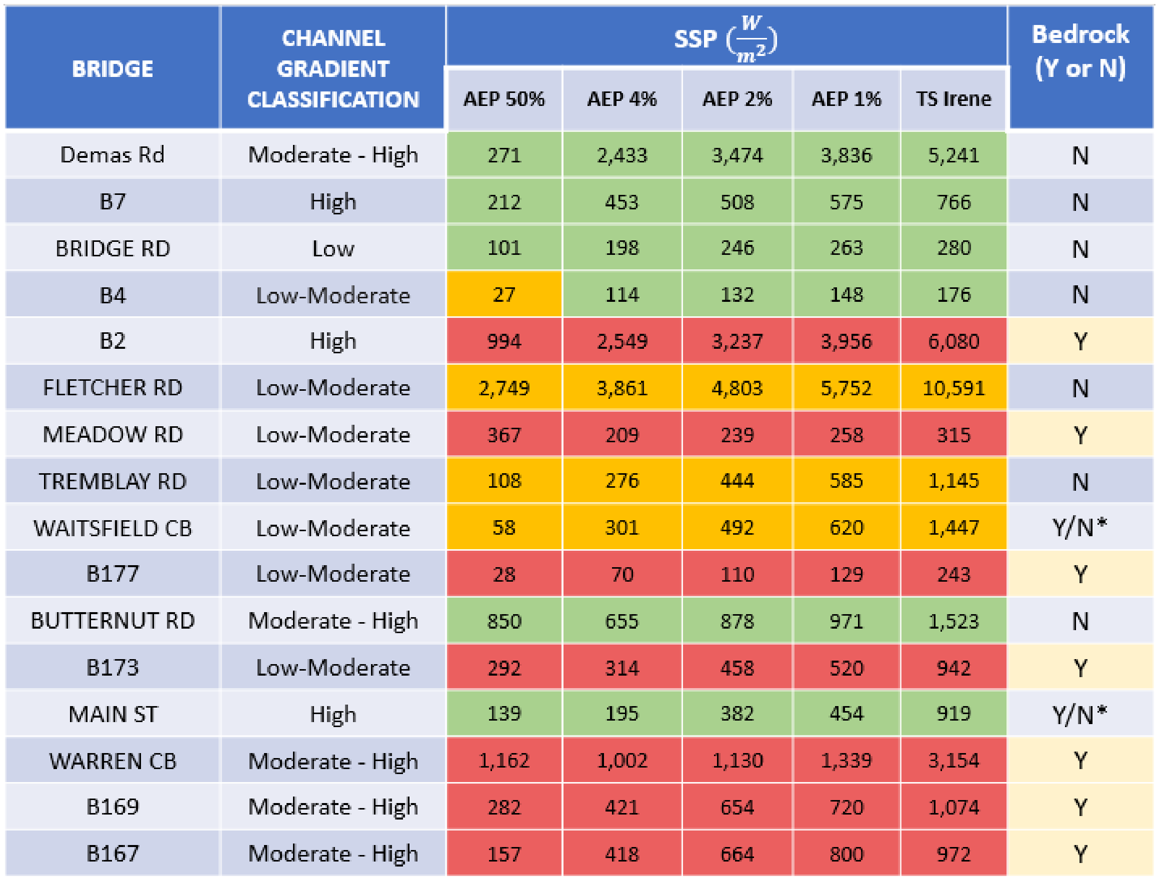
Flood interventions, or flood mitigation strategies, are dependent on stream and structure conditions. Stakeholders may choose different mitigation strategies due to current bridge and river conditions, cost, goals of individual land owners and other factors. Interventions can vary and may include: floodplain reconnection, addition of culverts, increased bridge deck elevation, revegetation, bridge span increase, among others. This framework is for stakeholders to screen for potential for flood risk to bridges, and preliminary assessment of ideal locations for interventions.

5.2 Framework Application to the Study Sections

A summary table is created for each river study section per the framework; it includes NAH channel gradient classification, specific stream power values for each simulated flood event, and presence of bedrock. Bedrock presence is identified at the bridge location and was determined through geospatial mapping and inspection photographs. Visual inspection is needed to confirm bedrock presence (and was precluded by COVID-19 restrictions on field work). For this study, bridge locations where presence of bedrock could not be determined with reasonable certainty, it was assumed to be not present. Specific stream power results are the highest value observed between the up and downstream bridge cross sections for each simulated flood event in 2D HEC-RAS. The bridge location is then categorized for potential intervention impact (*Maximum* [green], *Variable* [orange], or *Minimal* [red]), for each event.

Table 5.2 summarizes the results of the evaluation framework applied to the Mad River study area. All bridge locations that have a confirmed presence of bedrock are marked red for *Not Applicable*. Fletcher Rd., Tremblay Rd. and the Waitsfield Covered Bridge are all categorized as intervention locations that would see a *Variable* impact. All other bridge locations and flood events are categorized as areas that would see a *Maximum* impact. It should be noted that interventions can take place up- or downstream of the bridge, and not necessarily at the bridge location itself. For example, the Meadow Rd. Bridge is identified as red (*Not Applicable*) due to the presence of bedrock. However, this structure is known to have been damaged during the 2011 Tropical Storm Irene flooding. Due to bedrock, it may not be cost effective or feasible to intervene at the bridge location; but other flood mitigation efforts can occur up- or downstream of the bridge to mitigate potential damage.

Table 0.2 Intervention evaluation framework applied to the Mad River study section



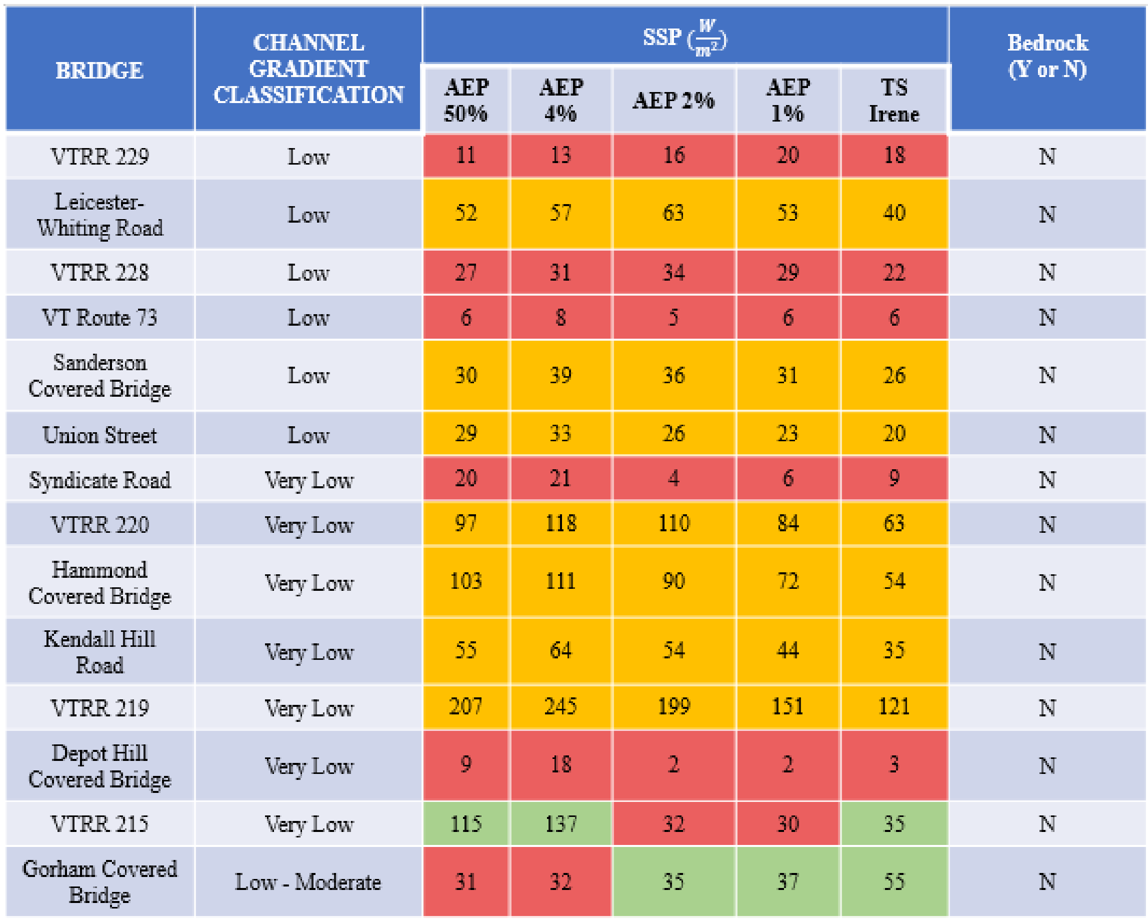
BRIDGE	CHANNEL GRADIENT CLASSIFICATION	SSP $(\frac{W}{m^2})$					Bedrock (Y or N)
		AEP 50%	AEP 4%	AEP 2%	AEP 1%	TS Irene	
Demas Rd	Moderate - High	271	2,433	3,474	3,836	5,241	N
B7	High	212	453	508	575	766	N
BRIDGE RD	Low	101	198	246	263	280	N
B4	Low-Moderate	27	114	132	148	176	N
B2	High	994	2,549	3,237	3,956	6,080	Y
FLETCHER RD	Low-Moderate	2,749	3,861	4,803	5,752	10,591	N
MEADOW RD	Low-Moderate	367	209	239	258	315	Y
TREMBLAY RD	Low-Moderate	108	276	444	585	1,145	N
WAITSFIELD CB	Low-Moderate	58	301	492	620	1,447	Y/N*
B177	Low-Moderate	28	70	110	129	243	Y
BUTTERNUT RD	Moderate - High	850	655	878	971	1,523	N
B173	Low-Moderate	292	314	458	520	942	Y
MAIN ST	High	139	195	382	454	919	Y/N*
WARREN CB	Moderate - High	1,162	1,002	1,130	1,339	3,154	Y
B169	Moderate - High	282	421	654	720	1,074	Y
B167	Moderate - High	157	418	664	800	972	Y

*Intervention impact potential is identified and categorized as either *Maximum* (green), *Variable* (yellow), *Minimum* (red), or *Not Applicable* (red).
+Bedrock maps may not be up to date and bedrock presence/absence should be confirmed through field investigation. See Figure 3.3 for bridge locations, listed here in order from downstream to upstream.

The screening framework was applied to the previously developed Otter Creek model under baseline conditions (Table 5.3). When the framework is applied, intervention categorization begins to differ between flood events. The Sanderson Covered Bridge, VTRR 215, and the Gorham Covered Bridge each have two different categorizations for flood events. This Otter Creek study also categorizes the following bridges: VTRR 229, VTRR 228, and VT Route 73 as *Minimal* due to stabilization. These are marked stable due to little change in channel gradient, and the specific stream power value below 35 W/m^2.

In general, the Otter Creek study section has a much lower gradient than the Mad River study section with only one portion upstream identified as low-moderate gradients. Specific stream power values for an AEP of 50% are much higher due to flood stage not being able to disperse into the floodplains. Two bridges are categorized as having a *Maximum* level of impact should an intervention take place: the Sanderson Covered Bridge and the Gorham Covered Bridge. In revisiting the Otter Creek model, the evaluation framework has identified that flood mitigation interventions may not be as effective on a network scale compared to the Mad River.

Table 0.3 Intervention evaluation framework applied to the Otter Creek study section

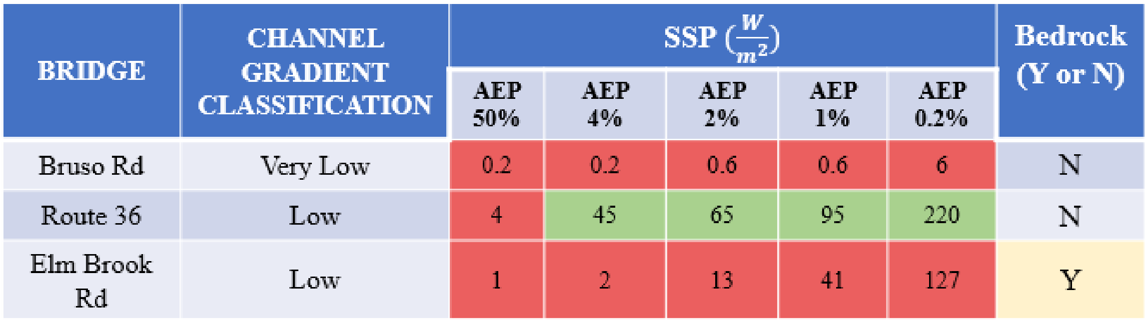


BRIDGE	CHANNEL GRADIENT CLASSIFICATION	SSP ($\frac{W}{m^2}$)					Bedrock (Y or N)
		AEP 50%	AEP 4%	AEP 2%	AEP 1%	TS Irene	
VTRR 229	Low	11	13	16	20	18	N
Leicester-Whiting Road	Low	52	57	63	53	40	N
VTRR 228	Low	27	31	34	29	22	N
VT Route 73	Low	6	8	5	6	6	N
Sanderson Covered Bridge	Low	30	39	36	31	26	N
Union Street	Low	29	33	26	23	20	N
Syndicate Road	Very Low	20	21	4	6	9	N
VTRR 220	Very Low	97	118	110	84	63	N
Hammond Covered Bridge	Very Low	103	111	90	72	54	N
Kendall Hill Road	Very Low	55	64	54	44	35	N
VTRR 219	Very Low	207	245	199	151	121	N
Depot Hill Covered Bridge	Very Low	9	18	2	2	3	N
VTRR 215	Very Low	115	137	32	30	35	N
Gorham Covered Bridge	Low - Moderate	31	32	35	37	55	N

Note: See Figure 3.5 for bridge locations, listed above in order from downstream to upstream.

The screening framework applied to the Black Creek study reach shows very low gradients compared to the Otter Creek and Mad River (Table 5.4). Only one bridge has confirmed bedrock presence. No bridge location has specific stream power values that reach the Magilligan's threshold of 300 W/m^2, but the Route 36 bridge does have flood events that show unstable values categorizing it as a potential *Maximum* level of impact should an intervention take place (Table 5.4).

Table 0.4 Intervention evaluation framework applied to the Black Creek study section



BRIDGE	CHANNEL GRADIENT CLASSIFICATION	SSP $\left(\frac{W}{m^2}\right)$					Bedrock (Y or N)
		AEP 50%	AEP 4%	AEP 2%	AEP 1%	AEP 0.2%	
Bruso Rd	Very Low	0.2	0.2	0.6	0.6	6	N
Route 36	Low	4	45	65	95	220	N
Elm Brook Rd	Low	1	2	13	41	127	Y

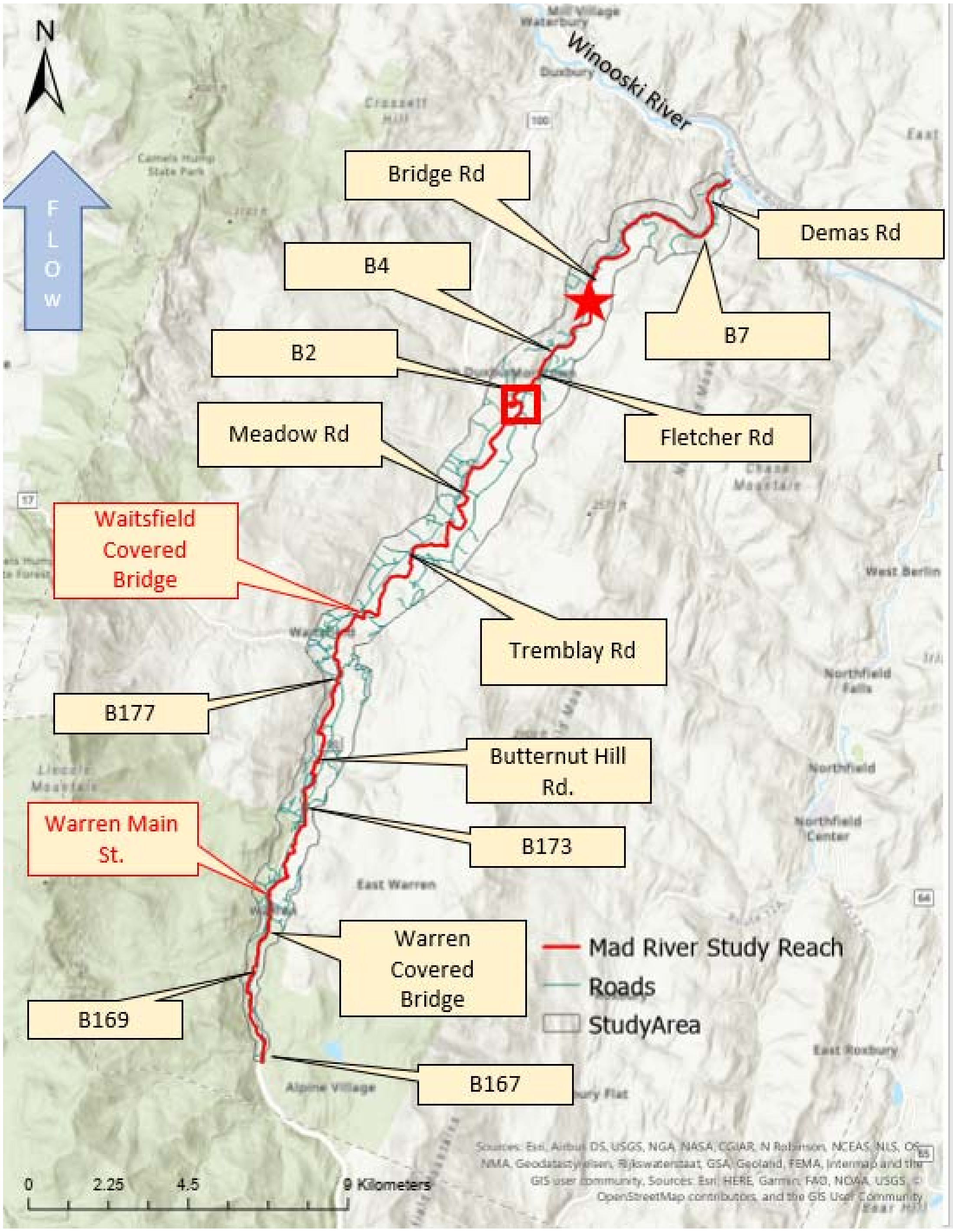
Note: See Figure 3.7 for bridge locations, listed above in order from downstream to upstream

5.3 Intervention Application

This section discusses how the evaluation framework was used to select specific bridge sites for intervention projects. Water surface elevation, specific stream power and inundation are observed at the project location and bridge locations throughout each river.

