The Pennsylvania State University

The Graduate School

Department of Civil Engineering

DESCRIBING DAMAGE TO STREAM MODIFICATION PROJECTS

A Thesis in

Civil Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

December 2013

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ABSTRACT

Complex relationships between stream functions and naturally stochastic processes make evaluation of stream modification projects difficult. Informed by vague objectives and little monitoring data, project evaluations can often be a subjective attribution of success or failure. Given that channel form is closely related to stream function, this research provides a framework to rapidly assess current conditions as a continuum of damage to channel functioning. The damage states focus on damage to hydraulic and geomorphic parameters that describe basic stream functioning and support higher level functions including managing water quality and supporting various life cycles. Based on widely accepted evaluations of physical habitat quality and stream stability, the damage states describe a continuum of damage in multiple categories related to the stream functions that are affected by the modification design. The highest level of damage in the damage categories provides an overall assessment of project conditions and the individual scores in the damage categories can be used to calculate relative vulnerability and relative risk associated with the stream modification project. Relative risk is determined using a vulnerability-criticality risk logic matrix which provides a category of recommended action based on project conditions and potential impacts. The damage states provide an objective characterization of post-construction project performance and the risk assessment provides guidance for allocating resources to project maintenance or rehabilitation. These tools can be used to improve the results of stream modification and protect environmental resources and physical assets.

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ACKNOWLEDGEMENTS

I would like to express my sincere thanks and appreciation to Dr. Peggy Johnson. As my advisor in this research she has been an exemplary mentor and an inspiration. I hope that in my career as a civil engineer I can be as supportive, knowledgeable, and motivating to aspiring civil engineers. I would also like to thank Dr. Mike Gooseff and Dr. Alfonso Mejia, it has been a pleasure working with and learning from you both. Of course, none of this could have been possible without the support of Pennsylvania State University and its laudable academic programs.

There are also a few people who have listened, provided feedback, and even volunteered to test out the framework developed in this thesis. For their help and friendship, I express my gratitude to Allison, Riddhi, Christa, Christine, and my husband. I am eternally grateful to and thankful for my husband Nathan for following me out to streams and listening to my endless flow of thoughts and ideas with unwavering patience, continuous support, and unconditional love. He unknowingly challenges me to achieve more in every aspect of life through his own passion, dedication, and example. Thank you!

Chapter 1

Introduction

The evaluation of stream modification projects is made difficult by the stochastic processes and intricately connected functions that govern the physical form of a stream. Failure is an ambiguous descriptor for these projects but damage to natural stream functions can be discussed in more concrete terms. In order to determine success or failure of stream modification projects, evaluation criteria must be tailored to the unique ecological and social goals of each project. However, resources for both monitoring and evaluation are scarce and project evaluation can be subjectively based on a combination of ecological, political, or social criteria. An alternative to declaring project failure following a hydrologic event is to define states of damage to hydraulic and geomorphic channel functions. Channel form is closely related to stream function and damage states can be used to rapidly assess damage to channel functioning.

Numerous studies have shown that urbanization or agricultural development can degrade stream ecosystems and result in a decrease of stream functioning. Activities that degrade stream functioning may not be reversible. Additionally, the ability to restore channels may be constrained by physical changes in the urban environment, such as infrastructure and property boundaries. The objective of this research was to develop a tool to describe damage to stream modification projects that:

- are based on natural channel functioning;
- account for both environmental goals and human-made constraints; and
- are widely applicable in urban settings.

The realization of these objectives is semi-quantitative damage states defined for hydraulic and geomorphic functioning of modified channels in urban or otherwise constrained settings. Stream modification projects intentionally change physical characteristics of the channel and therefore alter how water, debris, and sediment are transported in the modified channel. These hydraulic and geomorphic functions affected by modification govern the equilibrium state of the channel and are connected to higher chemical and biological stream functioning. While quantifying hydraulic and geomorphic functioning would be subject to large variations across regions and streams, the damage states are based on semi-quantitative assessment tools for widely recognized symptoms of damage, such as degradation, excessive sediment deposition or bank erosion.

In addition to evaluating damage, the damage states can be used to describe the vulnerability of modified channels in a semi-quantitative risk assessment procedure based on the current conditions of a project. The dynamic and stochastic nature of riverine ecosystems creates considerable uncertainty in predicting system responses to modification which results in risk to the environment and infrastructure. A vulnerability-criticality risk-logic matrix is proposed that can be used to determine relative risk of multiple stream modification projects with similar goals. This research proposes a novel framework for assessing damage and evaluating relative risk of stream modification projects.

Chapter 2

Literature Review

Riverine ecosystems support a wide array of biodiversity through complex physical, chemical and biological processes (Fischenich, 2006). These complex processes that maintain streams and rivers also benefit our communities by providing flood storage, drinking water, hydropower, fishing and hunting in addition to the immeasurable and invaluable contributions of beauty and tranquility. Development, such as installing roads, erecting buildings, and performing large scale agriculture, alters the landscape in order to meet our needs and the streams that catch water from altered watersheds become severely impacted. The mechanisms that lead to impacted stream ecosystems are muddled in complicated natural processes occurring at various spatial and temporal scales but the resultant degradation of stream ecosystems has been well documented (Allan, 2004). Figure 2-1 summarizes various impacts on streams due to land-use changes. Recognizing the importance of aquatic resources, construction projects are being performed all across the United States in an effort to restore, rehabilitate, and preserve the functions and services provided by stream ecosystems (Palmer, et al., 2007). Although stream restoration has become a billion dollar industry in the United States and throughout the developed world (Jahnig, et al., 2011), researchers wonder if billions of dollars are being spent on practices that do not work (Bernhardt and Palmer, 2011).

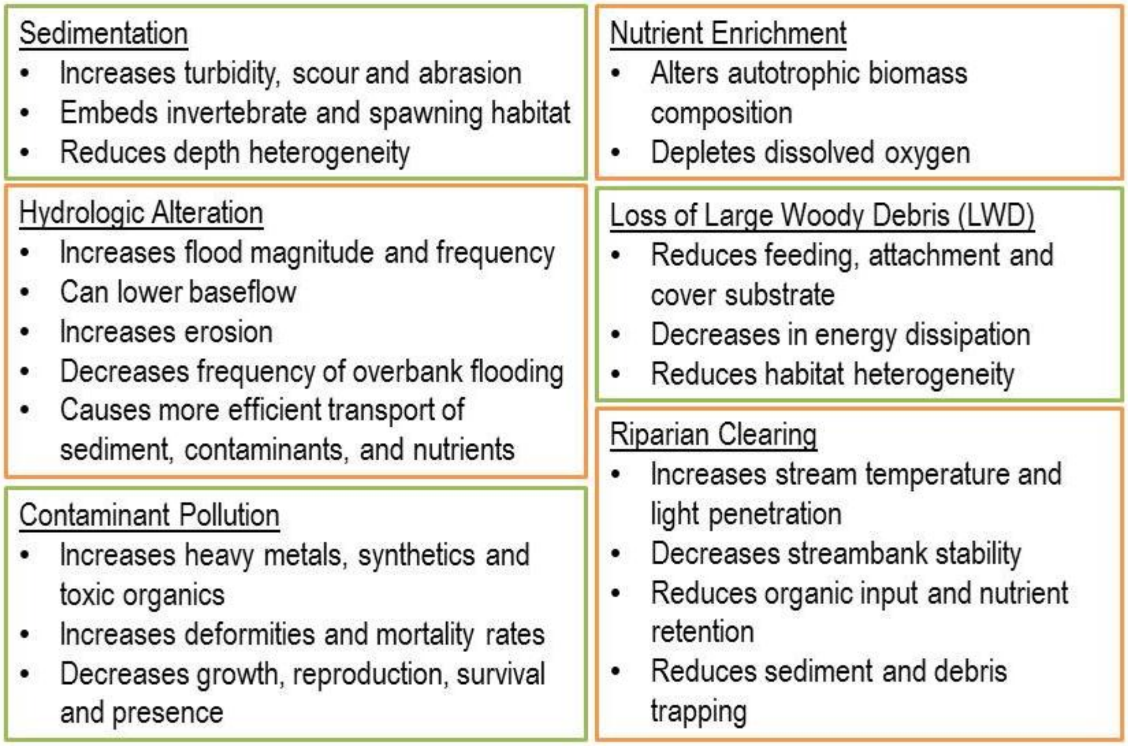

Figure **2-1**: Principal impacts to stream ecosystems from land use change and their effects. Adapted from Allan (2004).

2.1 – Introduction

The belief that restoration projects provide functional lift is widespread despite the fact that project assessment is rare (Doyle and Shields, 2012; Palmer, et al., 2005; Kondolf, 1995). Assessment or monitoring that would demonstrate progress toward goal achievement is performed only on roughly 10% of restoration projects in the US (Bernhardt, et al., 2005). Without any consistent definitions for success or failure the multidisciplinary field of stream restoration has rendered failure difficult to determine which prevents clear attribution of responsibility and liability when project results are questionable. Although engineers often sign and seal restoration plan sets there is a notable deficit of design standards and specific failure criteria compared with other fields of engineering (Slate, et al., 2007). Numerous lawsuits have been filed in an attempt to hold contractors or designers accountable for ineffective restoration; however the inconsistent performance standards used to define failure makes it difficult to hold anyone accountable.

2.1.1 – Stream Modification Terminology and Common Practices

In this research, the term stream modification will be used to broadly include stream restoration, rehabilitation, stabilization, naturalization, and any other modifications of a stream channel using practices that take natural processes into account or are environmentally sensitive. Stream restoration has become an umbrella term under which many projects that alter stream channel conditions are often incorrectly labeled as "restoration". The term restoration implies that actions restore a system to some prior condition, assuming that characteristics of a prior condition are available (NRCS, 2007). Due to widespread development within watersheds that prevents restoration (Rhoads et al., 2008) and lack of data describing pre-disturbance conditions, the term stream modification is more accurate.

A recent document from the United States Environmental Protection Agency (EPA) and US Fish and Wildlife Service (FWS) describes stream restoration as "generally considered to describe a set of activities that help improve the environmental health of a stream" (Harman, et al., 2012, p. 34). The terms restoration, restoration, rehabilitation, stabilization, and naturalization are usually grouped with or under stream restoration. Restoration is the process of "returning an ecosystem as closely as possible to pre-disturbance conditions and functioning" (NRCS, 2007, pp. 1-2) as opposed to rehabilitation which is described as the "return of a degraded stream ecosystem to a close approximation of its remaining natural potential." (Shields, et al., 2003, p. 575). A more specific definition of restoration is the process of "converting an unstable, altered, or degraded stream corridor, including adjacent riparian zone (buffers) and flood-prone areas, to its natural stable condition considering recent and future watershed conditions." (USACE Wilmington District, 2003, p. 8). A research group in Illinois prefers the term stream naturalization which "seeks to establish morphologically and hydraulically diverse, yet dynamically stable fluvial systems that are capable of supporting healthy, biologically diverse aquatic ecosystems" (Rhoads et al., 2008, p. 209). Recognized that ecological improvement was not the primary goal of many urban stream restoration projects, the Ohio Department of Natural Resources chose to define stream restoration projects as those that "within site constraints, one of the project goals was to maximize ecological condition" (Mecklenburg and Fay, 2011, p. 8). Given the lack of a standard definition for stream restoration, the term stream modification will be used throughout this document to describe any manipulation of physical channel characteristics that aims, at least in part, to improve natural channel conditions or functions.

Within the field of stream modification, projects can often be described by the design theory or practices implemented. Natural channel design is a popularized approach to stream modification that designs for the bankfull, or channel forming, flow event, taking the sediment load, flood-prone area, and bedform frequency into account (Doll, et al., 2003). Natural channel design typically employs in-stream rock structures that harden channel cross sections and planform. Some practitioners look to large wood influences in naturally stable, flood-prone environments for engineering inspiration in stream modification projects (FEMA, 2009). The Natural Resource Conservation Service (NRCS) provides instruction and technical resources on streambank soil bioengineering, the use of living or dead woody plant material to stabilize banks, reduce erosion, and establish streambank vegetation (Hoag and Fripp, 2002).

In an effort to avoid inaccurate expectations of stream modification projects Schiff, et al. (2006) developed a classification system for the design of modified channels that sets realistic goals and objectives. An unnatural rigid design would consist of modifications that take the channel's ability to transport large floods without eroding the bank into account (Schiff, et al., 2006). Unnatural rigid design does not take the natural form and processes of the channel reach into account. Channel modification that takes form and process into account but prevents channel evolution by restricting the planform is labeled semi-natural form design (Schiff, et al., 2006). Natural channel design falls under this label of semi-natural form design. The restoration of channel form and processes without constraints to the planform is called natural process design (Schiff, et al., 2006).

A stream modification project usually consists of multiple techniques or practices implemented to improve channel conditions. Common techniques include: modification of the profile, planform, and cross section; in-stream structures; large wood and log jams; fish passage restoration; and bank protection construction, modification, and removal (Cramer, 2012). This list covers broad, complimentary, and sometimes overlapping techniques of stream modification but within each technique there are multiple methods or practices. A list of stream modification practices within each of the aforementioned design categories is provided in Table 2-1. Brief descriptions of these practices are provided in Appendix A along with references for further information.

This review does not a provide a comprehensive list of stream modification practices, the science and practice are growing and practitioners modify existing practices and invent new ones to restore natural functioning in their region. Some techniques intentionally not included are those that do not alter physical channel characteristics, such as watershed and riparian management, floodplain structure alterations, and targeted biological interventions like beaver re-introduction (Cramer, 2012). These practices should not be overlooked by those intended to improve stream channel functioning but are not including in this review of stream modification.

Any number of the listed practices can be implemented in a stream modification project to manipulate physical channel characteristics and improve natural channel conditions or functions. Unnatural rigid design is effective for protecting channel banks and infrastructure with limited advantages to the channel environment (Schiff, et al., 2006). Semi-natural form design more closely mimics natural channels, protecting channel banks and infrastructure and improving the stream environment (Schiff, et al., 2006). These two categories of design balance imposed physical constraints with ecological functions and services of the channel while natural process design is only appropriate where the channel form is not restricted.

Table **2-1**: Stream modification practices. Descriptions and references for each practice are provided in Appendix A.

Unnatural Rigid Design Practices	**Semi-Natural Form Design Practices**	**Natural Process Design Practices**
Riprap, Boulder revetment	Cross vanes, Log drops, Weirs	Bank vegetation establishment
Imbricated riprap, Stacked stone	Log and rock vanes, Barbs	Channel modifications, Channel relocation, Streambank shaping
Rock toe	J-hooks	Rootwad revetment
Gabion baskets	Groins, Spur dikes, Engineered log jams	Roughness trees, Tree revetment
Geobags, Sand bags	Step pools	Coir fiber logs, Natural fiber rolls
A-jacks, Interlocking concrete jacks	Constructed riffles, Rock ramps, Roughened channels	Live soil lifts
Live crib walls, Log cribwalls	Wing deflectors	Natural fiber matting, Brush Mattresses, Biodegradable erosion control fabrics
-	Rock sills, Cut off sills, Linear deflectors	Live fascines
-	Lunkers, Mud sills	Live stakes, Pole plantings
-	Erosion control fabrics, Turf reinforcement mats, Manufactured retention system	Branch layering, brush layering
-	Soil lifts, Structural earth wall, Soil reinforcement, Vegetated reinforced soil slope	LWD placement

2.1.2 – Functions and Services in Modified Stream Channels

Waters of the United States are protected resources and permits for stream modification are granted for projects in compliance with the Clean Water Act Section 404 (33 U.S.C. 1344) and Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 401 et seq). The larger goal of any stream modification project is dictated by federal policy and permit restrictions which require that activities result in a net increase in aquatic resource functions and services (Nationwide Permit 27: Aquatic Habitat Restoration, Establishment, and Enhancement Activities).

For a project to achieve a net increase in aquatic resource functions and services it must first identify stream functions and services. Giller (2005) lists major ecosystem services as processing waste, recreation, flood attenuation, and providing potable water and food for animals, plants and humans. A more ecological view of stream services will include watershed protection, nutrient cycling, and providing habitat for various organisms throughout their life-cycle (Sweeney, et al., 2004). These services provided by stream ecosystems are products of the functions of the stream system.

Fifteen primary functions of healthy streams and their riparian corridor were systematically defined by Fischenich (2006). Recent work has built on these functions to create the stream function pyramid, which is being promoted by the EPA and FWS (Harman, et al., 2012). The stream function pyramid, shown in Figure 2-2, depicts the primary flow of dependency from hydrologic functions to hydraulic, geomorphic, physicochemical, and finally biologic stream functions (Harman, et al., 2012). It is important to note that the stream functions pyramid shows the dominant cause-and-effect relationships controlling natural stream ecosystems and there are relationships that flow opposite the hierarchy, or down the pyramid (Harman, et al., 2012).