5.3.1 Intervention Overview

Using Table 5.2 as a guide, multiple bridge locations are selected for modeling interventions in the Mad River study area 2D HEC-RAS model. Not all locations that are categorized as potential *Maximum* impact areas are selected to be modeled. The Main St Bridge, Waitsfield Covered Bridge, and just upstream of the B2 bridge are selected for intervention locations (Figure 5.6) for demonstration purposes. The Main St. Bridge, previously categorized as a potential *Maximum* impact location, is modeled first. This bridge is located upstream in the headwaters of the Mad River. Due to the change in slope classification up- and downstream of the bridge, and the presence of bedrock just upstream of this bridge, the specific stream power values are as high as 919 W/m^2 (Table 5.4). The intervention includes floodplain lowering and reconnection. This intervention is not necessarily practical because of the presence of bedrock outcrops in the vicinity, the very low acreage of floodplains in headwaters and sizeable human population on the banks of the river, but it serves as a good proof-of-concept to demonstrate the overall effectiveness of the screening framework, and how small changes in floodplain area can have a large impact along the entire river section.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 5.3 Image of Mad River study section with the floodplain lowering bridge projects highlighted and the culvert modification project outlined by a red box

The historic Waitsfield Covered Bridge, previously categorized as a *Variable* impact location, is also selected for a hypothetical flood mitigation intervention. After previous flood events, berm installations were implemented on each side of the river channel. The modeled intervention is 0.5 km upstream of the covered bridge at Couple's Park and across the channel at Wu Ledges Forest (Figure 5.4), and proposes removing the berms and lowering the floodplains to allow for floodwaters to access the floodplain, dissipate flood energies, which will reduce erosion and sediment transport during flood events. This intervention compared to the Main St. intervention is more practical, but would require landowner permission.

Figure 5.4 Couple's Park and Wu Ledges Forest project location highlighted in the red boundary upstream of the Waitsfield Covered Bridge showing a simulated flood event (AEP 50%) in the Mad River study section

Feedback from stakeholders helped in identifying specific locations where culvert size modification could enhance floodplain reconnection. Two culverts alongside Pony Hill Road, upstream of the B2 bridge are selected for a third flood mitigation intervention. This section of the road was not overtopped during the 2011 Tropical Storm Irene, but the B2 Bridge was significantly damaged from the storm and eventually replaced. The project location is upstream of the B2 bridge due to bedrock presence at the bridge location, which determined a categorization of *Not Applicable*.

Culverts that provide floodwater conveyance under or through roads, rails and fill material blocking the natural floodplain, can be a cost-effective flood mitigation strategy and can potentially be used to help reduce negative flood impacts to downstream infrastructure. From the evaluation framework, this area will not benefit from interventions due to the presence of bedrock. This location has been selected to model flood mitigation interventions, regardless of the bedrock presence to assess the overall effectiveness of the evaluation framework. In addition, this intervention is modeled to observe alternate flood mitigation strategies from floodplain lowering projects.

5.3.2 Intervention Impact on Structures

Floodplain reconnection at the Main St. Bridge is modeled for 50 m upstream of the bridge and 20 m downstream of the bridge, but terrain is not adjusted or modified directly under the bridge. The river banks are lowered by 8 m on the left-hand side looking downstream, and lowered by 6 m on the right-hand side looking downstream (Figure 5.5). This alteration expands out for 20 m on each side of the bank.

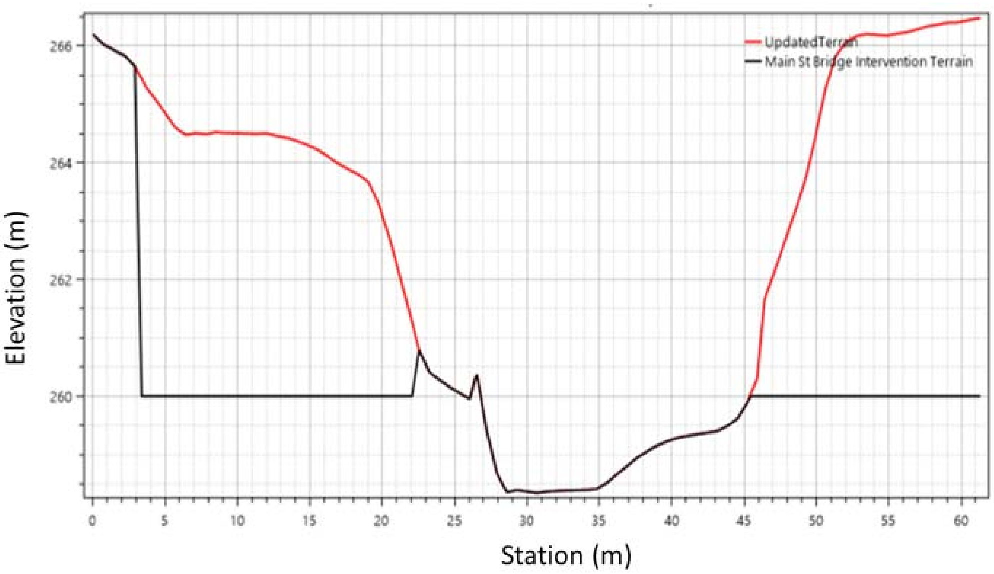


Figure 5.5 The cross section at Main St. project location showing proposed floodplain lowering proposal

Baseline conditions, flood conditions with no intervention in place, at the Main St. Bridge show no overtopping (Table 5.5). There is no record of damage to this bridge from Tropical Storm Irene. The 2D HEC-RAS model shows specific stream power values above the Magilligan’s threshold of 300 W/m^2 for AEPs of 2%, 1% and Tropical Storm Irene simulations (Figure 5.6) . These values drop below the Magilligan’s threshold for AEPs of 50% and 4%. The 2D HEC-RAS model also shows little to no bank overflow for all flood events including Tropical Storm Irene during baseline conditions and under intervention conditions (Figures 5.7 and 5.8).

Table 0.5 Water surface elevation at the Main St. Bridge in Warren showing baseline and intervention conditions

Flood Event (AEP %)	**Main St Bridge Water Surface Elevation (m)**	
	Baseline	Intervention
50%	259	258.8
4%	259.5	259
2%	260	259.5
1%	260.2	259.8
Tropical Storm Irene	261	260

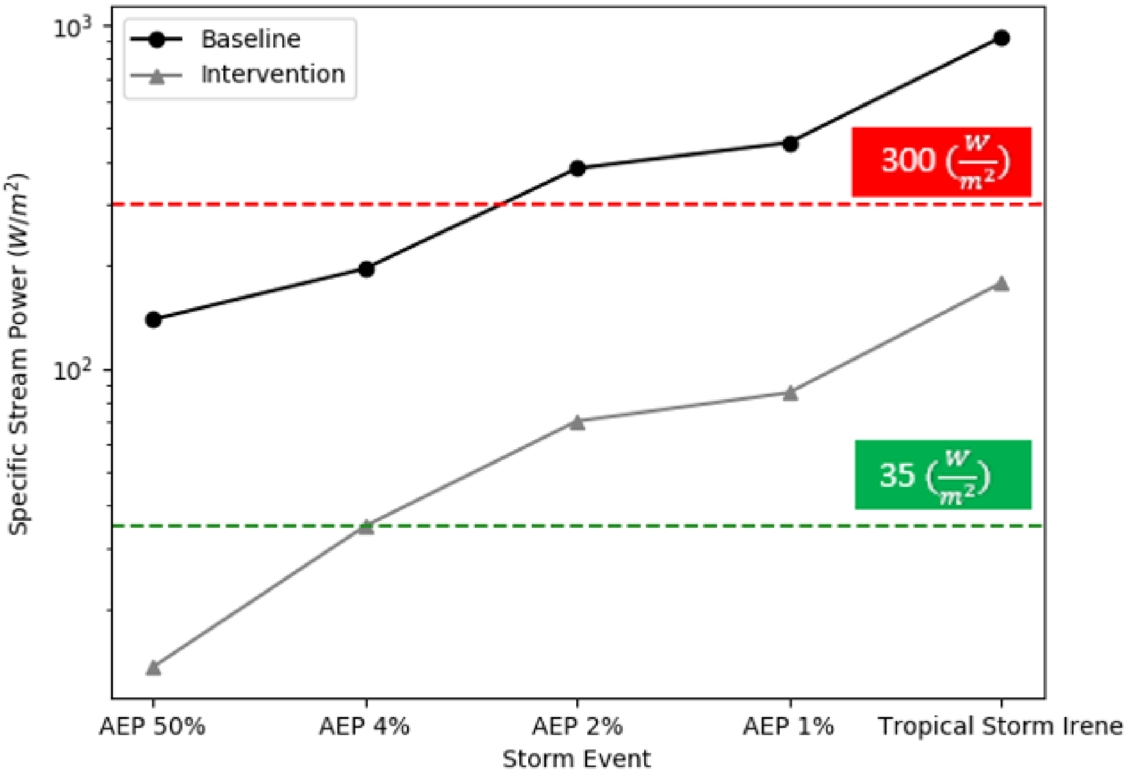


Figure 5.6 Specific Stream Power plot for the Main St. Bridge in Warren showing baseline values (black), and values of the Main St. Bridge floodplain reconnection intervention (grey)

With the simulated intervention, stream power values drop below the Magilligan's threshold for all flood events, and are considered stable for AEPs of 50% and 4% (Figure 5.6). The model shows fairly significant bank overtopping as the flow expands onto the newly connected floodplains (Figure 5.8). Water surface elevation at the bridge location shows little difference between the flood events, with Tropical Storm Irene flooding having the greatest water surface elevation difference of 1 m (Table 5.5). This shows little localized change, and that the flood mitigation intervention will not have a negative impact on the structure.

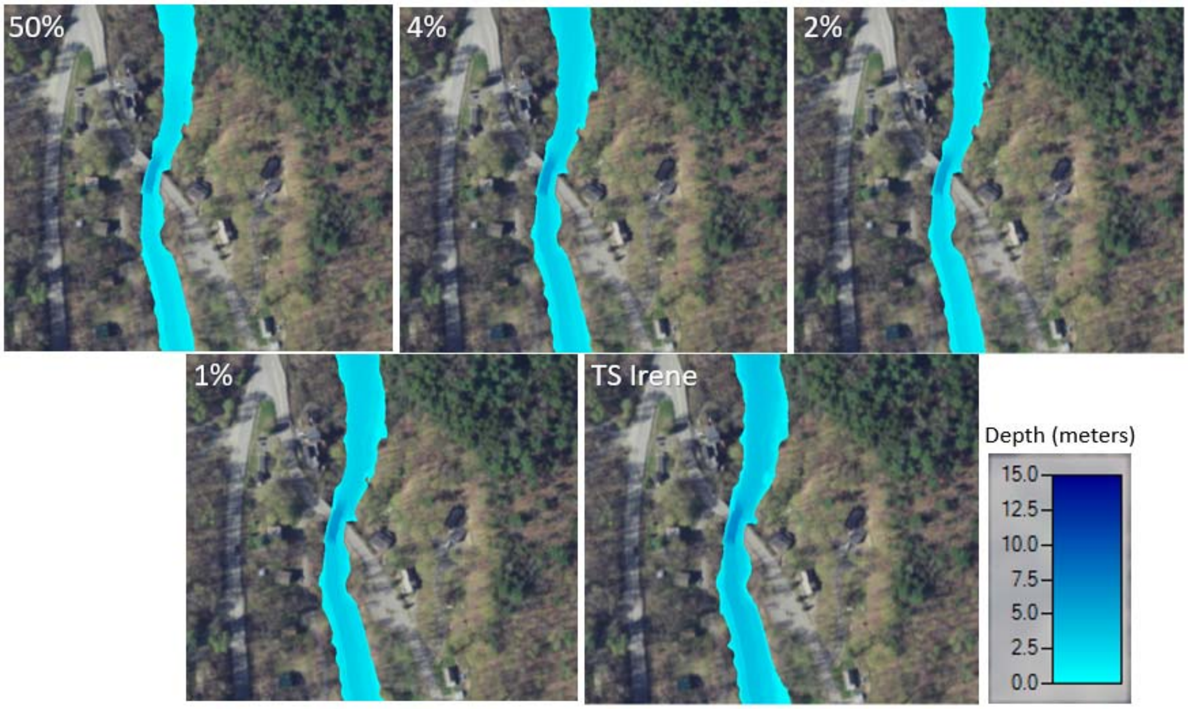


Figure 5.7 Plan view image of 2D HEC-RAS model showing Main St. bridge project location under baseline conditions

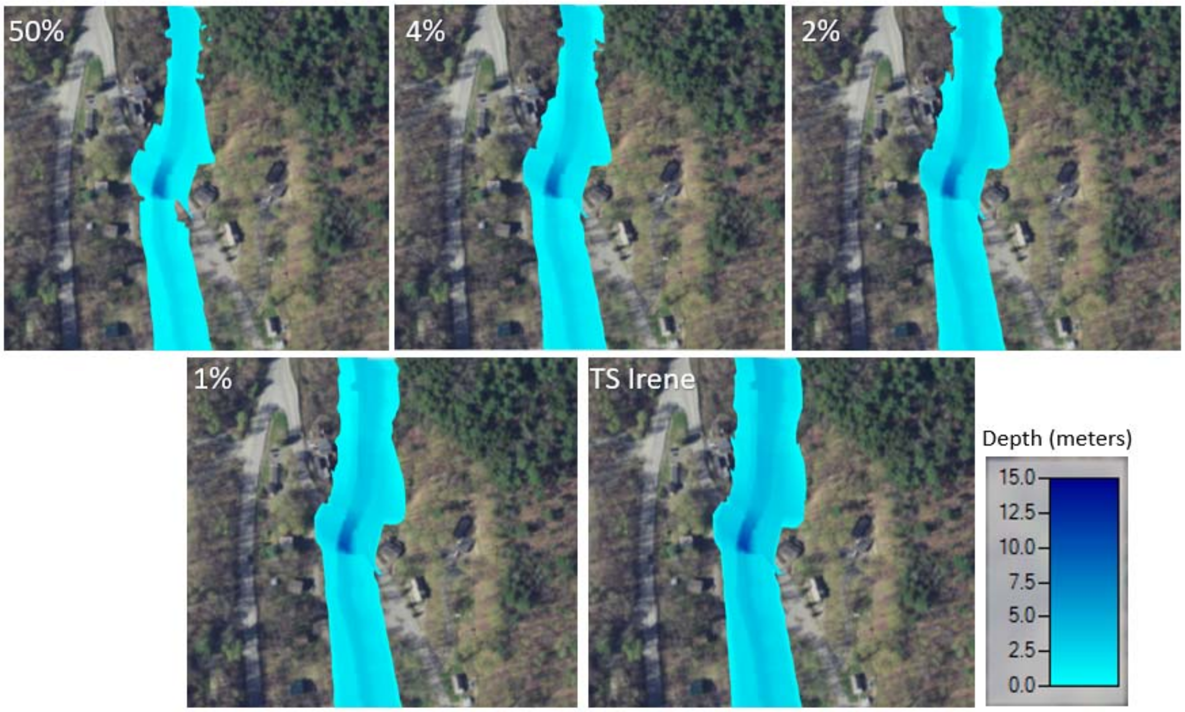


Figure 5.8 Plan view image of 2D HEC-RAS model showing Main St. Bridge project location intervention conditions

The floodplain reconnection at the Waitsfield Covered Bridge is simulated in a similar manner to the Main Street intervention. Berms are removed for 200 m on both sides of the river channel. The channel banks are lowered by 0.6 m and expands out for 100 m on either side of the channel to create a new floodplain elevation at the stage of a flood with AEP of 50% (Figure 5.9). Results of this intervention are in sharp contrast to the one for the Main St Bridge. At that upstream location a very small areal extent is reconnected, but to a greater depth, compared to the very long and wide but shallow area that is modeled at the Waitsfield Covered Bridge intervention. It should be noted that this intervention has a greater area of floodplain access when compared to the very limited floodplain access observed in the headwaters. In addition to greater floodplain area than the Main St. intervention, it is more feasible with little hinderance to the general surrounding population.