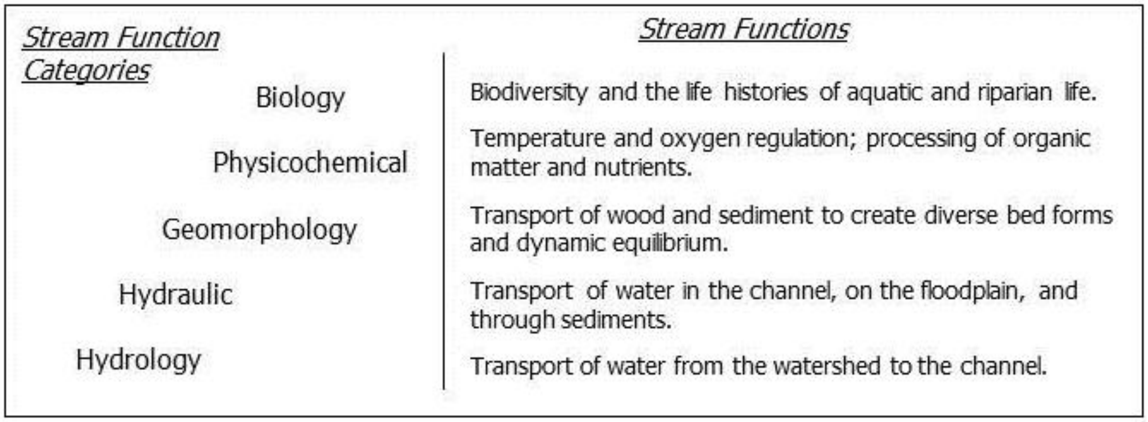

Figure **2-2**: Stream Functions Pyramid adapted from (Harman, et al., 2012, p. 46). Geology and climate provide the underlying control to all stream functions.

Since all stream functions depend on hydrologic functions, as shown in Figure 2-2, it follows that stream functioning could best be increased by assessing and addressing impairments in the watershed. Research has shown that watershed scale projects are more successful than reach or channel scale projects (Harman, et al., 2012; Shields, et al., 2003). As the effects of development on local hydrographs are better understood, the prevalence and efficiency of best management practices in urban and agricultural watersheds has also been increasing (Meierdiercks, et al., 2010; Kröger, et al., 2012). Unfortunately watershed improvements are not always practical or sufficient and stream channels are frequently altered to increase stream functioning. However, stream modification projects in altered watershed are not typically limited in scope to environmental improvement. In constrained environments, goals that serve the local political and societal needs must be considered in addition to environmental goals.

2.1.3 – Goals, Objectives, and Performance Standards

A National River Restoration Science Synthesis (NRRSS) found that 20% of over 37,000 stream modification projects had no goals stated for the project (Bernhardt, et al. 2005). While project goals and objectives are not always stated they usually address hydrogeomorphology, biogeochemistry, biological systems, socioeconomics, or cultural-personal values (McKay, et al., 2012). The NRRSS identified the five most common goals recorded for stream modification projects in the United States, shown in Table 2-2 (Bernhardt, et al., 2005). Other common goals of stream modification that focus on services performed that benefit humans include protecting property, protecting infrastructure, and restoring channel capacity (NRCS, 2007).

Table **2-2**: Most common goals of stream modification project (Bernhardt, et al., 2005) and corresponding function level from the Stream Functions Pyramid (Harman, et al., 2012).

Goal	**Functional Level**
Enhance water quality	4 – Physicochemical
Manage riparian zones	5 – Biology
Improve in-stream habitat	3 – Geomorphology
Fish passage	2 – Hydraulic
Bank stabilization	3 – Geomorphology

The NRRSS also found that while monitoring or assessment was performed on more than 20% of the projects in some regions of the United States, only 6% of projects in the Chesapeake Bay underwent monitoring (Bernhardt, et al., 2005; Hassett, et al., 2007). The Chesapeake Bay watershed has the highest concentration of projects per mile of river in the country in addition to lowest monitoring rate (Hassett, et al., 2007). Without clear expectations and requirements, practitioners and funding agencies have limited motivation to fund monitoring and assessment (Palmer, et al., 2005).

There is limited guidance on how to measure progress or achieve a net increase, rather than a net decrease, in functioning of modified channels. Regulations that dictate terms for design, construction, and monitoring of stream modification are concentrated on compensatory mitigation. Likely in response to the growing popularity of stream restoration and a lack of regulations, USACE enacted a mitigation rule (33 CFR Parts 325 and 332) in 2008 that requires mitigation projects to include objective and verifiable ecological performance standards based on the best available science that assess whether the project is achieving its objectives (Section 332.5). A regulatory guidance letter on minimum monitoring requirements was released the same year that set minimal monitoring standards (USACE, 2008). Neither document provides guidance on directly improving stream functioning through project objectives and ecological performance standards. The Federal Register refrains from defining specific metrics to evaluate stream modification projects due to large variation in resource types across the country and the constant advancement of the science of ecosystem restoration (33 CFR Parts 325 and 332).

Many USACE regional districts and states enforce regulations stricter than the 2008 mitigation rule on stream mitigation projects and provide guidance on performing stream modification in local environments. Multiple states and regions require or suggest monitoring procedures but do not clearly define performance standards or metrics; the success and failure criteria, or the threshold for remedial action (adaptive management), are left up to the individual project (USACE Savannah District, 2004; USACE Kansas City District, 2008; USACE, 2010a; USACE New England District, 2010) and are rarely defined prior to project installation. Typical guidance and regulations for monitoring stream project performance include photographs of site conditions, survey of stream profile and multiple cross sections, and vegetation survival rates (USACE Savannah District, 2004; Schiff, et al., 2007; USACE New England District, 2010; TN DEC, 2004; KDOW, 2007).

The USACE Wilmington district in North Carolina provides specific success standards in their stream mitigation guidelines (USACE Wilmington District, 2003). Determinations regarding substantial evidence of instability are made by monitoring morphology and photo reference sites and quantitative performance criteria are set for vegetation survival, bank height ratio, and entrenchment ratio within the project (Doll, et al., 2003; USACE Wilmington District, 2003; NCEEP, 2011). These criteria are related to channel functioning but they do not measure functional lift in modified channels. Additionally, a study found that these regulations have not translated to clear and achievable project goals and objectives in North Carolina (Hill, et al., 2011).

A few state protocols require the habitat assessment from the rapid bioassessment protocols (RBP) (Barbour, et al., 1999), a federal tool intended for widespread application, for monitoring stream mitigation projects (TN DEC, 2004; KDOW, 2007; WVIRT, 2010). This habitat assessment uses a visual assessment of hydraulic and geomorphic parameters related to aquatic life use that could limit aquatic biota (Barbour, et al., 1999). Tennessee requires a pre- and post-project habitat assessment be performed for mitigation projects (TN DEC, 2004). Kentucky has collected data in each bioregion of the state and delineated values on the RPB in each region that are fully supporting, partially supporting, or not supporting healthy aquatic communities (KDOW, 2008). These state protocols are exemplary in providing verifiable performance standards to achieve functional lift in the channel.

The deficit of clear and achievable performance standards for stream modification can be partially attributed to “the absence of comprehensive stream and wetland functional assessment methodologies” (WVIRT, 2010). There is a growing collection of guidance for quantitatively measuring functions of stream ecosystems (Fischenich, 2006; Harman, et al., 2012; WVIRT, 2010; Mecklenburg and Fay, 2011; USACE, 2010b; DSL, et al., 2012). The stream functions pyramid synthesizes experience and current research and provides performance standards for some measurement methods (Harman, et al., 2012). A regional guidebook for functional assessment of headwater streams in West Virginia and Kentucky (USACE, 2010b) results in functional capacity units that can be used for tracking impacts and credits in mitigation. The Ecosystem Management and Restoration Research Program (EMRRP), a research program under USACE, has recently published a detailed technical note (McKay, et al., 2012) that provides guidance for individual projects on forming concrete objectives and performance standards to evaluate environmental improvement. Note that the majority of these tools have been published within the last three years so data on their application and success is not yet available.

2.1.4 – Increasing Stream Function through Stream Modification

Despite the requirement that restoration activities in the waters of the US result in a net increase in aquatic resource functions, research has shown that projects decrease functioning in some cases (Doyle and Shields, 2012). It is frequently assumed without supporting data that physical, chemical, and biological integrity are increased by stream modification projects (Doyle and Shields, 2012).

Stream modification techniques can benefit or impact physical and biological conditions in a modified channel and the potential benefits vary widely between practices and site conditions (Cramer, 2012). Riparian planting is often attributed with being able to decrease stream temperatures through shading (Harman, et al., 2012). Some structures claim to promote hyporheic exchange which may increase nutrient cycling and reduce nutrient loading (Hester and Doyle, 2008). The potential and assumed benefits of different practices is demonstrated in a risk and benefit analysis in Table 2-3 that describes the functions of multiple bank stabilization structures (Niezgoda and Johnson, 2012). While none of the practices in Table 2-3 take the natural form of the channel into account, all of them, with the exception of the concrete retaining wall, can improve channel conditions in addition to protecting the stream bank. Note that since the concrete retaining wall does not target any channel condition improvements it is not considered a stream modification practice in this research. Imbricated riprap potentially improves some environmental function, creating gaps that provide refuge areas for fish (Schueler and Brown, 2004). As long as the riprap is intact, then it offers this improved habitat condition.

Table **2-3**: Functions of various bank stabilization practices from Niezgoda and Johnson (2012).

Bank Stabilization Practice	**Function(s)**
Concrete retaining wall	Armor and protect surface
Imbricated riprap	Armor and protect surface Enhance in-stream habitat
Vegetated gabion baskets	Armor and protect surface Enhance in-stream habitat Enhance riparian habitat
Live log crib walls	Armor and protect surface Enhance in-stream habitat Enhance riparian habitat Provide organic material

However, it will depend on the preferred habitat of local fish species whether the imbricated riprap could actually improve conditions since imbricated riprap can also increase local velocities and reduce complexity in the modified channel (Cramer, 2002). Similarly, not all riparian planting will significantly decrease stream temperatures and installing a structure may not reduce nutrient loading. Since tools that can accurately predict physical and biological response to channel modification are not readily available for evaluating project performance it is inappropriate to assume that potential benefits are achieved.

Instead of focusing on intended benefits to natural functioning consider the functions that are directly affected by the project design. In general, stream modification projects design for flow conditions and channel form, governed by hydraulic and geomorphic functions (Harman, et al., 2012). For example, in-channel structures impact channel hydraulics, sediment transport, bed scour, erosion and deposition, channel planform and profile, and wood recruitment and transport (Cramer, 2012). The hydraulic and geomorphic functions are described by various parameters, listed in Figure 2-3 consisting of structural variables, instantaneous indicators of stream function, or direct measurements of functions (Harman, et al., 2012).

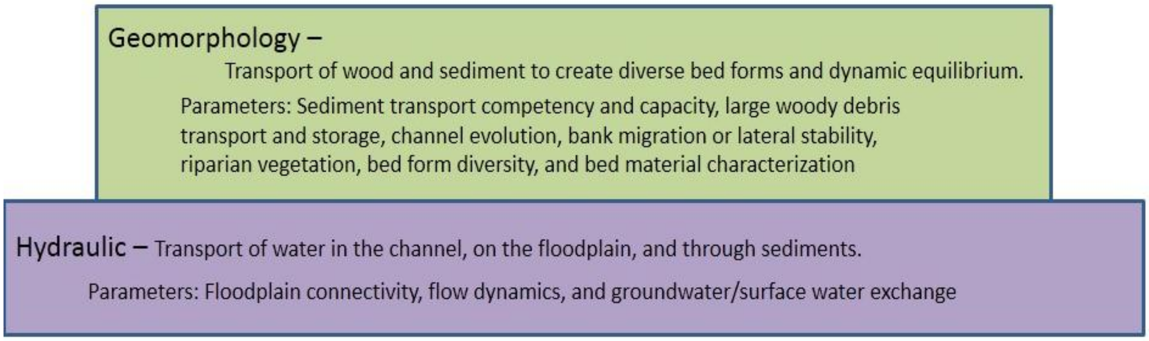

Figure **2-3**: Stream Functions Pyramid and function-based parameters of hydraulic and geomorphology function categories (Harman, et al., 2012, p. 50)

The relationship between stream form and function is critical to the design of stream modification projects. Consider that the design of imbricated riprap, a common bank protection practice, requires the calculation of maximum design flow and resulting shear stress in order to determine the appropriate size of rock to be placed in the channel. This design criteria is a measure of flow dynamics (ex. velocity, shear stress, and stream power) in the modified channel. In addition to flow dynamics, imbricated riprap sets a desired bank height and affects floodplain connectivity. When water accesses the floodplain during high flow events energy is dissipated, channel erosion is reduced, groundwater aquifers are recharged, and sediment, nutrients, and organic matter are distributed across the floodplain. The third parameter that describes hydraulic functioning is groundwater/surface water exchange (Harman, et al., 2012), also known as hyporheic exchange. Planform, sinuosity and bed profile drive hyporheic exchange (Hester and Doyle, 2008). Hyporheic exchange plays a critical role in regulating temperature and water quality (Hester and Doyle, 2008), common goals of stream modification projects. Some in-stream structures, such as steps and weirs, can increase hyporheic exchange in certain environmental settings (Hester and Doyle, 2008). Unlike floodplain connectivity and flow dynamics, the presence and influence of hyporheic exchange on local functioning is highly dependent on the hydrologic and geomorphic setting of the stream channel.

The relative importance of geomorphic functions is also dependent on the setting of the channel (Harman, et al., 2012). For example, in some settings the presence and transport of large wood maintains bedforms and the sediment balance within the channel. Sediment transport capacity and quantity are more important in streams with a high sediment load coming in from upstream (Harman, et al., 2012). Stream modification practices can directly impact the formation and location of bedforms within the reach, install bed material, arrest channel evolution, control lateral stability, and plant riparian vegetation. Designing for specific flow dynamics in the channel can dictate the sediment transport capacity and competency of the modified reach. A sediment imbalance can lead to deposition which results in embedded bedforms that degrade habitat and prevent hyporheic exchange; or to scour that results in incision, decreasing bank stability and lowering the water table. The water table is tightly coupled with riparian vegetation growth. Riparian planting can greatly impact hydraulic and geomorphic functions through providing bank stability, organic matter, nutrient processing, flood regulation, habitat, and water quality regulation (Sweeney, et al., 2004).

The equilibrium of channels is an important concept in stream modification that is characterized by channel evolution and lateral stability. Not all streams naturally achieve a state of dynamic equilibrium; glacial outwashes and alluvial fans can be naturally unstable (Harman, et al., 2012). Dynamic equilibrium is described as a channel adjusting to sediment and hydrological input alterations about an average trend over geological time scales (Gordon, 2004). Steady-state longitudinal river profiles are those that self-maintain a sediment transport rate (Phillips, 2009). In accordance with management concerns, dynamic equilibrium is defined for applied use in stream modification as lateral and vertical rates of change that are slow relative to engineering time scales, are not accelerating, and occur within the context of a balanced sediment regime (Rhoads, et al., 2008). This definition contrasts with the natural state of dynamic equilibrium and will be referred to a static equilibrium in this research.

Strongly related to the idea of equilibrium in stream channels and riverine ecosystems is the concept of ecological resilience. The resilience of a stream is the capacity of the channel to absorb disturbance and return to a stable state (Gunderson, 2000; Leuven and Poudevigne, 2002). Ecological systems can have multiple stable states and significant disturbance, such as watershed development or a large flood event, can change the stable state of the system (Gunderson, 2000). Streams are changing ecosystems that may undergo cycles of organization and collapse and have multiple stable conditions (Leuven and Poudevigne, 2002). This idea contributes to the conflict over the term stream restoration in urban settings, the goal may be stable channel or state of static equilibrium which may be different from the pre-disturbance, dynamic equilibrium state of the stream. The pre-disturbance equilibrium state may be desirable but unachievable depending on the type, amount, and duration of disturbance to the system. Stream modification projects that target static equilibrium intend to build a resilient system with one desired stable state through rigid engineering rather than a naturally resilient system that allows for transition between multiple stable states as complexity increases between natural disturbance events.

2.2 – Current Measures for Success and Failure

In the field of restoration ecology the term success is used in a many different ways with various meanings while mention of failure is rare (Zedler, 2007). Due to the stochastic nature and dynamism of stream systems, it is difficult to clearly delineate the line between success and failure (Kondolf and Micheli, 1995). Stream modification projects can be evaluated by a combination of objective and subjective criteria that include biodiversity, ecological traits, geomorphology, aesthetics, recreational value, education, advancement of restoration science, and economic benefits (Jahnig, et al., 2011; Palmer, et al., 2005). Project managers have reported aesthetics and public opinion as the primary indicators of success (Palmer, et al., 2007). While a positive opinion concerning project appearance may indicate social and political success of a project it does not indicate an improvement in stream functioning.

A list of criteria for establishing ecological success of a stream modification project requires physicochemical and biological improvements in the modified channel (Palmer, et al., 2005). In a study that reviewed the performance of urban stream modification projects (Brown, 2000) failure was based on physical attributes of installed practices, channel stability, and habitat while success was not attributed because the "true measure of success in stream restoration is how the aquatic community responds, which can only be assessed through biological monitoring" (Brown, 2000, p. 12). The Ohio Department of Natural Resources (Mecklenburg and Fay, 2011) measured success by ecological integrity, focusing on measurable channel characteristics that were necessary to ecological function and a product of the modification design. Research on measuring success of stream modification projects focuses on ecological improvements in the modified channel (Mecklenburg and Fay, 2011; Brown, 2000; Roni, et al., 2008; Ryder and Miller, 2005).

Success and failure are best determined by comparing the outcome of a project to the objectives of the design. Project goals and objectives are achieved in the design by implementing various techniques and installing structures with potential benefits that achieve project goals. A project that intends to protect infrastructure through hard bank stabilization could choose from the practices in Table 2-3 according to environmental project objectives. Live log crib walls have the potential to support four of the five most common goals in Table 2-2. Live log crib walls could protect infrastructure and enhance water quality, specifically the level organic carbon in the water, but measuring organic carbon is considered complex and intensive (Harman, et al., 2012). Since monitoring can be seen as costly and unnecessary (Skinner, et al., 2008) resources are not likely to be relegated to intensive chemical or biological monitoring. Additionally, project goals may not specify what aspect of water quality was impaired or targeted. Vague objectives have left the evaluation of project performance highly uncertain (Skinner, et al., 2008; Brown, 2000). When adequate biological and chemical monitoring is not implemented or objectives are vague, the determination of success is simply the absence of failure.