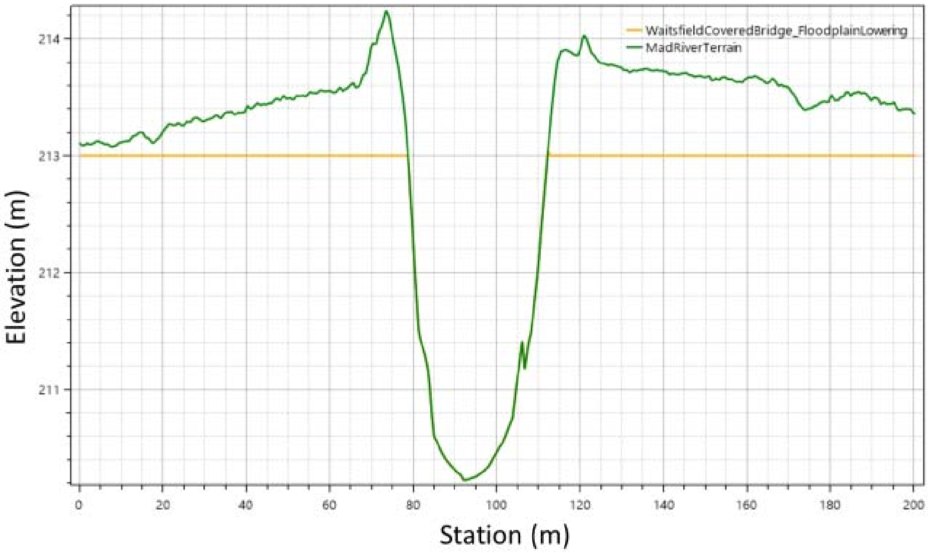


Figure 5.9 Cross-section upstream of Waitsfield Covered Bridge (green) showing proposed floodplain lowering intervention (orange)

The intervention resulted in a significant drop in water surface elevation at the Waitsfield Covered Bridge (Figure 5.10). Under baseline conditions, floodwater stage rose above the lower bridge chord elevation. The lower chord overtop condition was close to being met for an AEP of 1%. With the intervention, the modeled water surface elevation drops for each modeled storm, and the maximum stage of the Tropical Storm Irene was 0.85 meters below the lower bridge chord elevation. This reduces the risk of flood damage at this historic bridge. Inundation areas expand further during intervention conditions compared to baseline conditions (Figures 5.11 and 5.12). Specific stream power values also decrease and are below the 35 W/m^2 threshold for AEPs of 50% and 4% (Figure 5.13).

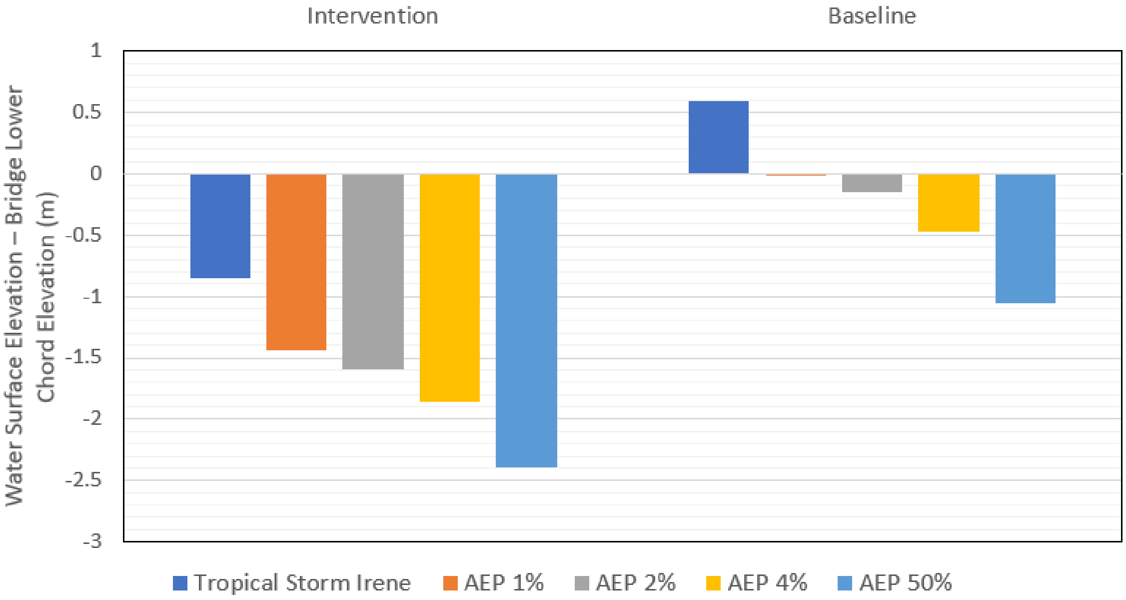


Figure 5.10 Computed water surface elevation minus the lower chord elevation of the Waitsfield Covered Bridge: Intervention conditions (left) and baseline conditions (right)

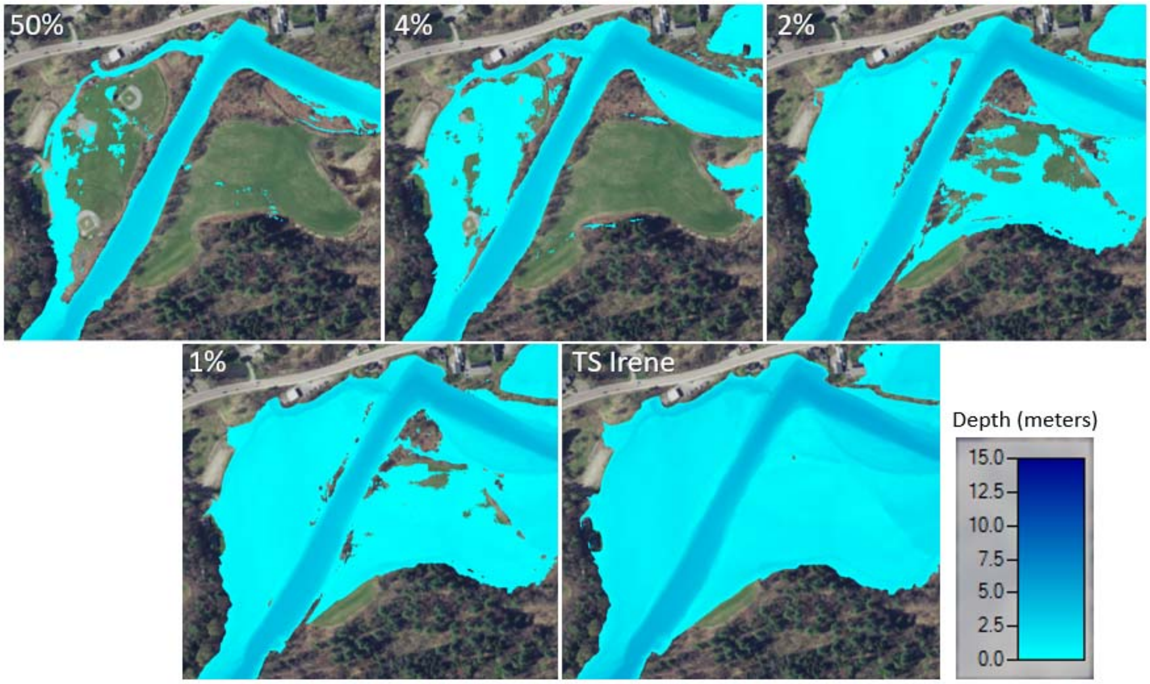


Figure 5.11 Plan view image of 2D HEC-RAS model showing Waitsfield Covered Bridge intervention location baseline conditions

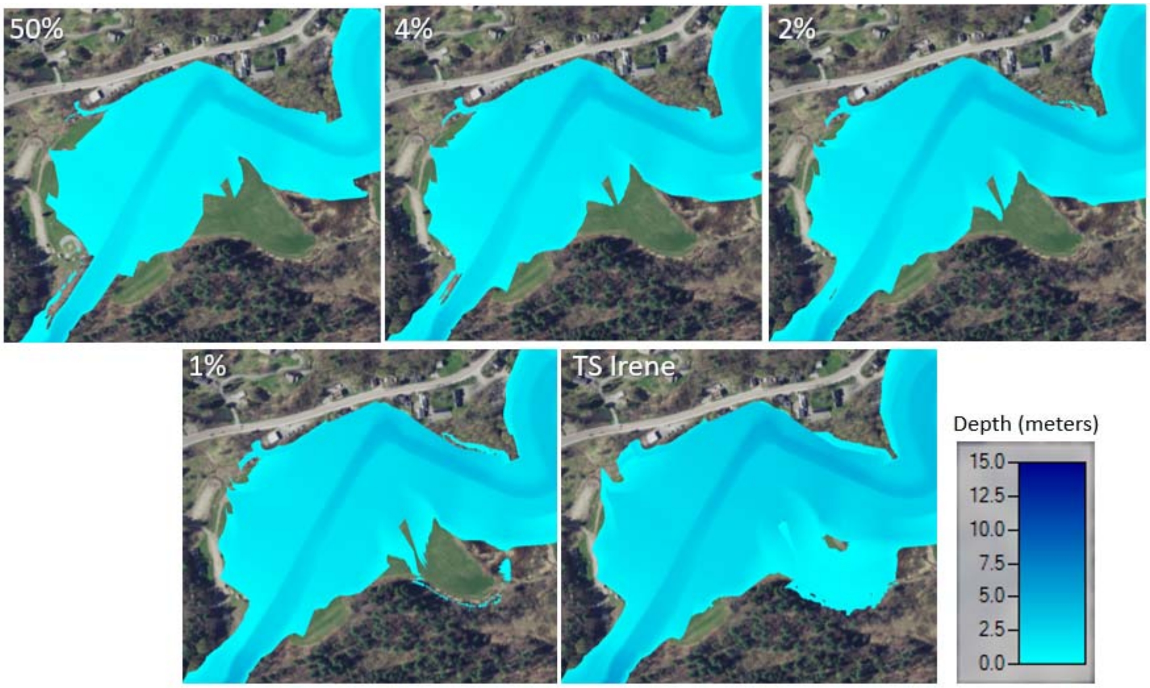


Figure 5.12 Plan view image of 2D HEC-RAS model showing Waitsfield Covered Bridge intervention location under floodplain lowering intervention conditions

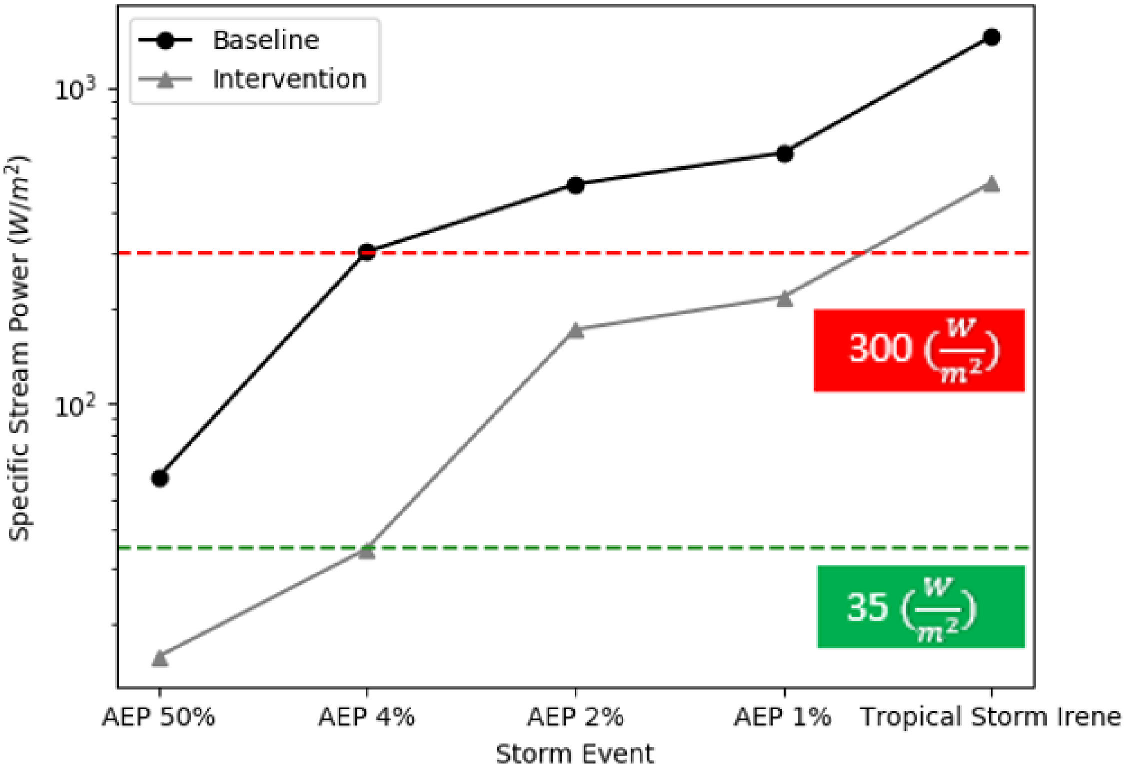


Figure 5.13 Specific Stream Power plot for the Waitsfield Covered Bridge showing baseline values (black), and the floodplain lowering intervention values (grey)

In the 2D HEC-RAS model simulation, the B2 bridge is not overtopped under baseline conditions. Records show severe damage to the bridge due to channel flanking and no direct overtopping from the river channel from Tropical Storm Irene (Anderson et al, 2017a). In vicinity of Pony Hill Road at a point 1,258 m upstream from the B2 bridge, two culverts convey runoff under the road. These culverts are circular, spanning 10.8 m underneath the road, 0.5 m high, and 0.5 m in diameter. The intervention involved maintaining the 10.8 m length, but changing the circular culverts to box culverts, 6 m in width and 1 m in height, to better convey floodwaters (Figure 5.14). Due to the higher elevation on the right side of Pony Hill Farm Rd, the culverts are angled to face upstream to capture flowing water that would move up in elevation and onto the adjacent field (Figure 5.18). Field elevations on the right side of the road are lowered by 2 m and expand out for 10 m.

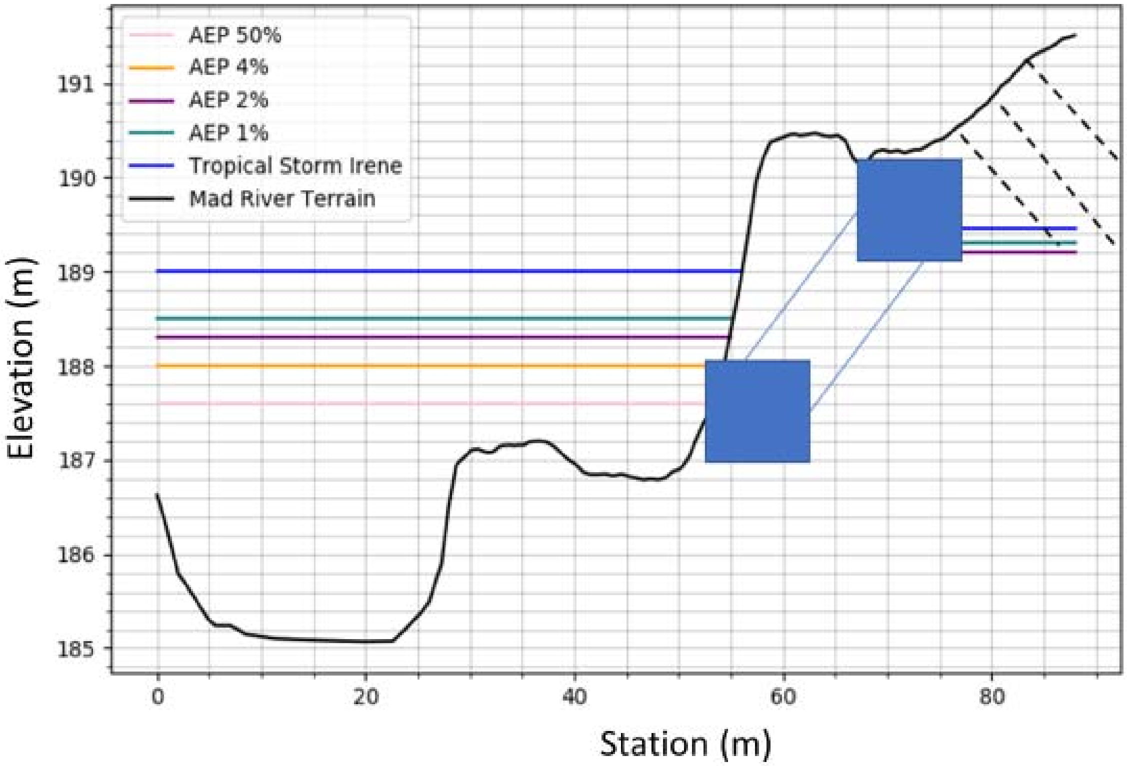


Figure 5.14 Image of Pony Hill Farm Rd culvert intervention (blue boxes) with associated water surface elevations and proposed soil removal (black dashed lines)

The modified culverts show no significant localized change at the B2 bridge. Water surface elevation shows little to no change at the B2 bridge (Figure 5.16). Additionally, specific stream power at the bridge site changes very slightly with only minimal reductions (Figure 5.17). All values remain critical, above the Magilligan's threshold possibly indicating the need for culvert adjustments or additional floodplain adjustments to better mitigate flood impacts on the structure.