2.2.1 – Determining Failure of Stream Modification Projects

Due to the unique nature of projects and a lack of quantifiable goals, when discussing failure it is common to discuss the performance of individual structures or practices (Brown, 2000). There is a significant body of research on the performance and failure of structures in stream modification projects (Frissell and Nawa, 1992; Thompson, 2002; Mooney, et al., 2007a; Brown, 2000; NRCS, 2007; Johnson and Brown, 2001; Roper, et al., 1998). Structural integrity is a popular measure of performance and failure because any intended benefits to the system may cease to be provided if the structure is damaged (Roper, et al., 1998).

Stream modification project managers in the Chesapeake Bay watershed interviewed as part of the NRRSS reported that public disapproval was the most common reason for claiming failure (Hassett, et al., 2007). The few respondents who considered their projects only partially successful or unsuccessful reported that the system did not respond as intended, natural disturbance, and structural failure as cause (Hassett, et al., 2007). A survey of water managers in Germany determined that success and failure were most often determined by gut feelings and that structural changes were the primary contributor to success (Jahnig, et al., 2011). Both of these studies reported structural integrity as a common source of failure.

While the success of stream modification projects may be measured by chemical and biological functional lift or improvement, the failure of projects has primarily been measured by the performance of stream modification practices. Stream modification practices alter hydraulic and geomorphic parameters (Figure 2-3) of stream channels (Harman, et al., 2012). In order to achieve the goal of functional lift, it is prudent to understand how lower level functions support higher functions. The NRRSS (Palmer, et al., 2007) concluded that improving restoration outcomes requires knowledge of how ecological processes are connected to hydraulic and geomorphic processes. The EPA reviewed stream assessment protocols (Somerville and Pruitt, 2004) and found that even though biological assessments are used to determine quality of stream resources, data on habitat, water quality, and geomorphology are more useful for stream modification design. A project design that does not recognize the complex relationships between form and processes in stream channels is likely to harm both the river form and function processes (Beechie, et al., 2010).

2.2.2 – Failure Modes of Structures

Structural and functional failures of stream modification practices lead to the perception that the stream modification project has failed (Hassett, et al., 2007; Niezgoda and Johnson, 2012; Johnson and Brown, 2001). A common approach to assessing failures of structures is to compile an exhaustive list of ways for individual structures to fail (Haldar and Mahadevan, 2000). Niezgoda and Johnson (2007) defined failure modes for stream modification projects as the ways in which a component of a structure could lead to the intended design function not being achieved. In a recent review on the performance of various structures, five separate definitions of failure were noted that fall into two clear categories: failure to stay in place and failure to function as intended (Niezgoda and Johnson, 2012). While structure displacement is easier to assess, structures that remain in place are not guaranteed to provide the benefits; i.e. the structures may not function as intended (Palmer, et al., 2010; Salant, et al., 2012). Therefore it is important to consider modes of failure that characterize both a failure to stay in place and a failure to function as intended.

Structure performance and failure of stream modification practices have been studied for decades as case studies of individual projects (Salant, et al., 2012; Klein, et al., 2007; Levell and Chang, 2008; Kondolf, 2011) and across multiple projects (Frissell and Nawa, 1992; Brown, 2000; Mooney, et al., 2007a; Violin, et al., 2011). Researchers have also used theory or models to study failure in individual practices under various conditions (Unger and Hager, 2006; Akter, et al., 2012; Kail, et al., 2007). Brown (2000) asked what percent of structure components have moved, whether the whole practice was displaced, the degree of unintended erosion, and the degree of unintended deposition. These questions cover the most common failure modes for a variety of stream modification practices: structure displacement, excessive erosion around the structure, and burying from sediment deposition (Mooney, et al., 2007a; Miller and Kochel, 2013). Table 2-4 provides a summary of common failure modes for various stream modification practices found in literature. Some failure modes are causal in that they lead to other failure modes; e.g. structure undermining leads to displacement. Excessive erosion is an easily detectable symptom of other failure modes including rapid widening, lateral migration, bed degradation, head cutting, undermining, and growth of scour pool (Niezgoda and Johnson, 2007).

In order to compile a comprehensive list of failure modes, it is recommended to consider whether the intended function is performed in the intended manner, such that safety standards and regulations are met, and at an appropriate performance level (Bluvband and Grabov, 2009). Also consider whether an unintended and undesired function is performed (Bluvband and Grabov, 2009). The failure modes in Table 2-4 primarily focus on structure functions of staying in place and preventing erosion. Since project objectives and intended functions of installed practices are not limited to structural integrity and preventing erosion this list is not exhaustive. Intended functional lift of stream modification projects must also be considered in addition to unintended degradation of channel functioning.

Table **2-4**: Failure Modes of various practices. Primary references include Brown (2000); Niezgoda and Johnson (2007); Niezgoda and Johnson (2012); Mooney, et al. (2007a); Akter, et al. (2012); Unger and Hager (2006); and Miller and Kochel (2013) additional references provided in table.

Failure Mode	**Example Practices**
Ineffective structure design or installation	All practices
Structural displacement	All practices
Sliding or rolling	Riprap, A-jacks, boulder revetments, step pools, constructed riffles
Slumping	Riprap, geobags
Structure overturning	Imbricated riprap, live cribwalls
Excessive scouring adjacent to structure	Riprap, imbricated riprap, boulder revetments, log revetments
Rapid lateral migration or channel widening	Weirs, vanes, constructed riffles, linear deflectors
Structure undermining	Riprap, imbricated riprap, geobags, log revetments, A-jacks
Bed degradation and head cutting	Weirs, vanes
Physical damage from debris, ice, rot, or root growth	Live cribwalls, lunkers, log revetments
Mass wasting	Riparian planting
Growth of scour pool	Weirs, vanes, J-hooks
Scour of bank opposite structure, upstream or downstream of structure	Riprap, imbricated riprap, boulder revetments, live cribwalls
Excessive sediment deposition	Lunkers, weirs, vanes, constructed riffles
Seepage (Hagerty and Parola, 2001)	Riprap
Flow piping under header rocks or through arm	Weirs, vanes, log revetments
Overtopping	Riprap, imbricated riprap, A-jacks
Vegetation death	Live cribwalls, riparian planting

A lack of clear objectives can make the intended function of installed practices difficult to ascertain. Some studies have sorted structures into functional categories in order to evaluate intended functions of structures. Functional categories for stream modification practices include hard bank protection, soft bank stabilization, grade control, flow deflection, flow concentration, and in-stream habitat structures (VA DCR, 2004; Schueler and Brown, 2004). These functional categories can assist in deciding whether the major intended design function is being achieved when intended functions are not reported.

Stream modification projects aim to improve natural channel conditions and functions through altering the physical form of the channel. Channel form and processes are intricately related and stream modification practices directly target the hydraulic and geomorphic functions of the channel. While considering the intended function of an installed structure is important to performance evaluation, modification practices impact hydraulic and geomorphic stream functions whether they are not targeted or not. Weirs and other large rock structures that span the channel can be used to provide grade control, fish passage, bank protection, floodplain reconnection, and in-channel habitat (Mooney, et al., 2007a). While all of these functions may not be relevant to every site they will all be affected when a weir is installed. If a cross vane is installed solely to provide grade control it will also affect fish passage, channel habitat, and floodplain connection and may impact bank stability. All of the hydraulic and geomorphic parameters in Figure 2-3 should be considered when evaluating stream modification practices.

2.2.3 – Application of Damage States to Complex Systems

Damage states have frequently been used to define threshold levels of damage experienced by structural components due to high loading events, such as earthquakes (Gulec, et al., 2011). In multi-component systems loading can cause various defects to occur simultaneously and failures can result from any number of defect permutations (Gulec et al., 2011). Bridges are one application in which damage states are effective in describing damage and failure to multi-component systems. Bridges that cross streams have distinct damage states for a multitude of components considered in HAZUS99-SR2. The Oregon Department of Transportation (ODOT, 2009) summarized the damage states described by HAZUS99-SR2 bridge model into damage states that describe visible damage to various bridge components, such as the abutment, shear keys, deck, and columns. A level of required repair is associated with the damage states; a complete failure requires replacement while slight damage requires no more than cosmetic repair.