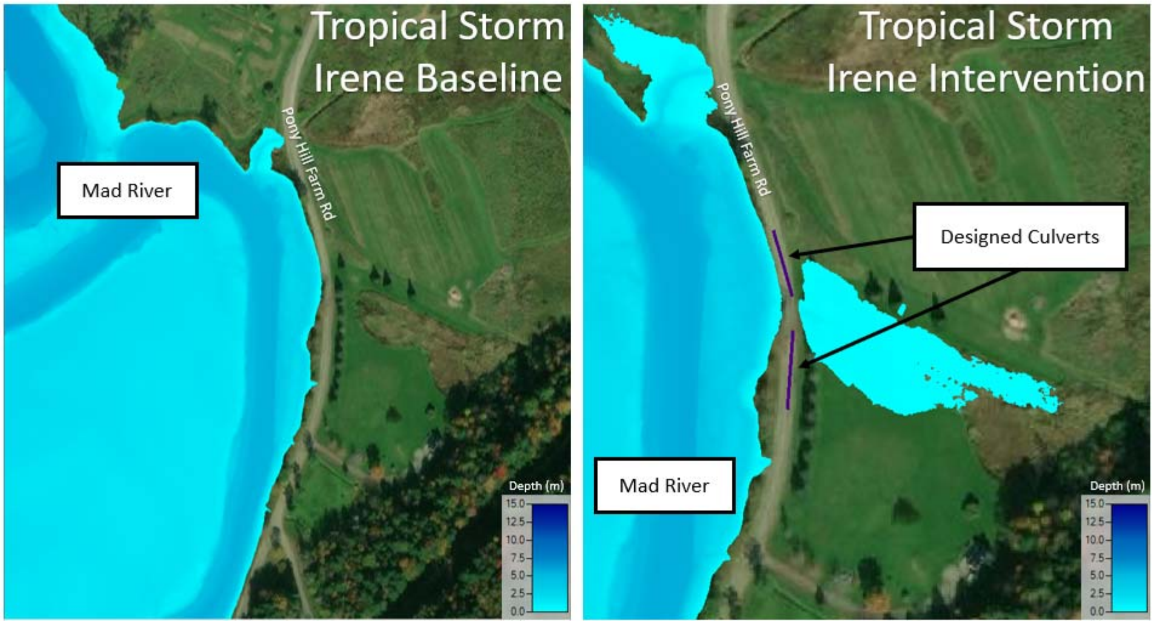


Figure 5.15 Plan view image of 2D HEC-RAS model of Pony Hill Farm Rd upstream of the B2 bridge showing Tropical Storm Irene baseline conditions (left) and Tropical Storm Irene with proposed culvert intervention (right)

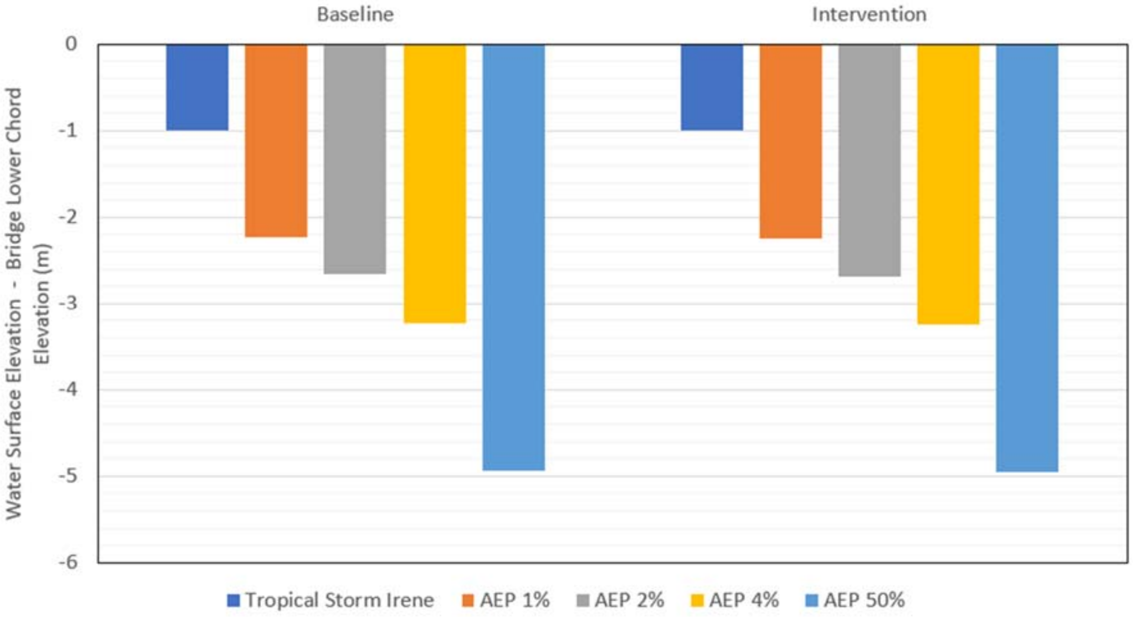


Figure 5.16 Computed water surface elevation minus the lower chord elevation of the B2 bridge: baseline conditions (left) and intervention conditions (right)

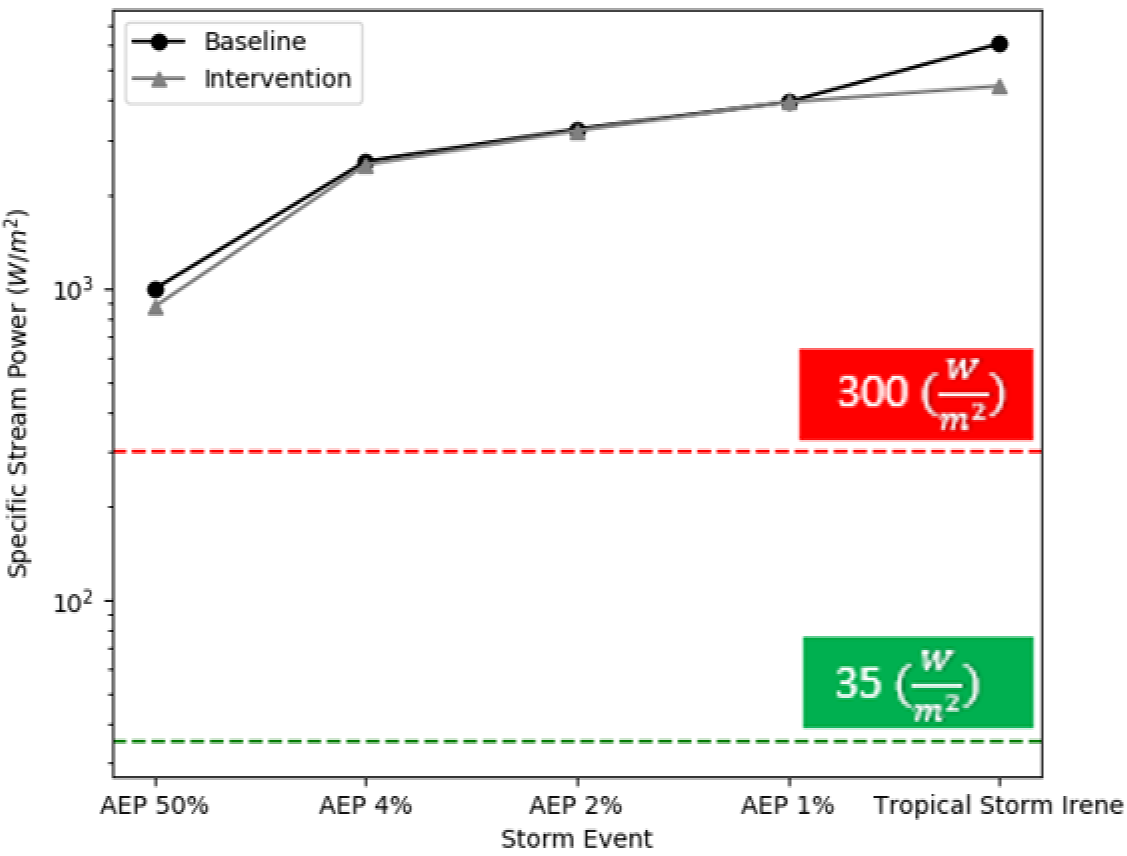


Figure 5.17 Specific stream power plot for each flood event comparing baseline conditions (black) to intervention conditions (grey) at the B2 bridge

5.3.3 Intervention Impact to the Entire River Section

The intervention at the Main St. Bridge in Warren initially showed a reduction in specific stream power at the bridge location but very little change in water surface elevation. These values are also calculated at each bridge location up- and downstream of the intervention. From Figure 5.19, specific stream power is reduced at every bridge location except for the Butternut Hill Bridge (Plot 6). Specific stream power is significantly reduced to either stable or almost stable conditions upstream of the intervention location at B167 and further downstream at B177 and B7. Twelve out of the 16 bridges have at least one simulated flood reduced to below 35 W/m^2 or had at least one simulated flood drop below the Magilligan's threshold. The impacted bridges have gradient classifications ranging from low to high. However, bridges within the immediate vicinity of the intervention location have minimal reductions in specific stream power.

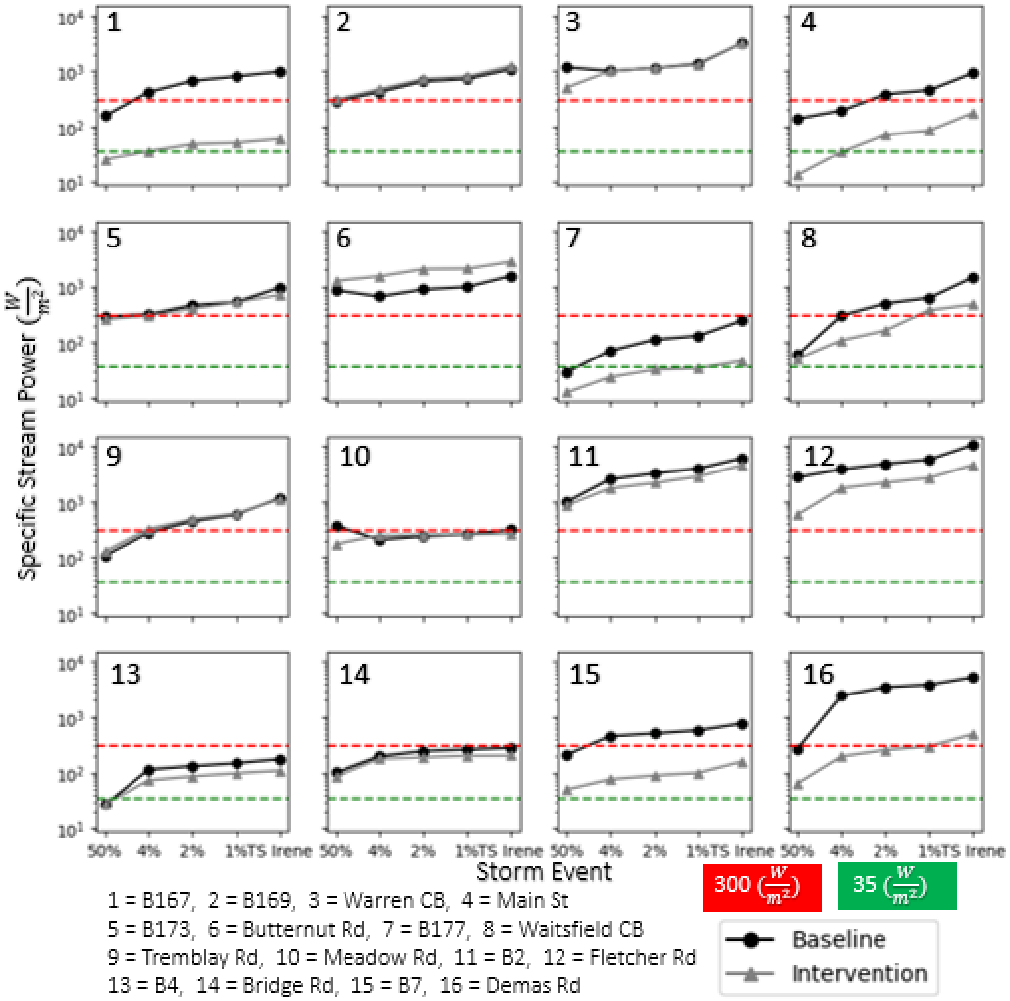


Figure 5.18 Specific stream power values at each bridge location in the Mad River study section comparing baseline results to the Main St. Warren intervention results

Water surface elevations simulated at each bridge location within the Mad River study section are summarized in Figure 5.19. The intervention reduced all peak water surface elevations for the modeled floods. Bridges that overtopped during baseline conditions are no longer overtopped with the intervention in place (Figure 5.19).

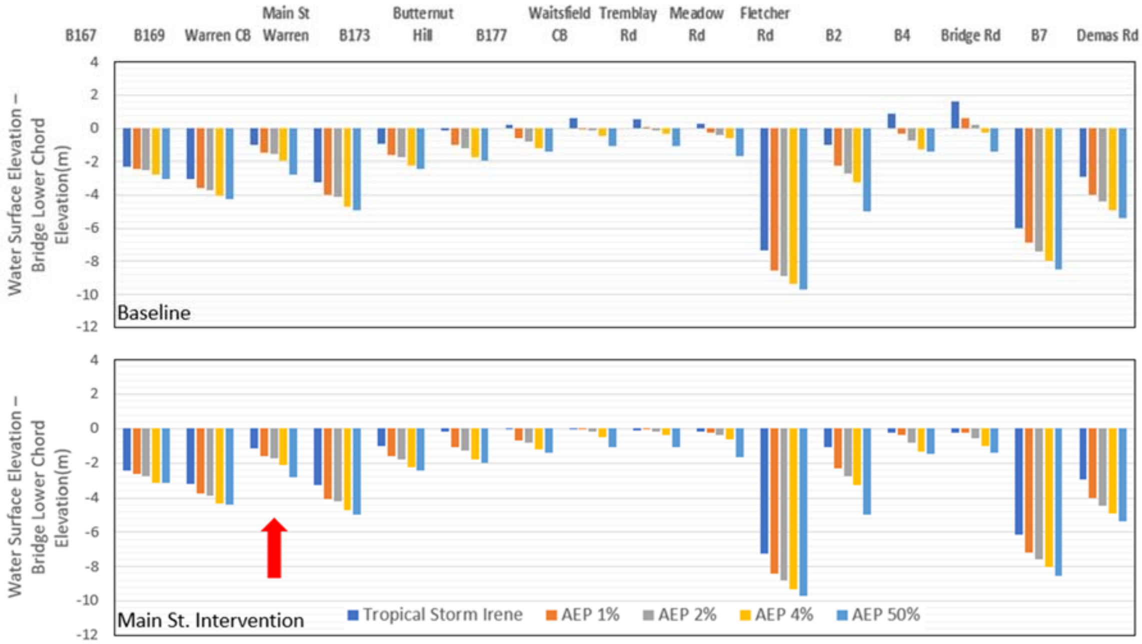


Figure 5.19 Computed water surface elevation minus the lower chord elevation of bridges for all flood events considered in the Mad River study section: Main St. Warren floodplain lowering intervention conditions (bottom) and baseline conditions (top); bridges ordered from upstream (left) to downstream (right); the arrow in the bottom panel indicates location of floodplain lowering intervention

Results are also examined at the Waitsfield Covered Bridge study area. A significant drop in water surface elevation and specific stream power are seen at the single bridge location, but is also reviewed for all bridge locations in the river (Figure 5.20). Fifteen out of 16 bridge locations have a decrease or no change in specific stream power (Figure 5.20). Specific stream power at B173 bridge increased only slightly. Specific stream power at B177 bridge decreased and dropped below the 35 W/m^2 threshold. Similarly, the B7 bridge had a flattened curve that dropped all simulated flood events below Magilligan's threshold, but still remain unstable. Overall these results have cascading effects up and downstream from the intervention location. The most noticeable impacts take place at bridge locations with moderate or low gradients and located downstream of the intervention.

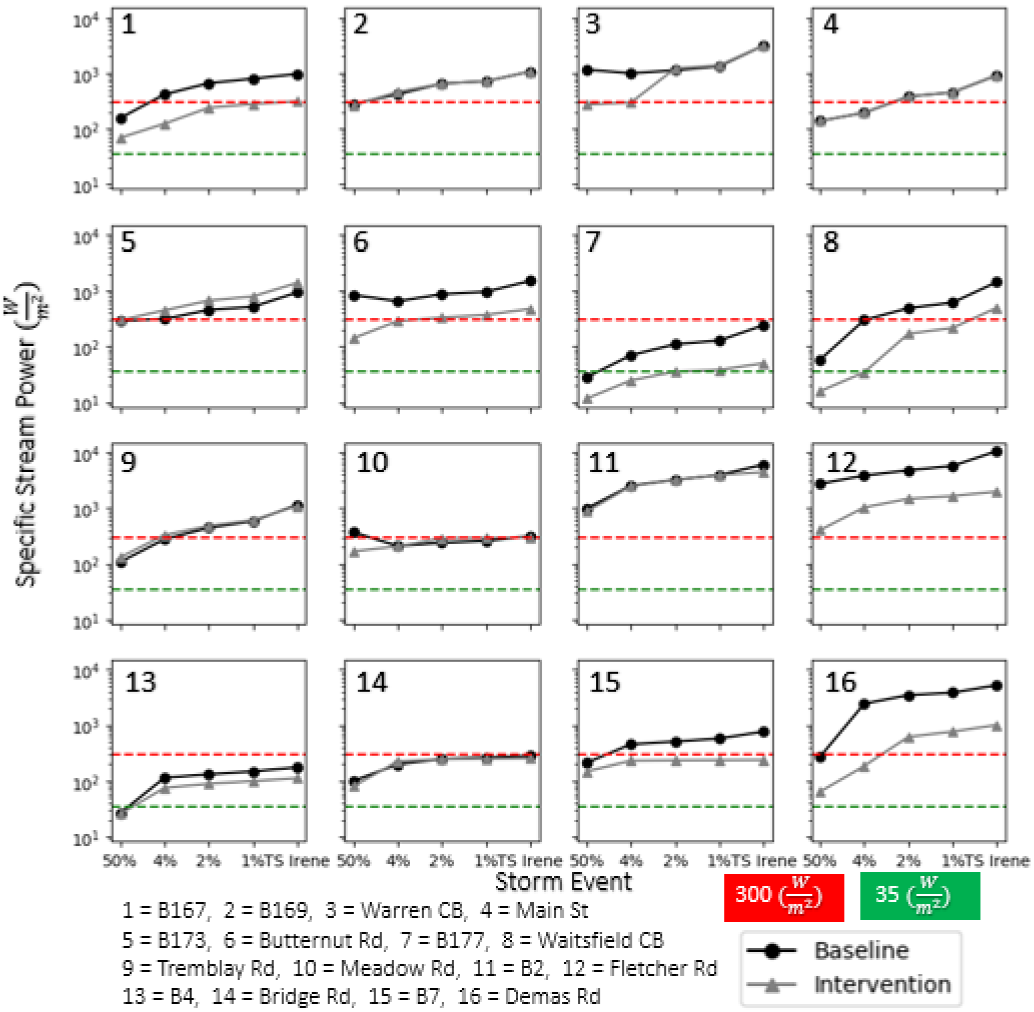


Figure 5.20 Specific stream power values at every bridge location in the Mad River study area comparing baseline results to the Waitsfield Covered Bridge floodplain lowering intervention results.

Under intervention conditions, the Waitsfield Covered Bridge has a reduction in water surface elevation. This reduction can reduce the potential for overtopped conditions during flood events. These values are also calculated for each bridge along the river study section. Under the intervention conditions all bridges have reduced water surface elevation. Previously overtopped bridges in the baseline conditions are no longer overtopped (Figure 5.21).