Damage states are common in structural engineering and have been successfully applied to water infrastructure and environmental systems as well. National Oceanic and Atmospheric Administration (NOAA) applied damage states to combine economic, business, social, and environmental impacts in risk assessment of natural hazards (Flax, et al., 2002). In each step of the assessment, data from various components or stakeholders were used to determine priority states based on potential damage (Flax, et al., 2002). In considering risks to infrastructure, a partitioned multi-objective risk method is used to understand the consequences of an initiating event, such as an attack, on infrastructure (Ezell, et al., 2000a). An event tree is created with a series of events that could follow the initiating event that ends in various consequences, or states of damage. Ezell et al. (2000b) provided an applied example of the partitioned multi-objective risk method to a municipal water distribution system in which the initiating event was a water tank contamination. The final damage states in this example were a small, medium, or large percent of people exposed to contamination.

Damage states have not been directly applied to stream modification but their utility in describing damage to stream systems and modification practices has been demonstrated. One study on the performance of stream modification structures defined a state of partial failure in which physical damage had occurred but the intended function was still being performed (Holburn, et al., 2009). A study on riprap failure in streams near bridge piers outlines four stages of damage that lead to failure of the riprap (Unger and Hager, 2006). In the study on urban stream modification practice performance, responses to evaluation criteria had brackets for the percent of original practice remaining intact and described damage due to unintended erosion, deposition, and soil erosion as none, slight, moderate, or significant (Brown, 2000). In one study (Miller and Kochel, 2013), 558 practices (rock cross vanes, rootwads, log and rock vanes, J-hooks, and weirs) were assessed using a rapid field assessment that rated erosion and deposition near structures on a scale of 0 to 5 and rated structures as intact, damaged, impaired, or failed. In order to reduce subjectivity, evaluations such as those listed provide detailed descriptions of damage criteria (Miller and Kochel, 2013).

Similar to the performance assessment tools above there are protocols in use that define states of quality (not damage) for physical parameters of natural channels. The widely used rapid bioassessment protocol has a habitat assessment tool that ranks 10 physical habitat parameters on a scale of 0 to 20 (Barbour, et al., 1999). For each of the ten habitat parameters a score of 0 to 5 represents a poor habitat state, 6 to 10 represents a marginal state, 11 to 15 is suboptimal, and a score of 16-20 is optimal habitat. In order to protect bridges from stream instabilities, a channel stability assessment tool rates thirteen channel stability indicators as poor, fair, good, or excellent (Johnson, 2005). An overall classification for the channel of poor, fair, good, or excellent is assigned based on the sum of the thirteen scores and the type of channel (pool-riffle, cascade, braided, etc.). Both of these assessments evaluate the overall condition of the stream system by combining multiple components of the system.

Stream functioning depends on a complex combination of processes relating surface water behavior, groundwater exchange, sediment transport, channel morphology, and many more processes. Stream modification directly alters the ability of the channel to transport water and sediment in the channel and to the floodplain, affecting the physical habitat in the channel. By applying damage states to the hydraulic and geomorphic functions of modified stream channels, a continuum of damage to installed practices and physical channel characteristics could be used to assess risk a define failure of stream modification projects.

2.3 – Methods for Assessing Risk in Modified Streams

Risk and uncertainty need to be explicitly addressed in stream modification projects (Suedel, et al., 2012). The purpose of a risk and vulnerability analysis is to allow decision makers to identify and prioritize risks and vulnerabilities, implement risk-reducing measures, and prepare for failure or hazards (Hokstad, et al., 2012). Uncertainty contributes to risk and the sources of uncertainty in stream modification are numerous. A few of the sources of uncertainty in the practice of stream modification include empirical design tools with limited applicability; a deficit of data necessary for applying these tools; the stochastic nature of flood events; and the instability of climate, land use, and community values (Darby and Sear, 2008). Uncertainty due to limited knowledge and inherent randomness of nature are the two primary types of uncertainty in the practice of stream modification (Wheaton, et al., 2008). In order to further the practice of stream modification the first source of uncertainty must be addressed and the second embraced. Risk analyses can help practitioners manage both types of uncertainty and yield informed expectations.

The first stage of risk analysis is preparation. Preparation consists of defining objectives, identifying stakeholders, determining system boundaries. System boundaries include the type of hazard being considered and categories of consequence. Consequence categories consist of the type and dimensions of consequences considered. Hazard causes are identified along with societal critical functions related to the hazard. Societal critical functions include electricity supply, water and sewage transportation and treatment, and transportation networks. Once the consequences of the identified hazard are understood, the factors that affect the probability of hazard occurrence and consequences comprise a vulnerability analysis. The final step of the risk analysis is to assess risk and suggest methods to reduce risk. (Hokstad, et al., 2012)

The EPA has published guidelines for ecological risk assessment (EPA, 1998) that echo the steps outlined above promoting problem formulation, characterization of exposure (vulnerability), and characterization of ecological effects or consequences. An approach to risk assessment was recently published specifically for managing risk and uncertainty associated with ecological restoration (Suedel, et al., 2012). Risk is defined by the likelihood and consequences of adverse effects which can be assessed by risk-ranking methods or quantitative methods, if sufficient data is available. Quantitative methods, including Monte Carlo Simulation, require significant resources and time to perform (Suedel, et al., 2012). Johnson and Brown (2001) examined the uncertainty associated with the practice of stream modification and found that quantitative analyses, such as Monte Carlo simulation, require considerable detailed information and quantified parameters to characterize the system. Detailed analyses such as these can be ruled out as inappropriate due to the system complexities and lack of data (Johnson and Brown, 2001). This section will focus on risk-ranking methods for describing risk and uncertainty of stream modification projects. Risk-ranking methods, such as failure modes and effects analysis, fault trees, and vulnerability-criticality risk matrices can use available quantitative data to evaluate relative risk (Suedel, et al., 2012).

2.3.1 – Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) is a systematic framework that identifies, evaluates and prevents system failures (Bluvband and Grabov, 2009). In order to perform FMEA an exhaustive and mutually exclusive list must be made of all possible failure modes of the system being studied (Haldar and Mahadevan, 2000; Johnson and Brown, 2001). After compiling this list, the effects and likelihood of failure mode occurrence are used to calculate a risk priority number that focuses attention and resources on the highest risk failure modes in the system (Johnson and Brown, 2001). This method is noted as very effective in systems where function continues (components continue to carry loads) after failure has occurred and where the primary failure mechanism can be determined (Haldar and Mahadevan, 2000).

Johnson and Brown (2001) applied this method to the design of stream modification projects to determine the relative risk of design components in a stream modification project. The design components considered were vanes, rootwads, cross sectional geometry change, channel relocation, and meander construction. Failure modes for each component and the consequences (C) of each failure mode were considered with respect to other system components and the whole system. The likelihood of occurrence (O) was determined based on professional experience and published studies on practice performance. The ease of detection (D) for every failure mode was also considered. These three criteria were evaluated on a numerical scale and their product provided a risk priority number (RPN) that could be used to reduce risk of failure of individual structures.

FMEA has also been applied to selecting measures to prevent scour near bridges (Johnson and Niezgoda, 2004) and selecting bank stabilization measures (Niezgoda and Johnson, 2012). The most recent study took the method a step further in detail and performed a cost-benefit analysis (Niezgoda and Johnson, 2012). Table 2-5 below provides an example of FMEA applied to two failure modes of imbricated riprap and shows that structural displacement of imbricated riprap is a higher priority risk than excessive scour (Niezgoda and Johnson, 2012). This study also calculated benefit priority numbers following the same procedure used to calculate the risk priority numbers, multiplying potential benefit with likelihood of occurrence and ease of detection (Niezgoda and Johnson, 2012). By also considering the costs of repair and construction, these studies took qualitative and quantitative input and ranked stream modification practices to inform decision making and reduce risk.

The primary limitation of FMEA is the potentially subjective nature of the criteria established for rating consequences, occurrence, and detectability (Johnson and Brown, 2001).

Care must be taken in defining the criteria and scoring of these terms before applying the FMEA. In cases similar to those mentioned, where published studies are used to determine occurrence values, the unique setting of the project may be effect the likelihood of failure.

Table **2-5**: FMEA analysis of two failure modes for Imbricated riprap. Adapted from Niezgoda and Johnson (2012).

Failure Mode	**Consequences for other components**	**Consequences for system**	**C**	**O**	**Detection Criteria**	**D**	**RPN**
Excessive scour	Clog downstream infrastructure	Downstream deposition	6	10	Bank scalloping, bank cutting, vacancies between rocks	1	60
Structure displacement	Slide into other measures	Bank erosion, lateral movement, sediment input	8	6	Rock movement downstream, wall pulling away from bank	4	192

2.3.2 – Fault Tree Analysis and Cut Sets

Fault trees are a detailed causal risk analysis (Hokstad, et al., 2012) that have been applied to scour at bridges (Johnson, 1999) and infrastructure failure in urban stream modification projects (Hess and Johnson, 2001). A fault tree is a detailed hierarchy of unions and intersections of events that contribute to a system failure (Haldar and Mahadevan, 2000). This analysis can be either qualitative, providing information on the relative importance of events that lead to failure, or quantitative, calculating the probability of event sequences (Johnson and Brown, 2001). Cut sets are subsets of a fault tree in which combinations of basic events that are known to lead to failure are considered. A cut set is usually applied to qualitative analyses in which information is known about relative importance of basic events that lead to failure.