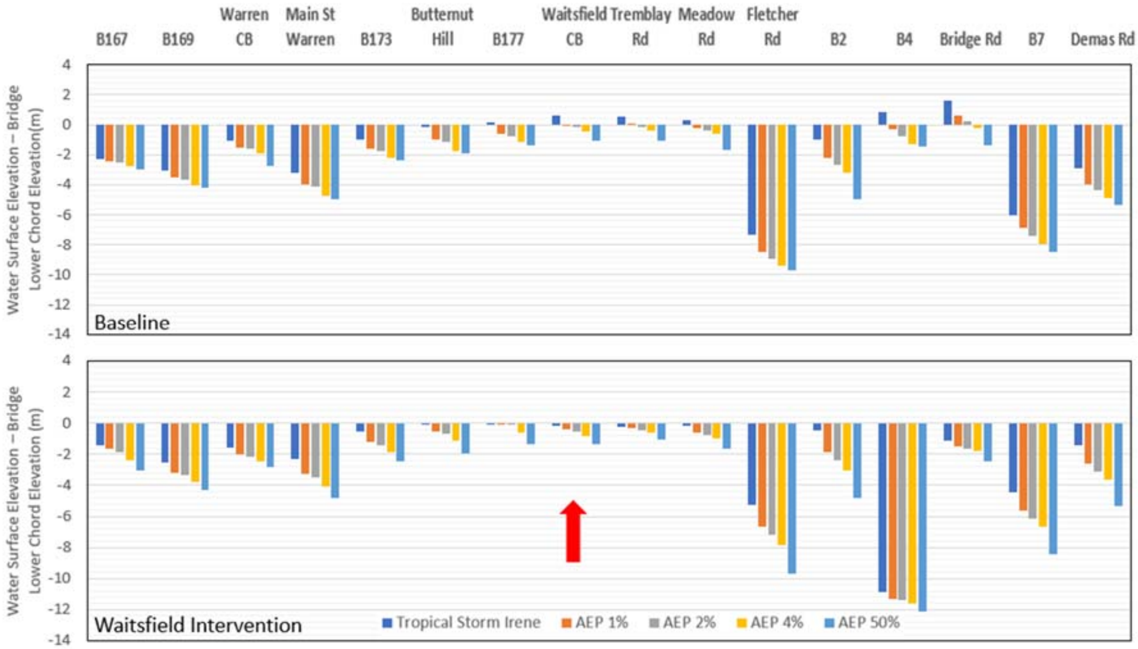


Figure 5.21 Computed water surface elevation minus the lower chord elevation of bridges for all flood events considered in the Mad River study section: Waitsfield Covered Bridge floodplain lowering intervention conditions (bottom) and baseline conditions (top); bridges ordered from upstream (left) to downstream (right); the arrow in the bottom panel indicates location of floodplain lowering intervention.

The river reach-length impacts from the modified culverts at Pony Hill Rd are also modeled. These results show little changes to bridges located directly up and downstream of the intervention. However, specific stream power is reduced at the following bridges: B167, B4, B7, and Demas Rd (Figure 5.22). The B167 and B7 bridge have specific stream power values that fall below the Magilligan's threshold, but not below the 35 W/m^2 threshold, showing that the designed intervention can have far reaching impacts up- and downstream of initial site. The impacted bridges have gradient classifications ranging from low to high, and are found up and downstream the river.

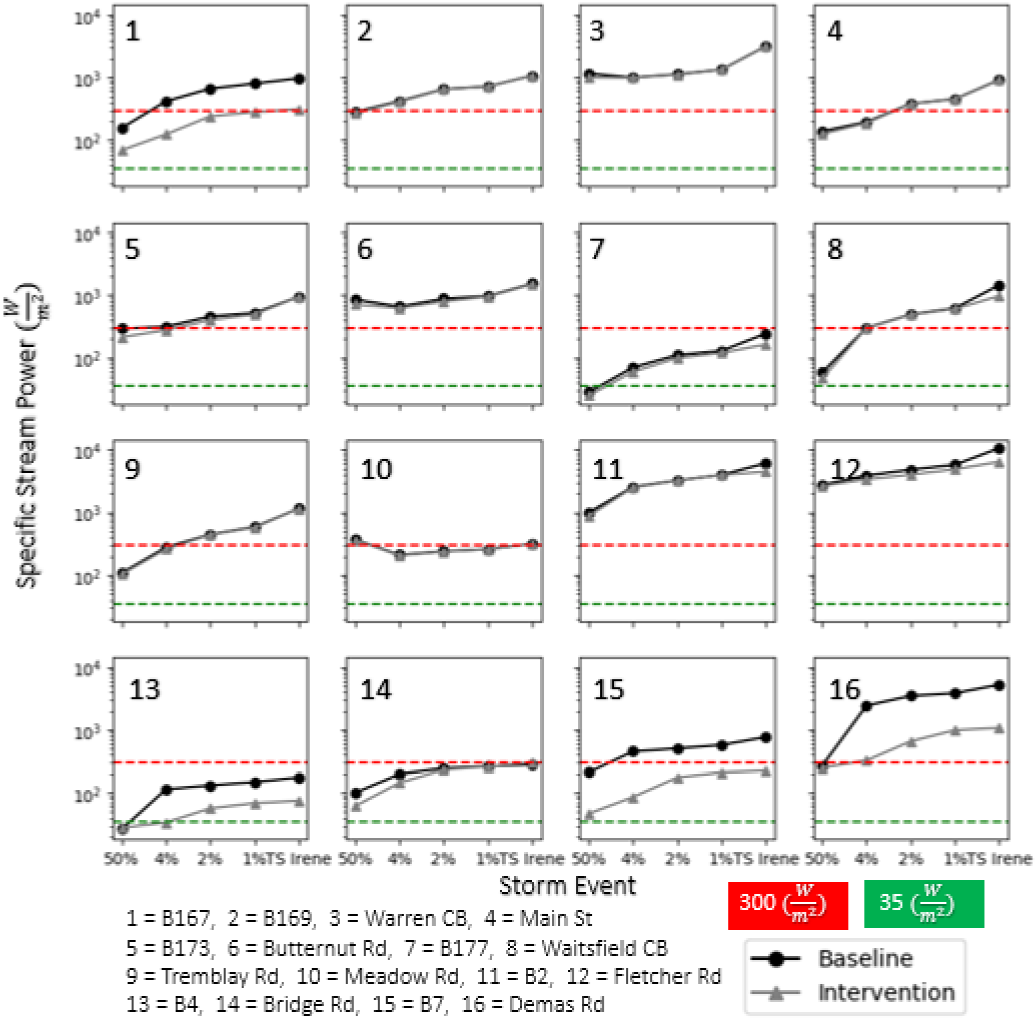


Figure 5.22 Specific stream power plots for each bridge location in the Mad River comparing baseline conditions (black) to culvert modification conditions (grey)

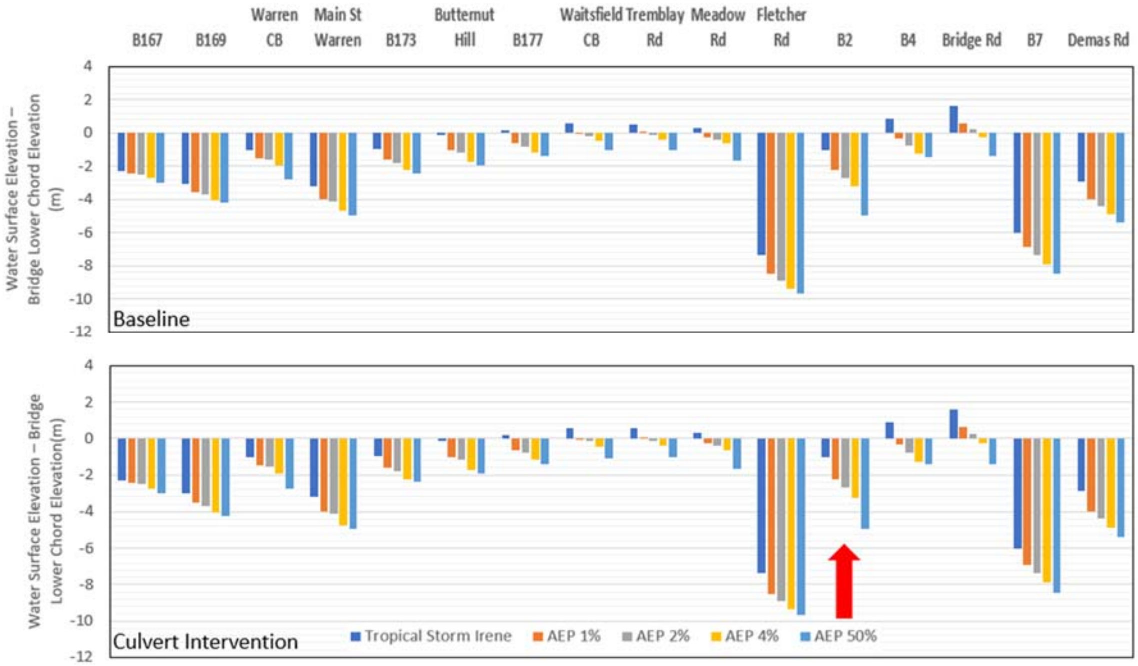


Figure 5.23 Computed water surface elevation minus the lower chord elevation of bridges for all flood events considered in the Mad River study section: culvert intervention (bottom) and baseline conditions (top); bridges ordered from upstream (left) to downstream (right); the arrow in the bottom panel indicates location of floodplain lowering intervention.

Water surface elevation compared to the bridge's lower chord elevation is also compared (Figure 5.23). Intervention values remained similar to baseline conditions. Some bridge locations have minor reductions in water surface elevation. Bridges that overtopped under baseline conditions remain overtopped during intervention conditions.

5.4 Summary

A screening framework is developed using geomorphic and hydraulic characteristics to evaluate bridges and determine locations for flood mitigation interventions to potentially reduce flood damage at bridge locations in a river. The framework is constructed based on indicators used in previous studies such as specific stream power and channel slope and combines these to better indicate bridges within a river that would be best suited for floodplain intervention. Bridges are categorized based on the potential level of structure and reach impact, should an intervention take place.

The screening framework is applied to each study section and a summary table is constructed showing NAH channel gradient classification, specific stream power values that correspond to given flood events, and the presence of bedrock at each bridge within the river study section. Based on this information, each flood event is categorized and assigned a color representative of one of the framework outputs: green for *Maximum* impact, yellow for *Variable* impact, and red for either *Not Applicable* due to bedrock or *Minimal* impact due to assumed stable conditions.

Three locations are selected in the Mad River study section to model flood mitigation interventions based on the evaluation framework results. The Main St. bridge models a floodplain lowering intervention and is categorized as a good location for intervention. The Waitsfield Covered Bridge models a floodplain lowering intervention including berm removal and is categorized as a potentially good place (*Maximum* impact) for intervention. Finally, the B2 bridge models a culvert modification intervention and is categorized as a location that is not likely needed (*Not*) for intervention, due to the presence of bedrock at the bridge location. By selecting different framework categorization locations, impacts can be evaluated and compared at the bridge and river section level within the Mad River.

The results from each individual intervention show cascading effects up- and downstream of the project location. The floodplain lowering interventions had the largest impact at individual bridge locations, thereby lowering the specific stream power and stabilizing some locations under certain flood events. The culvert modification intervention had minimal impact (little change in surface water elevations) on bridges, but did lower specific stream power at various downstream bridge locations. Water surface elevation was reduced at all bridge locations under the Main St. and Waitsfield Covered Bridge intervention conditions. Bridges that were overtopped during baseline conditions are no longer overtopped under intervention conditions.

Overall, these results show that interventions in higher gradient sections of the river will have a greater impact on structures throughout a river with varying gradients. While these impacts might not occur in the immediate vicinity of the intervention itself, the cascading changes in water elevations, velocity, floodplain inundation can occur and are often more prevalent further up- or downstream dependent on changes in stream gradient throughout the river. In general, interventions in lower gradient sections of the river will not impact structures located in higher gradient sections. Additionally, interventions modeled in the Mad River study section, which has an overall moderate gradient, will have less intuitive impacts across structures throughout the river.

Chapter 6: Intervention Comparison across Multiple Rivers

This chapter discusses the relationship between specific stream power and change in channel slope across rivers of different gradients, and how this relationship affects flows observed at bridge locations in multiple rivers. Other Northeast river reaches with similar climatic and geographic conditions are further explored using an evaluation framework to better protect the longevity of transportation infrastructure.

6.1 Mad River Intervention Discussion

The three interventions modeled in the Mad River study section show impacts to the river section up- and downstream of each intervention project location. The two floodplain-lowering simulations at Main St. Bridge in Warren and up-stream of the Waitsfield Covered Bridge have the largest impacts on the river. The culvert intervention upstream of the B2 bridge has minimal localized impacts and shows little impact to the river as a whole.

It was previously reported that the Waitsfield Covered Bridge floodplain lowering intervention helped reduce specific stream power across the majority of bridges within the Mad River (Figure 5.22). Compared to baseline conditions during Tropical Storm Irene, specific stream power is reduced under intervention conditions in the Mad River (Figure 6.1). However, specific stream power begins to rise moving upstream as slopes move from low to moderate (green) to moderate to high (yellow). Downstream of the project location specific stream power values begin to rise just before the gradient classification change at 27,000 m (Figure 6.1). This suggests that river impacts from the intervention are greatest within sections of similar gradients, and that intervention impacts might reduce once reach sections change classification. Significant reductions in specific stream power at the individual bridge scale are seen at B167, B177, the Waitsfield Covered Bridge and the Demas Rd Bridge (Figure 5.23). These bridges are located throughout the river including upstream in Warren and all the way downstream just before the Winooski River. This shows that a significant reduction in hydraulic characteristics can be seen up and downstream of an intervention project site. Additionally, all bridges have a gradient classification of either low to moderate or moderate to high. This suggests that reduction in flood effects will have a greater impact on structures with low or moderate gradients.

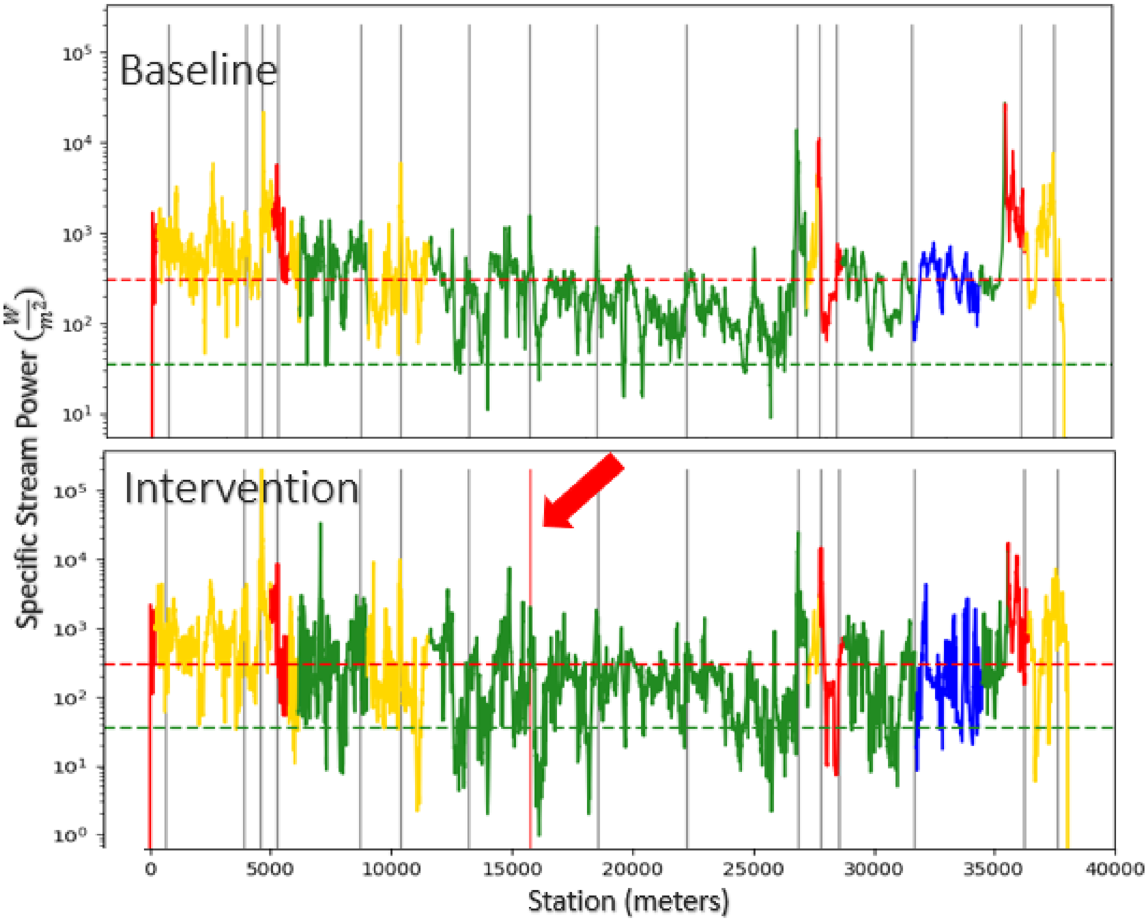


Figure 6.1 Specific stream power values starting upstream (0 m) going downstream (40,000 m) for baseline conditions (top panel) and intervention conditions (bottom panel) during Tropical Storm Irene for the Waitsfield Covered Bridge intervention (red arrow).