Johnson (1999) applied quantitative fault tree analysis to the failure of a bridge due to scour. Bridge scour can be divided into independent categories of erosion consisting of local scour at abutments or piers, contraction scour near the bridge opening, and channel degradation, widening, or lateral migration. These five categories can lead to failure at the bridge abutment or a bridge pier, either of which would indicate a system failure. In this example, fault tree analyses provided a systematic method to assess risk in a riverine system where failure was dependent on processes that are not fully understood or predicted (Johnson, 1999). The analysis was quantitative; estimates of the probability of occurrence of each failure mode were obtained through simulation.

Fault tree analysis was also applied to stream flow induced infrastructure failure in urban stream modification projects (Hess and Johnson, 2001). Infrastructure failure in the urban stream corridor, and thus failure of the stream modification project, occurred when property was damaged or lost, or sewer lines, water lines, a road embankment, culvert, or bridge failed. The failure of each infrastructure component can be broken into multiple sequences of sub-events and terminal events. Sub-events in this analysis consist of hydraulic and geomorphic deficiencies in addition to structural inadequacies. For example a culvert can fail due to planform change that occurs because of lateral migration and a change in channel slope or due to an inadequately sized culvert and a flood event (Hess and Johnson, 2001). The probabilities of occurrence for the numerous terminal events in this analysis were unknown and therefore quantitative analysis was not possible. A qualitative analysis was performed that identified critical paths to failure and the most common terminal events that could lead to failure (Hess and Johnson, 2001). Critical paths to failure, also known as cut sets, are the paths to failure that require the fewest events to occur. For the culvert failure example discussed above the most critical path to failure was determined to be a debris jam, requiring only one event to result in failure.

The two examples presented above demonstrate that both quantitative and qualitative fault tree analyses can be useful in identifying vulnerabilities and informing design and maintenance for work in stream channels. Fault tree and cut set analysis is most effective in binary and unchanging systems; dynamic systems with multiple states may not be well suited for this analysis (Hokstad, et al., 2012; Johnson and Brown, 2001). Hess and Johnson (2001) were able to define project failure in terms of infrastructure failure, meeting social and political goals of their example stream modification project but their analysis neglected environmental goals related to functional lift. In order to perform fault tree or cut set analysis it is necessary to first define system failure (Johnson and Brown, 2001).

2.3.3 – Risk Matrices

A vulnerability-based risk assessment has recently been applied to stream instability at bridges (Johnson and Whittington, 2011). This study implemented a relative risk assessment that utilized a risk matrix. Risk matrices are semi-quantitative analyses that break probability of hazard occurrence and consequences of occurrence into discrete intervals that combine to map to relative risk ratings (Hokstad, et al., 2012). Risk matrices sort situations into three categories: those that require risk-reducing measures and more analysis; those for which risk-reducing measures should be considered; and low priority risks (Hokstad, et al., 2012). Risk matrices have been used by a range of federal agencies, including the Federal Highway Administration (Ashley, et al., 2006), the Federal Aviation Administration (FAA, 2000), and the EPA (EPA, 2010).

The EPA (2010) has produced risk assessment software for water and wastewater utilities (VSAT) in which risk is defined as the product of three dimensions: consequences, vulnerability and likelihood of threat occurrence. Risk is reduced by decreasing vulnerability to or consequences of the hazard and reductions are measured using a risk reduction unit matrix (EPA, 2010). This risk reduction matrix is similar to the risk-logic matrix applied to vulnerability and criticality ratings used by the (FAA) shown in Figure 2-4 and applied to bridges by Johnson and Whittington (2011).

Vulnerability \ Criticality		1	2	3	4
		Catastrophic	Very Serious	Moderately serious	Not serious
A	Extremely high probability	**1A**	**2A**	**3A**	**4A**
B	Very high probability	**1B**	**2B**	**3B**	**4B**
C	Moderately high probability	**1C**	**2C**	**3C**	**4C**
D	Low probability	**1D**	**2D**	**3D**	**4D**

White shaded cells are those in which the risks are unacceptable, striped cells are situations in which the risks may be acceptable. The grey cells are those in which the risks should be unacceptable but risk review agencies may choose to accept these risks.

Figure **2-4**: Risk-Logic Matrix for criticality and vulnerability from the FAA Security Risk Management Guide (FAA, 2000).

Vulnerability, the likelihood of damage, has been characterized for environmental resources, such as coastline and groundwater aquifers, by combing multiple descriptive parameters of the resource. The coastal vulnerability index (CVI) uses six geologic and physical process variables that affect coastal evolution: geomorphology, historical shoreline change rate, regional coastal slope, relative sea-level change, mean significant wave height, and mean tidal range (Pendleton, et al., 2004). In this study (Pendleton, et al., 2004) each variable is rated on a scale from very low (1) to very high (5) and the values delineating these categories were calibrated for Assateague Island National Seashore. Ratings were combined by taking the square root of the product mean of the ranked variables. The CVI implemented the product mean after testing six amalgamation methods and it was determined to be more sensitive than formula based on the mean of the parameters (Gornitz, et al., 1994). The vulnerability of groundwater to pollution is often determined using the DRASTIC model which combines seven aquifer parameters using the weighted sum method (Saatsaz, et al., 2011; Aller, 1985). A weighted sum method is the most common amalgamation method applied in multi-criteria decision making (Hobbs and Meier, 1994; Husdal, 2005). In both of these procedures the result of combining the parameter ratings is used to determine a relative vulnerability such as those in Figure 2-4.

The criticality, or consequences, of hazard occurrence can similarly be described by combining multiple parameters. For stream modification projects consequences of project damage or failure may include damage to infrastructure, economic losses, and degradation of stream functioning. The Department of Homeland Security (DHS) has 16 sectors of critical infrastructure and performs large scale risk analysis within and between these sectors. In calculating risks within the transportation sector, values for cargo and passenger volume, proximity to population centers, and system dependence are considered (DHS, 2010a). The population served, onsite stored chlorine, and critical customers served (i.e. level 1 trauma, large venues, etc.) are considered by the water sector when calculating risk (DHS, 2010b). The VSAT assesses criticality in four categories across two dimensions for water and wastewater utilities (EPA, 2010). Societal consequences are quantified by the expected number of fatalities and injuries and economic consequences are measured by utility financial impact and regional financial impact.

A study by Johnson and Whittington (2011) applied vulnerability-based risk assessment that utilized the risk-logic matrix shown in Figure 2-4 to determine the relative risk of bridge loss due to stream stability problems. Vulnerability and criticality assessments were made primarily using information from the National Bridge Inventory (NBI) (FHWA, 1995). Four factors contributed to vulnerability, a stream stability assessment rating (Johnson, 2005) and three items from the NBI: channel condition, waterway adequacy, and scour criticality. The weighted sum of these four factors was used to determine a vulnerability category of low (D), moderate (C), high (B), or very high (A). Criticality measured the consequences and impacts of the bridge loss and considered factors from the NBI related to the cost to replace the bridge and the service provided by the bridge including increased travel time, functional class, and average daily traffic.

While risk matrices have been widely applied as an effective and simple risk assessment tool, in some situations the application of risk matrices has been noted to result in poor resolution, errors in final risk categorization, suboptimal resource allocation, and ambiguous inputs and outputs (Cox, 2008). One limitation especially applicable to stream modification is ambiguity since uncertainties can leave the categorization process subjective. Subjective categorization can be limited by developing and testing procedures similar to those in the bridge loss vulnerability analysis. Additionally if factors are missed in the vulnerability and criticality dimensions of the assessment then the results would be inaccurate (Cox, 2008).

2.4 – References

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Chapter 3

Describing Damage to Stream Modification Projects

The failure of a stream modification project is often a subjective determination. One primary reason that determining failure is difficult is because measurable and unambiguous goals seldom exist for a stream modification project. This research addresses this hindrance and describes a tool for rapid assessment of damage to stream modification projects. The term stream modification is used to describe the manipulation of channel form that takes natural stream processes into account or employs environmentally sensitive practices. As stream modification projects are required to increase stream functions, damage states are described based on the hydraulic and geomorphic functioning of the modified channel. Assessing damage to stream modification projects based on their hydraulic and geomorphic functioning will improve the practice of stream modification by focusing on the processes that control channel conditions. A stream modification project focused on processes, rather than solely on form, is more likely to yield stable conditions that protect infrastructure, property, and the environment. The proposed framework utilizes criteria consistent with the best available science to systematically assess damage to basic channel functions.