The Waitsfield Covered bridge project location has a gradient of 0.31% and is classified as low to moderate. This area also has increased access to floodplains compared to the Main St. intervention location; however, this accessibility is dramatically reduced due to berms and channel incision. Channel incision and entrenchment can result in a bottleneck effect, where flow is forced through a narrow channel. This results in increased water surface elevation and specific stream power seen previously (e.g., Figure 5.24). When the berms are removed and the floodplain is lowered these values drop allowing water to flow freely without the upstream bottle-neck effect. For example, under the Waitsfield Covered bridge intervention, inundation depths and specific stream power are reduced at upstream Bridge 177 (Figure 6.2). This reduction is largely due to the relatively small change in gradient between bridge locations. If channel gradients were to increase before the B177 bridge, it is reasonable to assume that changes to the inundation and specific stream power would be smaller in magnitude, similar to the conditions seen at the Butternut Hill Rd. At this bridge, specific stream power is reduced, but did not drop below 35 W/m^2 and this difference can most likely be attributed to the change in gradient. The gradient at this bridge increases to moderate to high from low to moderate. The bridge is also located further upstream, however previous interventions show that significant impacts can be made to structures further upstream from the initial project location but are highly dependent on gradient.

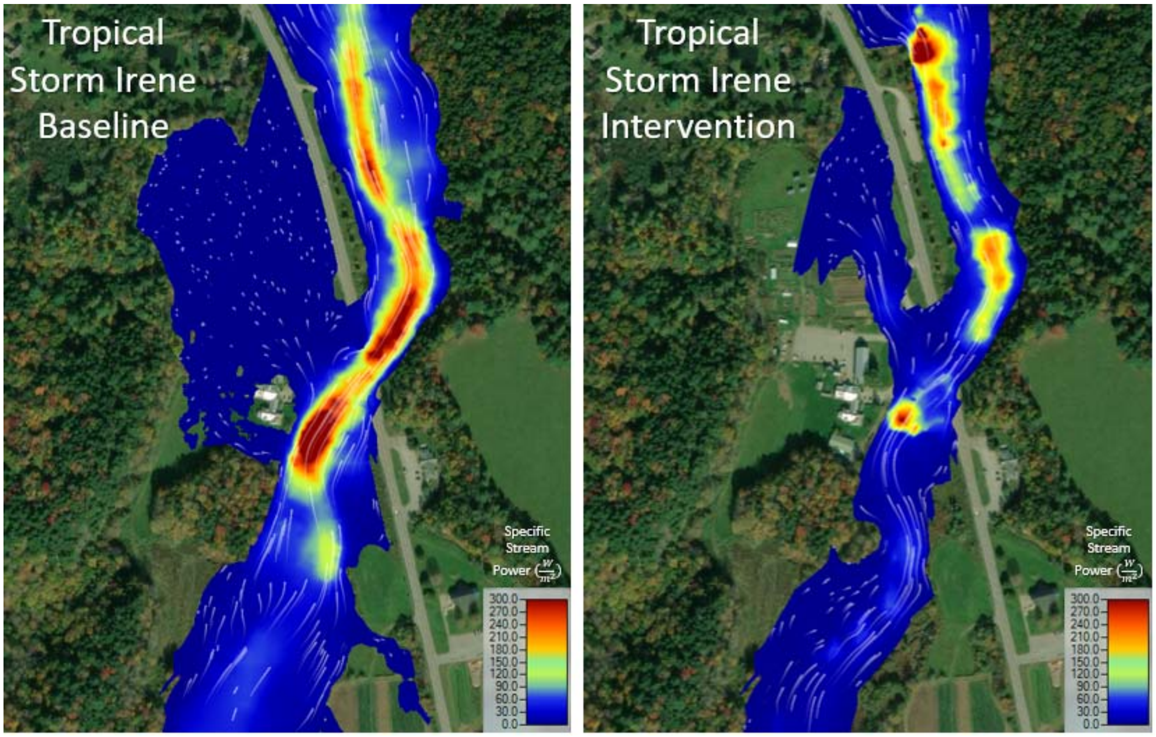


Figure 6.2 Plan view image of 2D HEC-RAS model of the B177 bridge on the Mad River showing specific stream power during baseline conditions (left) and during the Waitsfield Covered Bridge intervention conditions (right)

There is little change in specific stream power values downstream until the Demas Rd Bridge. However, there is a significant reduction in water surface elevation at each bridge location (Figure 5.23). When these values are compared to gradient, the largest water surface elevation reduction is seen at bridge locations with a classification of *moderate to high* or lower (Figure 5.23). Bridge locations with gradient classifications of *high* have water surface elevation reduction but not as significant. One noticeable example is the B4 bridge. This bridge has a gradient classification of *low-moderate*. In baseline conditions the bridge is overtopped in the Tropical Storm Irene simulation and the remaining simulations have water surface elevations with less than 2 m of freeboard. The Waitsfield Covered Bridge is no longer overtopped under intervention conditions for any flood simulation and has minimum freeboard distance of 7 m (Figure 5.23). Bridges with high gradient classifications, such as the B2 bridge, have a reduction of water surface elevation, but not as significant. These results further suggest that flood mitigation interventions do impact bridges up- and downstream the river, but will have a varying effect that is largely dependent on reach gradient.

The Main St. flood mitigation intervention has slightly different results than the Waitsfield Covered Bridge intervention. This intervention involved lowering the floodplain in the headwaters, where floodplains are relatively small or not developed. The project location has a gradient classification of *high* and has high specific stream power. When this intervention is modeled, effects cascade up- and downstream of the intervention location, with the most noticeable impacts at bridges B167, B177, B7 and the Demas Rd Bridge (Figure 5.21). These bridges have gradient classifications ranging from *low to moderate*, *moderate to high*, and *high*. The range of gradient classifications is different than the Waitsfield Covered Bridge intervention as this one includes bridges with high gradients.

When the 2011 Tropical Storm Irene is modeled across the entire study area, the resulting specific stream power is reduced throughout the majority of the river under the Main St. floodplain lowering intervention (Figure 6.3); areas classified as high gradient have noticeable lower specific stream power compared to the baseline conditions. When specific stream power values for the Main St. Bridge intervention are compared to the Waitsfield Covered Bridge intervention the results are almost identical (Figures 6.1 and 6.3). This suggests that on a river section scale there is little difference between an intervention that takes place in a high gradient reach versus an intervention that takes place in a low to moderate gradient reach. However, when specific stream power is observed at individual bridge locations the Main St. intervention location shows greater impact on more individual bridges and a greater range of gradient classifications (Figure 5.21). This further supports the notion that flood mitigation interventions done in the headwaters might impact bridge-river interactions on a greater scale.

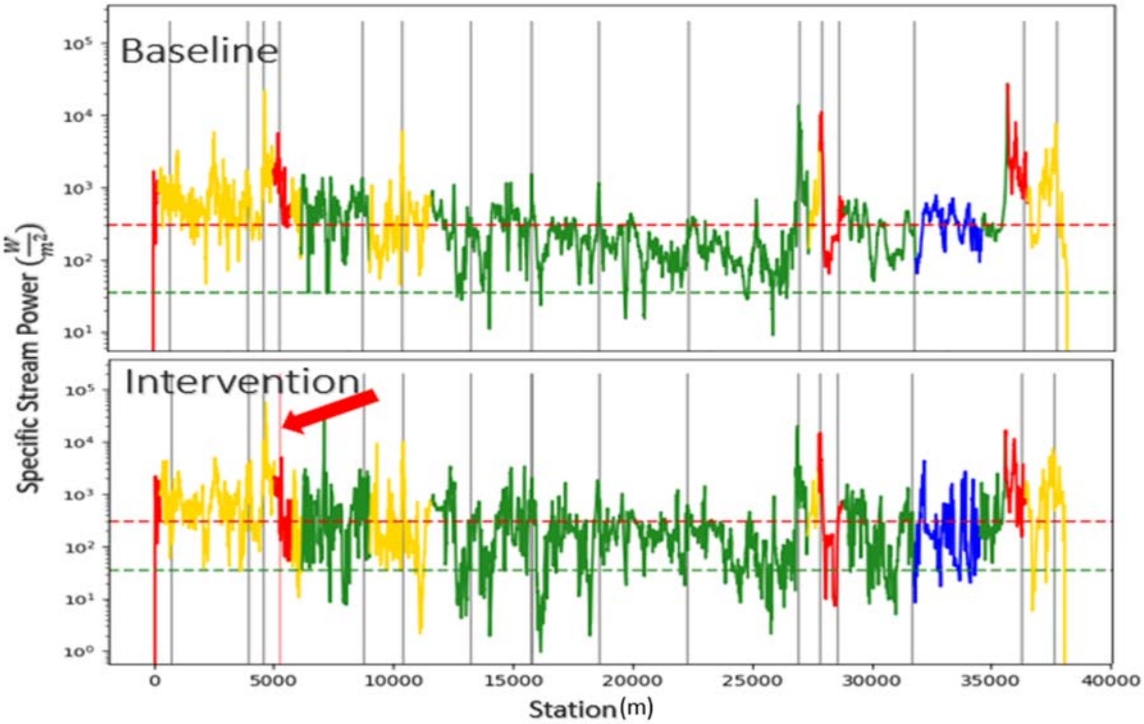


Figure 6.3 Computed specific stream power values starting upstream (0 m) going downstream (40,000 m) for the baseline conditions (top) and the Main St. Bridge (red arrow) intervention conditions (bottom) during the 2011 Tropical Storm Irene

Water surface elevation reduction at each bridge location under the Main St. Bridge intervention is not as significant as the Warren Covered Bridge intervention (Figure 5.21). Even though all bridges saw similar results, and no bridges were overtopped during either intervention across all flood event simulations, the Waitsfield Covered Bridge intervention had a significantly greater impact, most likely explained by the greater size of the intervention. The Waitsfield Covered Bridge intervention encompassed a larger area and extended further into the floodplain.

However, it had a smaller impact on specific stream power, which governs the overall stability of the channel. Because the Main St. intervention saw a greater decrease in specific stream power across a wider range of gradients and mitigated overtopping of the bridges for all storm event scenarios, we conclude this intervention has a larger impact on the river compared to the Waitsfield Covered Bridge intervention.

The culvert modification was also performed in a location with *high* gradient classification, but yielded very different results compared to the two previous interventions. Overall, this intervention saw little to no change in water surface elevation and bridges still remained overtopped during all flood simulations (Figure 5.26). When specific stream power for Tropical Storm Irene is plotted and examined across the entire river reach, values show a similar pattern to the previous interventions, where specific stream power seems to have reduced (Figure 6.4). However, at individual bridge locations specific stream power remains constant except for reductions seen at B167, B4, Bridge Rd, B7 and Demas Rd (Figure 5.25). These bridges have gradient classifications that range from *low* to *high*. These reductions in specific stream power are not as significant as the previous interventions; no bridges have specific stream power values that drop below the 35 W/m^2 threshold in this intervention.

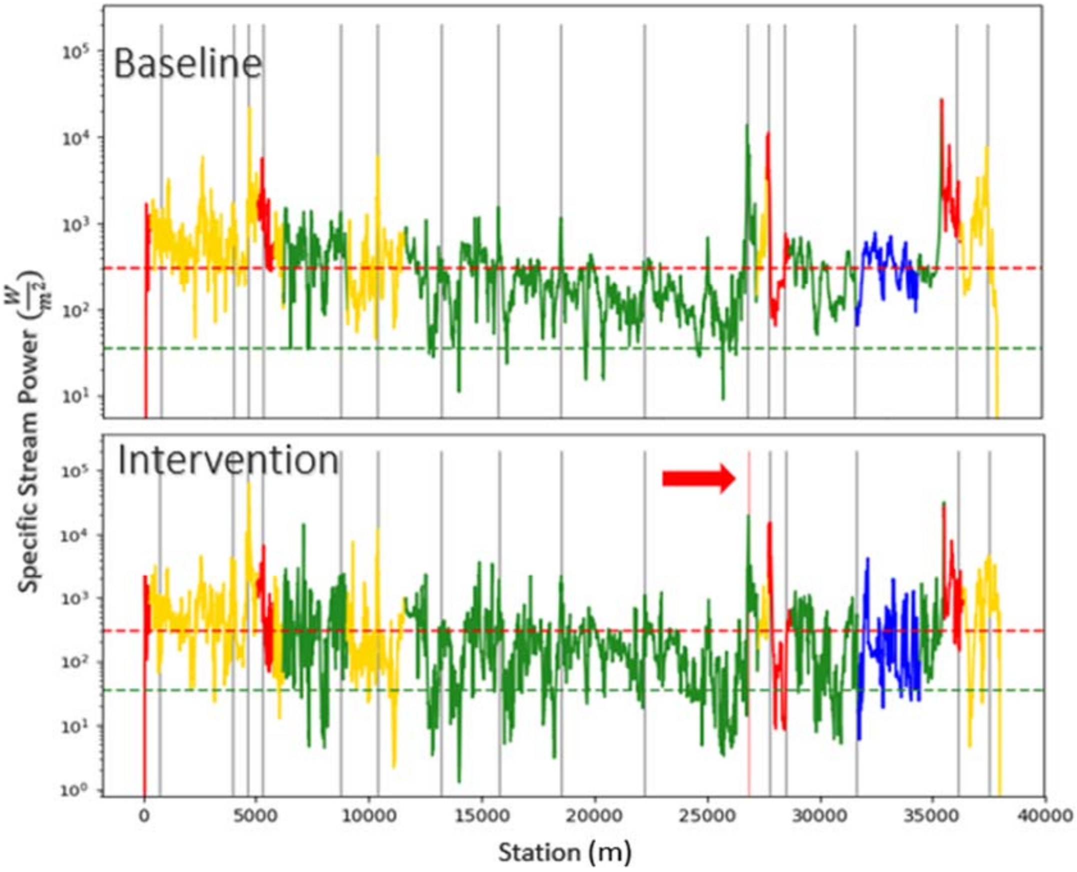


Figure 6.4 Computed specific stream power values starting upstream (0 m) going downstream (40,000 m) for baseline conditions (top) and the culvert modification (red arrow) intervention conditions (bottom) during the 2011 Tropical Storm Irene

Additionally, this intervention shares similarities with the Main St. intervention. Both interventions had direct impact on river reaches classified as high gradients, while the Waitsfield Covered Bridge intervention only impacts bridges up to a *moderate to high* gradient classification. This supports the notion that flood mitigation interventions will have a greater impact on the entire river if implemented in high gradient reaches. However, the results also show that the overall impact at each bridge location is gradient dependent. Due to the constant change of gradient classification throughout the river hydraulic impact reduction at bridge locations are not consistent throughout the river or between interventions.

6.2 Bridge-River Network Comparison Across Study Sections

The Otter Creek and Black Creek study sections have greater consistency in channel gradient compared to the Mad River study section. There are fewer channel gradient classifications, and they change less frequently than the Mad River. These two river study sections also have a significantly lower elevation difference. The Otter and Black Creek's topographic relief is 8 m (Figure 5.4) and 6 m (Figure 5.3), respectively. The Mad River reach has elevations that span almost 200 m (Figure 5.5). The corresponding elevation consistency or inconsistency can impact the hydraulic conditions within the river. This consistency or inconsistency is further reflected in specific stream power values at bridges within each study reach.

The Black Creek study section has specific stream power values that all fall below the Magilligan's threshold (Figure 6.5). The Bruso Rd. Bridge is the only one to have all simulated flood events values below the 35 W/m^2 threshold, and the Elm Brook Rd. Bridge have additional values below this threshold for every flood event except for the AEP of 1% which is slightly above the threshold. The water surface elevations are also very low compared to the bridge deck, with only one bridge overtopped during the AEP 0.2% flood event (Figure 6.6). These results are very different from the Mad River study section and show more intuitive interactions between reach sections.

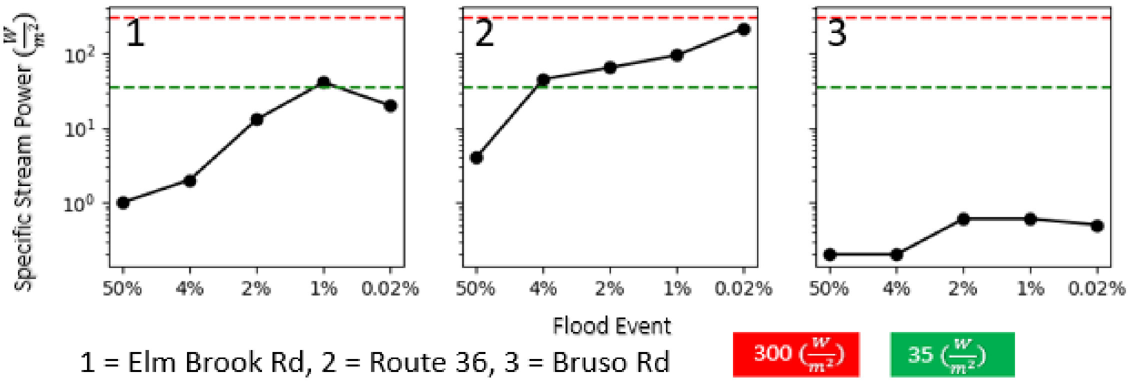


Figure 6.5 Channel Specific stream power values at bridges within the Black Creek study area

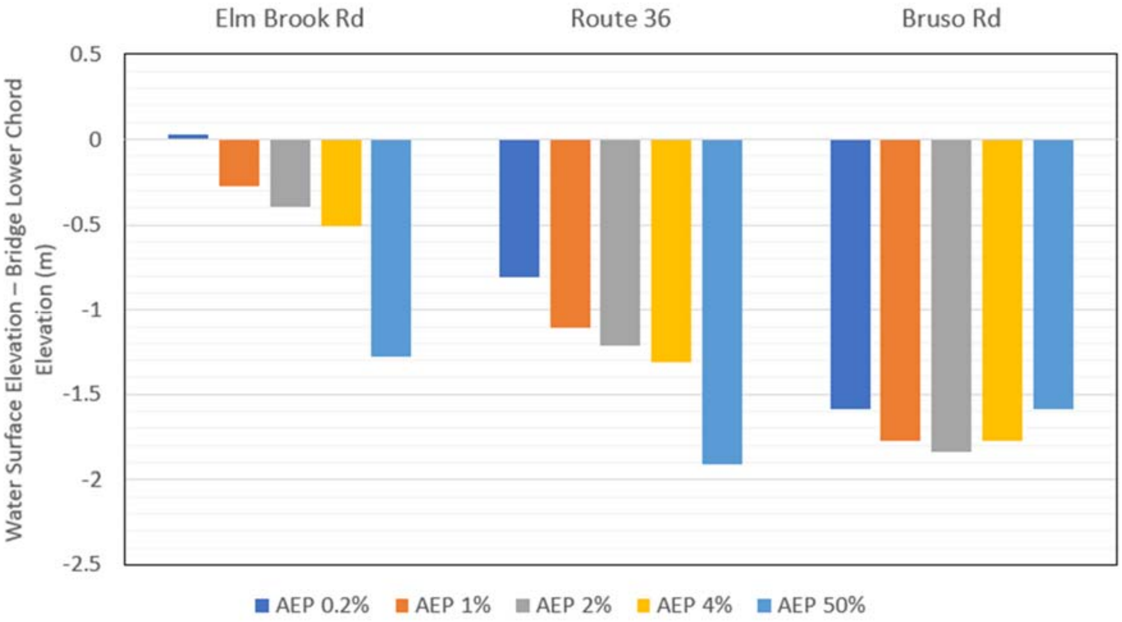


Figure 6.6 Computed water surface elevation of simulated flood events compared to lower chord deck elevation of bridges in the Black Creek study section.

The Black Creek study reach has only three gradient sections starting from *low* to *moderate* dropping to a *low* classification and finally a *very low* gradient classification (Figure 5.5). This gradual decrease in stream gradient contrasts with the Mad River which has varying slope decrease and increase throughout the study area (Figure 5.3). The consistency of minimal hydraulic impacts seen in the Black Creek can largely be attributed to overall *low* gradient and ample channel connection to a wide floodplain (i.e., the channel is not incised or entrenched). An intervention is additionally modeled to further observe the consistency of hydraulic impact on the Black Creek. The Black Creek's Route 36 Bridge was the only bridge to be categorized as having a *Maximum* impact should an intervention take place, due to the high specific stream power values and gradient changes similar to what can be seen in some locations in the Mad River. The intervention modeled at the Route 36 Bridge is a bridge span increase by expanding the cross sections at the bridge location by 20 m to simulate the bridge abutments being pushed back (Figure 6.7). Only the AEP of 0.2% was modeled.

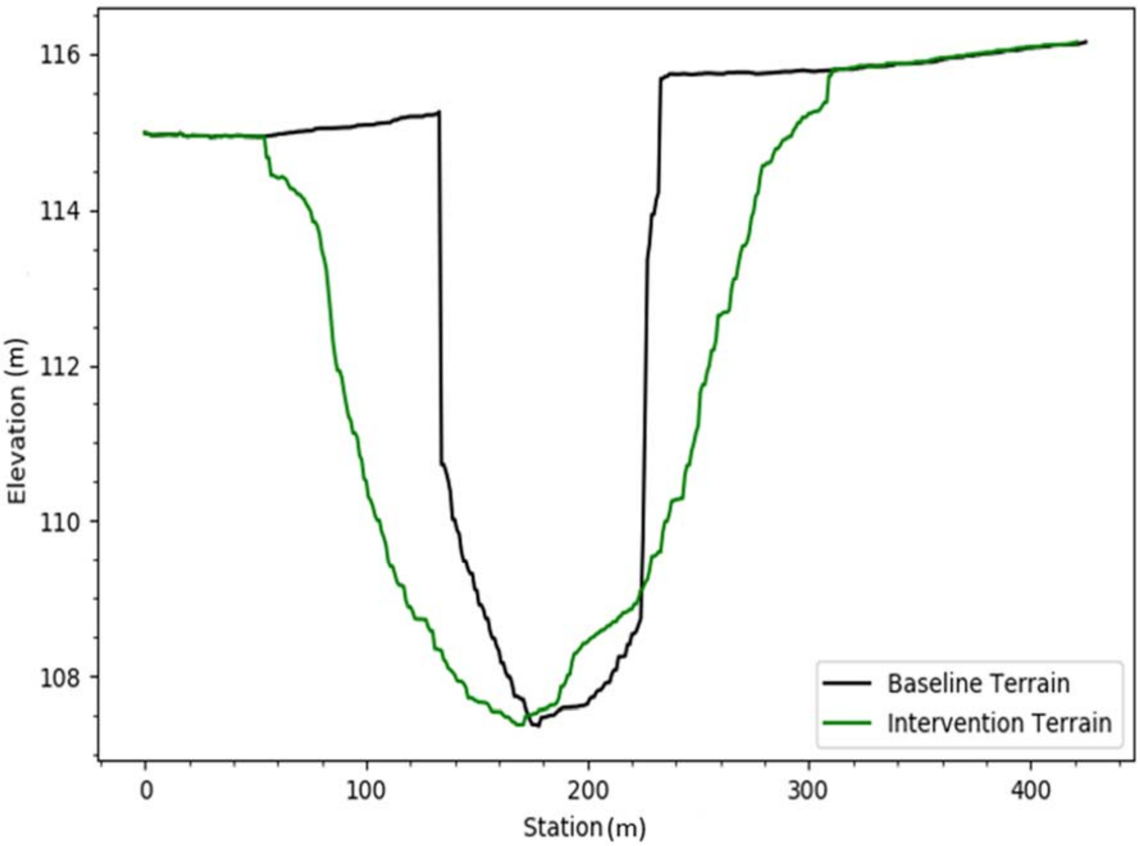


Figure 6.7 Route 36 Bridge cross section showing baseline terrain (black) and bridge span expansion intervention (green)

The model showed a significant reduction of specific stream power at the bridge location. The baseline conditions originally has specific stream power values of 220 W/m^2, but the intervention results in specific stream power values of 56 W/m^2 (Figure 6.8). This is similar to the Main St. intervention and Waitsfield Covered Bridge intervention on the Mad River because all of the interventions had significant impacts at the bridge locations and reduced specific stream power.

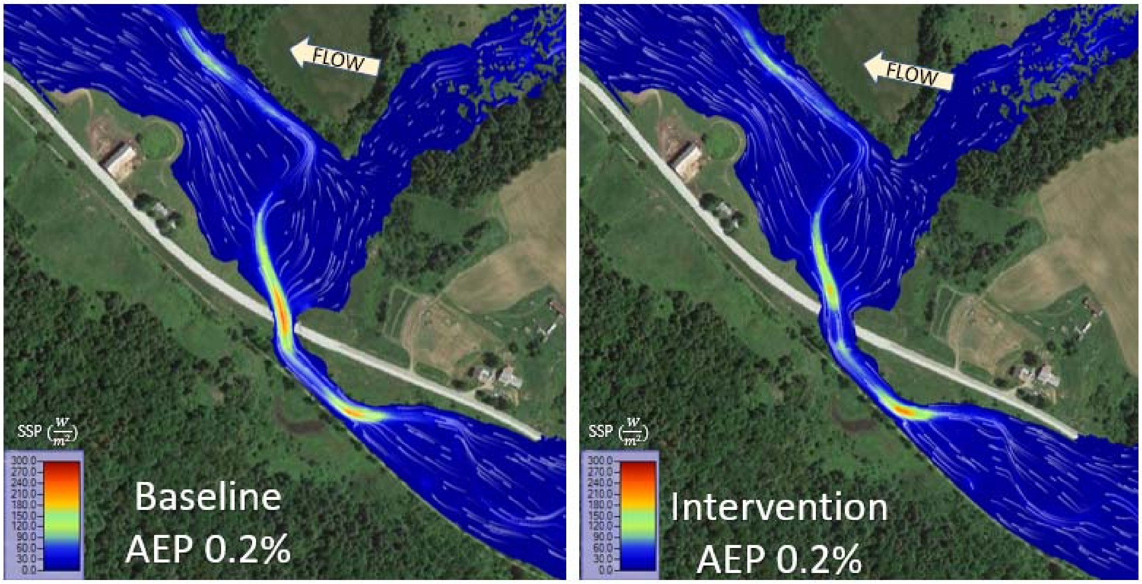
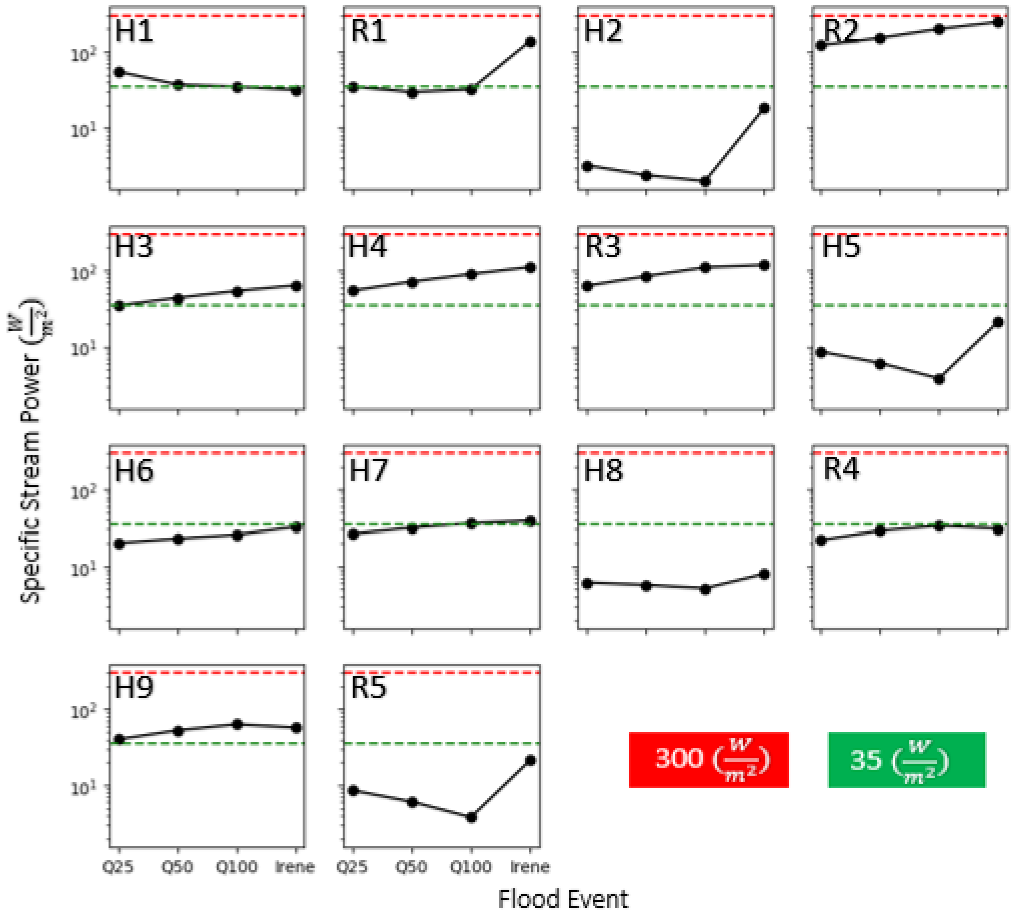


Figure 6.8 Plan view image of the Black Creek study section 2D HEC-RAS model of the Route 36 during an AEP 0f 0.2%: baseline conditions (left panel); bridge span expansion intervention conditions (right panel)

Another similarity, is the intervention on the Black Creek had cascading impacts up- and downstream of the project location. The Bruso Rd Bridge located downstream of the modeled intervention location had minimal reduction of specific stream power, which changed from 6 W/m^2 to 1 W/m^2. However, the Elm Brook Rd bridge located upstream had specific stream power values change from 127 W/m^2 to 10 W/m^2. At this location, which is known to have bedrock presence, the specific stream power values changed from unstable to dropping below the 35 W/m^2 threshold.

This is quite an intuitive response to a significant-sized intervention such as a bridge span increase by 20 m on either side. This is very similar to the Mad River which also saw sizeable decreases in specific stream power under the Waitsfield Covered Bridge intervention and the Main St. Bridge intervention. However, the Black Creek has more intuitive bridge-stream interactions, meaning that where there are reductions in specific stream power at one location there are similar reductions at bridge locations just up- and downstream of the intervention project location. This is very different than the Mad River, which has somewhat counterintuitive bridge-stream interactions. For example, the Waitsfield Covered Bridge intervention had a significant reduction of specific stream power at the bridge location, but little to no change at multiple bridges downstream until many kilometers further down at the Fletcher Rd. Bridge (Figure 5.20). This interaction is much less intuitive compared to the Black Creek, and this can largely be attributed to the size of the study section, as well as the different channel gradients between the two rivers.

Intuitive interactions can also be seen on the Otter Creek, that has a similar gradient profile to the Black Creek but on a longer study section. The specific stream power values at each bridge location are also well below the Magilligan's threshold, with some locations falling below the 35 W/m^2 threshold (Figure 6.9). However, many bridges could overtop under multiple flood events (Figure 6.10). This contrasts the Black Creek, which had only one overtopped bridge, but is similar to the Mad River, which has multiple bridges that overtop for different flood events.



H1 = Gorham Covered Bridge, R1 = VTRR 215, H2 = Depot Hill Covered Bridge,
R2 = VTRR 219, H3 = Kendall Hill Rd, H4 = Hammond Covered Bridge,
R3 = VTRR 220, H5 = Syndicate Rd, H6 = Union St, H7 = Sanderson Covered Bridge,
H8 = VT Route 73, R4 = VTRR 228, H9 = Leicester-Whiting Rd., R5 = VTRR 229

Figure 6.9 Specific stream power for each simulated flood event at bridge locations within the Otter Creek study section

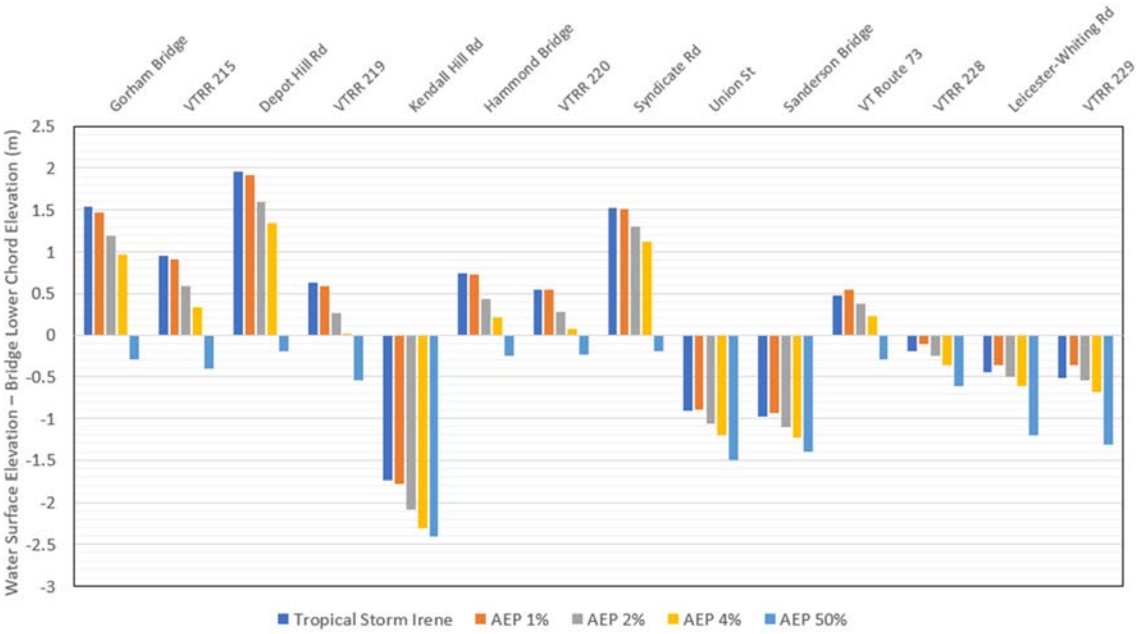


Figure 6.10 Water surface elevation of simulated flood events compared to lower chord deck elevation of bridges in the Otter Creek study section

To better compare the intuitive or counterintuitive bridge-stream interactions across study reaches, an intervention was also modeled on the Otter Creek. Due to the high floodplain connectivity, and little encroachment and entrenchment on the Otter Creek, the intervention was designed to exasperate flood conditions. This is done to observe extreme bridge-river interactions that can be easily identified and compared to the Black Creek and Mad River study sections. The intervention modeled, is a berm installation just upstream of the VTRR 229 rail bridge found downstream of the study area in the Otter Creek. The berm raises the bank elevation by 1 m on either side of the river and extends upstream for 50 m (Figure 6.11). The 2011 Tropical Storm Irene was then simulated and the specific stream power is computed at every bridge location. The specific stream power value at the VTRR 229 rail bridge is 18 W/m^2 under baseline conditions. Under intervention conditions the specific stream power decreases slightly to 11 W/m^2 (Table 6.1). When specific stream power is assessed on a reach scale, it increased at almost every bridge location (Table 6.1). The increase is most significant at the Kendall Hill Rd. Bridge, where the baseline conditions meet the 35 W/m^2 threshold, but then increase past the Magilligan's threshold to 308 W/m^2.

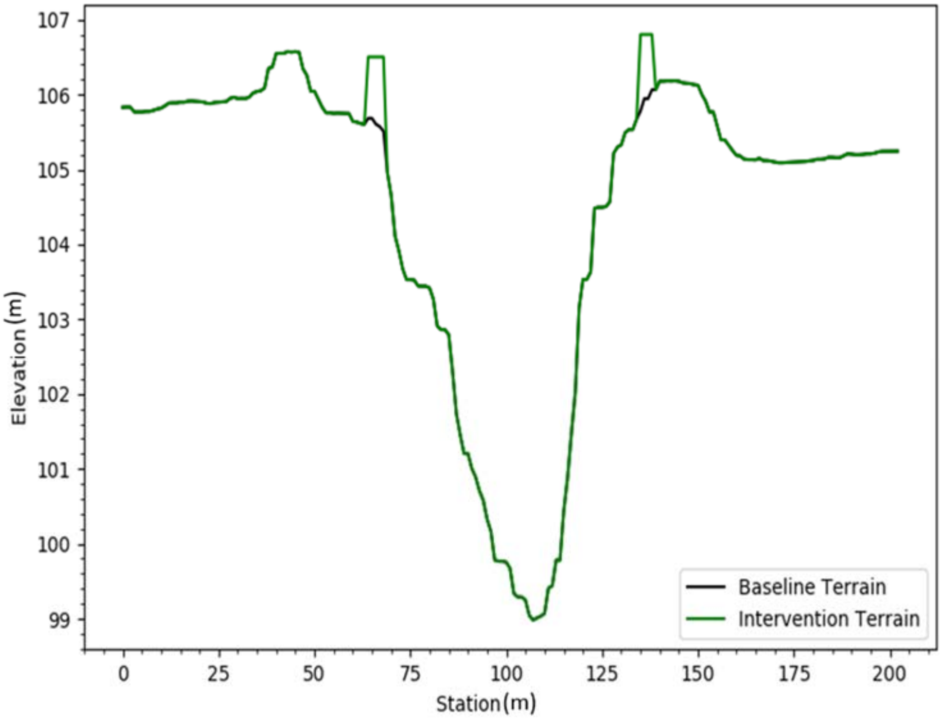


Figure 6.11 Otter Creek berm addition intervention terrain.

Table 0.1 Specific Stream Power values at bridge locations on the Otter Creek during baseline, and berm addition conditions

Bridge	Tropical Storm Irene Specific Stream Power (W/m^2)	
	Baseline	Intervention
Gorham Covered Bridge	55	56
VTRR 215	35	164
Depot Hill Covered Bridge	3	18
VTRR 219	121	69
Kendall Hill Rd	35	308
Hammond Covered Bridge	54	125
VTRR 220	63	116
Syndicate Rd	9	22
Union St	20	34
Sanderson Covered Bridge	26	40
VT Route 73	6	17
VTRR 228	22	33
Leicester-Whiting Rd	40	77
VTRR 229	18	11

These bridge-stream interactions are still considered to be intuitive, similar to the Black Creek. This is because an impact is seen at each bridge location moving upstream from the berm installation. This is similar to the decrease of specific stream power at each bridge location under intervention conditions at the Black Creek. Trueheart et al. (2020) also observed that interventions, such as bridge removal, on the Otter Creek had cascading impacts up- and downstream of the project location. The authors noted that these interventions consistently impacted bridges directly up- and downstream of the project location. Additionally, it was suggested that in some cases only larger size interventions would show substantially larger impacts on bridges throughout the river (Trueheart et al., 2020). These types of interactions on the Otter Creek are intuitive, similar to the Black Creek which has a similar channel gradient profile.

The Mad River has a very different channel gradient, with more moderate slopes that frequently change throughout the study area. All three interventions modeled at this study reach did not have intuitive interactions like the Otter Creek and the Black Creek. The Main St. and Waitsfield Covered Bridge interventions both impacted the specific stream power at the bridge location similar to the interventions on the Black Creek and the Otter Creek. However, the cascading impacts to bridges up- and downstream for the Mad River interventions were not as consistent compared to the Otter Creek and the Black Creek. The Mad River interventions sometimes did not impact bridges directly up- and downstream from the intervention project location, but instead impacted bridges many kilometers away all the way upstream, as seen in the culvert addition intervention. This is unlike the Otter Creek and Black Creek interventions which consistently saw impacts to bridges directly up- and downstream of the project location and cascading impacts on the reach scale.

6.3 Screening Framework Evaluation and Application Analysis

The screening framework is developed to assist in the evaluation of a bridge-stream network and determine if a particular structure would benefit from flood mitigation interventions. The framework is further designed to allow stakeholders to make preliminary screenings without the need of hydraulic/hydrologic modeling. Specific stream power, channel slope and presence of bedrock can all be determined through field calculations and observations. In order to determine the overall effectiveness of the framework, it is applied to all river reaches under baseline conditions.

When the evaluation framework is applied to the Mad River, seven bridges are clearly categorized as locations that are *Not Applicable* to intervention due to the presence of bedrock (Table 5.2). Out of these seven bridges two experienced damage during Tropical Storm Irene. It should be noted that bridges categorized as *Not Applicable,* means that interventions are most likely not practical or cost-effective in that area, but interventions could instead take place up or downstream to reduce construction cost due to the presence of bedrock. The screening framework further identifies three bridges that would have a *Variable* impact, all of which had negative flood effects, such as overtopping or other damages, during Tropical Storm Irene, and six bridges that would have a *Maximum* impact*,* three of which have known negative flood effects seen during Tropical Storm Irene. Overall the framework identified the majority of bridges with known damages from flood impacts for flood mitigation intervention.

When three flood mitigation interventions were modeled, one each was modeled in an area identified as a *Maximum impact*, *Variable* impact and *Not Applicable*. The Main St. intervention was categorized as a *Maximum* impact area, and the modeling results show a large positive network scale flood mitigation impact for the entire river. This intervention done in a high gradient section of the river reduced specific stream power at most bridge locations, and no bridges experienced direct overtopping of the bridge deck. The Waitsfield Covered Bridge was identified as a *Variable* impact area and has been overtopped during previous flood events, and was damaged during Tropical Storm Irene, so an intervention was modeled at this location. The results show a cascading positive flood mitigation impact on the entire river network, creating stabilized bridge locations and overtopping eliminated at all bridges. The culvert modification intervention is done in an area known to have bedrock, which is why this area is categorized as *Not Applicable*. The results do show minor reduction in specific stream power but not as impactful as the Main St. or Waitsfield Covered Bridge intervention. The results from all three interventions match the original categorization from the evaluation framework, affirming its applicability to rivers with *moderate* to *high* gradients.

The screening framework is further applied to the Otter Creek (Table 5.3) and Black Creek (Table 5.4) and categorizations are compared against previous records of negative flood effects modeled at each bridge location. The screening framework identified only the Route 36 bridge to be a *Maximum* impact area on the Black Creek. To the best of our knowledge this bridge has not experienced flood damage, and no overtopping is predicted in the various flood simulations. However, our modeling shows a bottleneck effect at this bridge. Water is constricted at the bridge location and then quickly expands just upstream of the bridge (Figure 6.9). This constriction contributes to the unstable specific stream power values and could lead to erosion and damages in the future. The instability and potential for damage make this bridge a good location for intervention. The framework further categorized the remaining bridges as either *Minimal* impact areas or *Not Applicable* due to bedrock presence. However, the Elm Brook Rd. bridge is overtopped in model under Tropical Storm Irene, but the presence of bedrock makes this location undesirable for intervention. Based on observations from the Mad River interventions, floodplain reconnection or an alternate intervention at the Route 36 bridge could have potential positive network level effects reducing water surface elevation at the Elm Brook Rd. bridge. Overall the evaluation framework could not identify bridges with previous damage in this lower gradient river, but it is able to identify bridges that have the potential to see damages in the future and locations that could reduce negative flood impacts on a network scale.

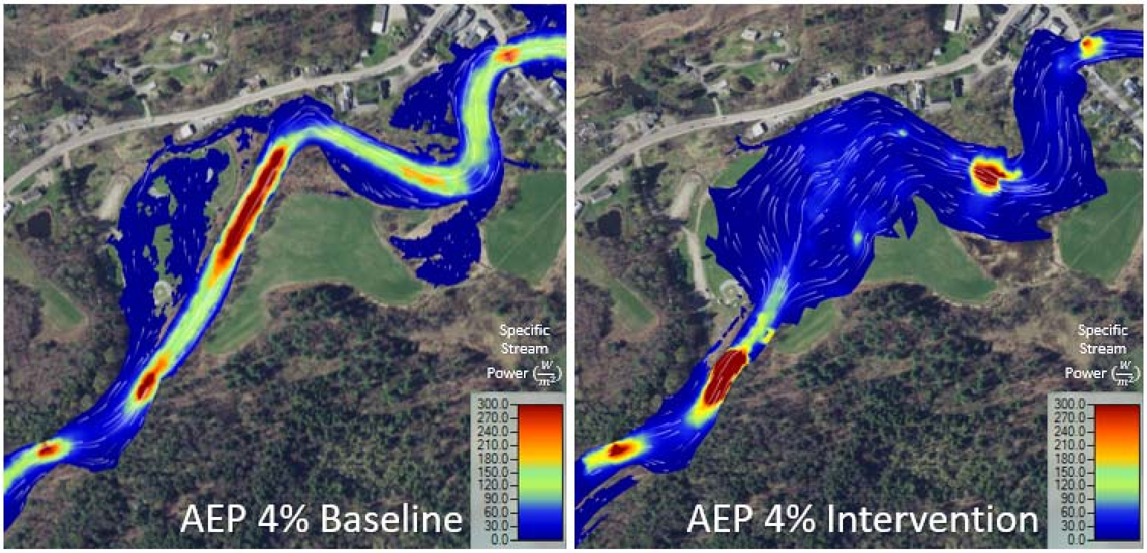


Figure 6.12 Plan view of the 2D HEC-RAS model of the Waitsfield Covered Bridge project location showing specific stream power baseline conditions (left) and the intervention conditions (right)

When the screening framework is applied to the Otter Creek only two bridges are identified as *Maximum* impact areas for some simulated flood events. When these bridges are compared to previous records, one has recorded overtopped conditions and the other has reports of erosion on the banks affirming the framework's categorization. Out of the remaining bridges, seven are categorized as *Variable* impact areas. Out of these seven, five bridges show overtopped conditions under modeled flood events. The remaining two bridges do not have a history of negative flood impacts, showing mixed results and affirming the framework's categorization for *Variable* impact areas. The final five bridges are categorized as *Minimal impact* areas. Two of these locations show overtopped conditions under modeled flood events. The remaining structures have no history of observed negative flood effects. The Sanderson Covered Bridge is located between the two structures that observed overtopped conditions during simulated flood events, and was categorized as a *Maximum* impact area. An intervention at the Sanderson Covered Bridge could improve conditions at the surrounding structures and reduce water surface elevation. Overtopped bridges in the Otter Creek study section have very low specific stream power, which reduces the risk of damage while being overtopped. The evaluation framework applied to the Otter Creek was able to identify the majority of hydraulic crossings that experienced damage during previous flood events as *Maximum* impact or *Variable* impact areas.

The screening framework when applied to all study reaches was able to correctly identify the majority of structures that had experienced negative flood impacts as *Maximum* impact areas. Only a few bridges that have actually experienced negative flood impacts were categorized by the screening framework as *Not Applicable* or *Minimal* impact, and this is largely due to the presence of bedrock. The framework was also successful in identifying locations that did not see previous negative flood impacts, but could potentially see damages in the future based on their hydraulic and geomorphic indicators. Overall the evaluation framework is applicable to all study reaches of varying slopes and conditions.

This research shows that specific stream power can be a powerful indicator in combination of observed hydraulic impacts such as water surface elevation to identify bridges in unstable conditions. The 2D HEC-RAS models used in this study do not model sediment transport. However, the Magilligan's threshold is known to be used to identify high probabilities of large sediment transport and bank instability. It is used in combination of other indicators such as incision and sinuosity in alternate studies to determine channel stability (Buraas et al., 2014), and similarly in this study to determine risk of erosion along banks and bridges for risk of erosion and scour.

The screening framework is additionally designed to assess bridges and project locations without the need of advanced hydraulic/hydrologic modeling, however the use of modeling allows stakeholders to observe potentially dangerous high flow events. For this study, the stream power values were computed using the 2D HEC-RAS model, but they can be estimated without the need of complex models. The framework is best applied to rivers with *moderate* to *high* gradients, since these rivers have frequent gradient classification changes throughout the reach. The screening framework is still able to identify bridges that would see a variable impact should an intervention take place in lower gradient rivers, but relies more on previous flood damage history. Additional parameters such as incision ratio and sinuosity could improve the framework to better identify bridges in more immediate need of intervention. This early identification allows stakeholders to prioritize projects and resources for bridge rehabilitations, holistic design of bridges and address stakeholder concerns raised in response to planned alterations. Based on previous observations, the screening framework is a tool that stakeholders can utilize for preliminary evaluation of current infrastructure for flood mitigation projects in river reaches with similar geographic and climatic conditions as the ones used in this research.

Chapter 7: Conclusions and Recommendations for Future Work

This chapter summarizes overall conclusions derived from this work and suggests recommendations for future work.

7.1 Conclusions

This research led to the following conclusions:

- A 2D HEC-RAS model was developed for ~42 km section of the Mad River and was successfully calibrated for the 2011 Tropical Storm Irene. Additional flood events of multiple exceedance probabilities were also modeled (1%, 2%, 4%, 50%).
- The modeling results showed that interventions in a moderate or high gradient river will have less intuitive cascading up and downstream effects compared to a low gradient river. For example, the Mad River sees cascading effects up- and downstream from the modeled Main St. floodplain lowering intervention, but these effects are not directly seen in the immediately surrounding bridges. The Otter Creek perturbations had more significant impacts in bridges directly up- and downstream of the initial location.
- Given a site-specific intervention, the benefit of reducing stream power is more pronounced and varying in *moderate to higher* gradient rivers.
- Interventions in a high gradient reach of a river can significantly impact low, moderate and high gradient reaches of the river throughout its length. For example, the Main St. floodplain lowering intervention was modeled in a high gradient reach of the river, and it impacted bridges in low, moderate and high gradients up- and downstream of the intervention location.
- The calibrated model showed how site-specific interventions have cascading consequences throughout the river study section, which were often counterintuitive, something that would not be captured through 1D modeling. Overall, this demonstrated the value of 2D transient modeling.
- Longitudinal cascading impacts appear to be more extensive in low gradient rivers, but are dependent on bridge-river physical characteristics.
- A screening framework was developed using geomorphic and hydraulic characteristics and applied to low, moderate and high gradient river reaches.
- The screening framework proved more useful in moderate to high gradient rivers where changes in gradient are more dramatic and frequent. However, the screening framework may be successfully applied to low to moderate gradient rivers, if supporting data are available. For example, the screening framework identified many bridges in the Otter Creek as *Variable* or *Maximum* impact areas with available supplementary inspection reports. Additional structural data are required, such as previous records of damage due to flood events, or current inspection reports that depict degradation that could be exacerbated from extreme flood events.

- The screening framework may be used without the need of complex models. Determining the presence of bedrock and channel slope is best done through field work; thus, specific stream power can be estimated based on field observations. However, a complex hydraulic/hydrologic model allows a user to simulate non-intuitive impacts for potentially high flow events that are unable to be captured through field observations alone.

7.2 Intellectual Merit and Broader Impacts

The authors identified the following intellectual merit and broader impacts of the research presented in this report:

- This study, as far as the authors are aware, is only the second to quantify the flood impacts on hydraulic bridge infrastructure under high-risk transient conditions on a river scale; and is the first study to do so on multiple rivers, and compare and contrast the model results across multiple rivers leading to an attempt of making some generalizable conclusions for bridge-stream networks in mountainous region in temperate climates such as in Vermont.
- The screening framework developed in this research may be valuable for resource prioritization, holistic design of bridges, and bridge and river rehabilitation projects. This framework may be applied to additional rivers under similar geographic and climatic conditions. However, various alterations and adaptations to the framework may be required depending on site-specific conditions, but overall can be employed as a solid basis to further research and infrastructure evaluation.
- This study serves as a proof of concept for a methodology to quantify bridge-river interactions on a river scale, and the developed model and the screening framework may be used to address stakeholder concerns about cascading impacts of planned bridge projects.
- The 2D HEC-RAS model of the Mad River study section is currently being used in other projects that examine additional interventions such as revegetation, flood chute connection, flood benching, and additional culvert modification and addition. It is also being used in research to develop an optimization wrapper for the 2D HEC-RAS program to simulate and prioritize multiple interventions. This research is being done by Drs. Kristen Underwood and Donna Rizzo with doctoral student Lindsay Worley.
- This research directly or indirectly involved 5 other graduate students and 10 undergraduate students.
- The research associated with this study has been presented to the Vermont Department of Transportation, Transportation Infrastructure Durability Center conferences, and the Friends of the Mad River.

7.3 Benefits of the Research to Transportation Industry

The research methodology and results presented here could be useful to the transportation industry in the following ways:

- This research demonstrates the value of performing 2D transient hydraulic modeling for river-scale bridge-river analysis and design. Such comprehensive evaluations of bridge-river interactions at a river scale are not possible using 1D modeling.
- The screening framework developed in this research can be employed for resource prioritization, holistic design of bridges, and bridge and river rehabilitation projects.
- The screening framework can be applied to other rivers under similar geographic and climatic conditions.
- This study shows how floodplain reconnection can be an effective method to reduce potential adverse flood impacts on infrastructure. However, this method is not always feasible or realistic due to nearby property that could be flooded, and bedrock constraints.
- This study serves as a proof of concept for a methodology to quantify bridge-river interactions on a river scale, and able to demonstrate how such 2D models could be used to address stakeholder concerns about cascading impacts of planned bridge projects within their river reaches.

7.4 Recommendations for Future Work

The following avenues for future work are recommended:

- This research relies on Vermont river corridors. However, hydraulic structure design and construction may vary within the New England region, which may complicate application of the evaluation framework to other bridge-river networks in similar geographic and climatic conditions. Additional 2D HEC-RAS models constructed for bridge-river networks outside of Vermont are recommended to further test and refine the screening framework.
- The applicability of the screening framework to other river systems is presumed to be variable. Additional research may result in supplemental parameters, such as land use or additional specific stream power thresholds, not explored in the current version of the screening framework.
- This research concluded that interventions performed on high gradient sections will have greater impacts on a wider range of gradients. Additional high gradient rivers could be modeled to further explore the cascading up- and downstream effects of potential interventions.
- Additional interventions that focus on bridge modification such as raising deck elevation, and bridge span expansion should be studied to assess their cascading impacts up- and downstream. These interventions can potentially be more realistic in rivers with little to no floodplain access and for communities where floodplain reconnection and lowering is too expensive.

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