The damage states are intended to assess the condition of stream modification projects lacking clear objectives and resources for monitoring. A minimum level of knowledge related to stream modification and stream ecosystems is necessary to apply the damage states. The practice of stream modification is multidisciplinary and practitioners should meet minimum knowledge requirements laid out in the Stream Restoration Body of Knowledge (Niezgoda, *et al.,* 2014). This research focuses on wadeable streams, first to fourth Strahler order streams (EPA, 2013a), on which stream modification projects are most often performed (Hill, et al., 2011). The damage states are not meant to be used for monitoring the progress, success, or failure of a project.

Monitoring is an essential component of stream modification and a monitoring plan that is tailored to the ecological and social goals of the project should be implemented to assess project success and failure when resources are available. The damage states provide a standard of measure for completed stream modification projects in the event that no monitoring or post-project assessment was performed and knowledge of pre-modification conditions is limited.

3.1 – Levels of Achievement

Due to the wide variety of techniques implemented in stream modification design, damage to stream modification projects is discussed according to the level of achievement of the project. This research groups projects into levels of achievement based on the functions that are directly altered by the project design. Stream modification practices alter the form of the channel, impacting hydraulic and geomorphic processes by manipulating the physical characteristics of a stream reach (Figure 3-1). Although these functions can vary significantly in form and importance between different regions, collectively they govern the physical shape of every stream channel.

Stream modification projects were grouped into levels of achievement following the naming convention used to evaluate sustainable infrastructure (ISI, 2012). Within this rating system, credits are awarded for a variety of sustainable practices including those that preserve aquatic functions of wetlands and streams. The six levels of achievement for sustainable infrastructure are conventional, improved, enhanced, superior, preserving, and restorative (ISI, 2012). While the six levels of achievement can be applied to the management of streams, only four are considered stream modification as defined in this research. The least sustainable level of achievement, conventional, considers the channel solely as infrastructure for the built environment. Conventional projects alter the channel without regard for natural function and consist of practices such as concrete channels or drainage systems. The other five levels of achievement consider the role of the channel in the natural environment to progressively greater extents.

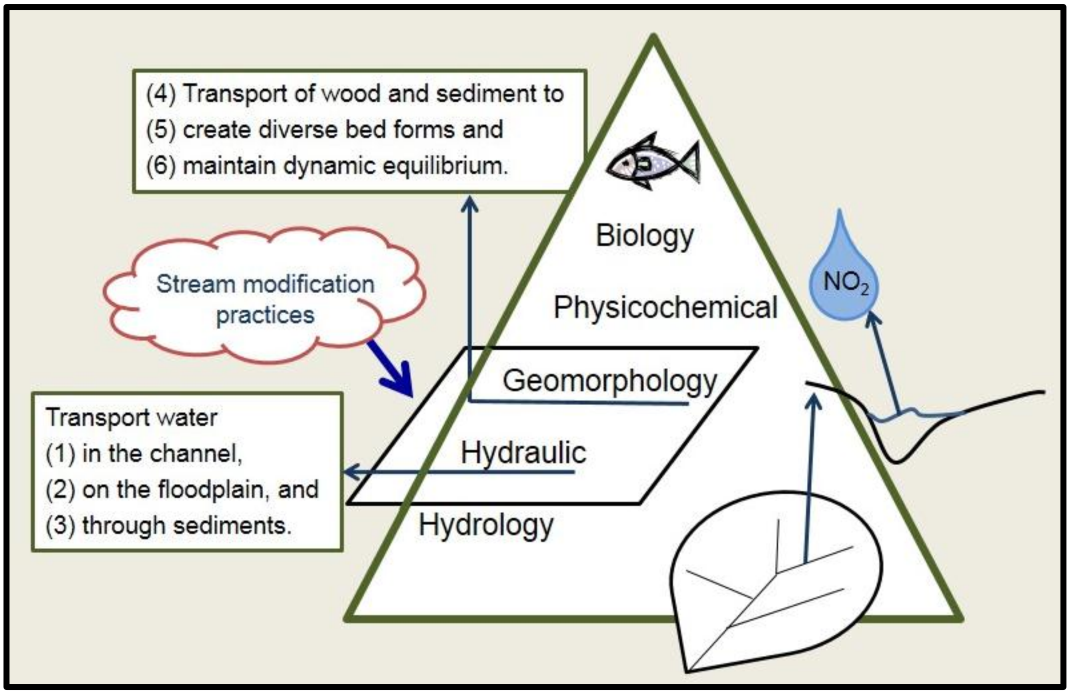

Figure **3-1**: Hydraulic and geomorphic functions of the stream functions pyramid (modified from Harman, et al., 2012).

The improved level of achievement consists of practices that harden a channel bank in place without constraining an entire channel cross section. The practice of hard armoring stream banks is a common response to large flooding events when infrastructure may be threatened by bank erosion (Schiff, et al., 2006). Improved projects use unnatural rigid design practices (Table 2-1) to permanently arrest bank erosion, often to protect infrastructure or property while allowing natural function to continue and potentially offering some benefit to natural stream functioning. At this level of achievement the channel is expected to maintain a state of static equilibrium, i.e. minimal adjustments to disturbances are expected surrounding the armored bank. Improved practices directly alter the transport of water in the channel and to the floodplain through changing the dimension, roughness, and composition of the bank to permanently armor and protect streambank surfaces.

Stream modification projects that fall into the enhanced level of achievement are common, particularly in urban environments. These projects implement semi-natural form design (Table 2-1) to attain a permanent state of static equilibrium using in-stream structures to harden cross sections and constrain the planform and profile. Enhanced projects confine the channel shape which governs the transport of water, wood, and sediment in the channel. These projects affect all hydraulic and geomorphic functions in the channel while targeting a state of static equilibrium instead of dynamic equilibrium (see Figure 3-1). An enhanced project could entail relocating a portion of a channel and locking the new channel in place with structures. Alternatively, an enhanced project could consist solely of one or two hardened structures across the channel in place to arrest erosion or degradation. In both of these cases the channel planform and profile are constrained where cross sections are hardened. Adjustments to disturbance are very limited in enhanced projects as lateral and vertical movement can impact installed structures.

The superior level of achievement is similar to the enhanced level of achievement but these projects target dynamic equilibrium. Superior projects use semi-natural form and natural processes design (Table 2-1) to temporarily arrest the channel planform, profile and cross sections while natural stability develops. Since the project targets dynamic equilibrium, gradual channel adjustments are acceptable within a wide floodplain. Rapid channel adjustments would be indicative of instability and considered damage in these projects. All hydraulic and geomorphic functions are directly affected in superior stream modification projects.

The preserving level of achievement is passive and entails the prevention of impacts to natural stream functioning. When it is possible to do so, preservation of habitat and natural functioning is preferable to stream modification. Impacts to the stream include direct impacts to the channel and alterations in the watershed that lead to degradation within the stream. Therefore preservation techniques can include the protection of the channel and large portions of the watershed. Preserving projects do not include any manipulation of physical channel characteristics.

The final level of achievement used in describing sustainable infrastructure is restorative. Restorative stream modification projects aim to restore all natural stream functioning; hydraulic, geomorphic, physicochemical, biologic, and in some cases hydrologic. Restoration requires detailed knowledge of a previous or desired state, an understanding of local conditions and processes, and room to allow for adjustments to disturbances. While restorative projects are desirable, permanent disturbances to the channel, floodplain, or watershed can prevent the restoration of a stream channel to a previous condition.

The four levels of achievement applicable to stream modification projects, expectations, and affected functions are summarized in Table 3-1. The conventional and preserving levels of achievement are not considered stream modification as defined in this research. Conventional projects modify a stream channel without regard for natural functioning and the preserving level of achievement is passive. Passive techniques employed in preservation do not physically alter the stream channel.

When considering static equilibrium versus dynamic equilibrium the idea of system resilience, the capacity of the channel to absorb disturbances and return to a stable state, is important. The stable state is characterized by the equilibrium, dynamic or static, sought by the project design. Dynamic equilibrium has been defined for managed systems as channels in which rates of change are slow relative to engineering time scales. Static equilibrium requires minimal adjustments and tolerates no rate of change. While static equilibrium can be necessary to protect property or infrastructure, it restricts resilience because channel adjustments may be interpreted as damage. Therefore enhanced projects restrict resilience the most, requiring static equilibrium across entire cross sections. Improved projects have a higher capacity for resilience provided that one bank is relatively free to adjust to disturbances. Superior and restorative projects that target a natural state of dynamic equilibrium would tolerate more adjustment and have more resilience.

Table **3-1**: Levels of achievement for stream modification projects and associated expectations, affected functions, and examples of practices at each level.

Level	**Expectation**	**Affected Functions**[1]	**Example of practice**[2]
Improved	Unnatural rigid design Permanent	Static Equilibrium 1, 2	Riprap, revetments
Enhanced	Semi-natural form design Permanent	Static Equilibrium 1, 2, 3, 4, 5	Vanes, Cross vanes, Step pools
Superior	Semi-natural form design Semi-permanent	1, 2, 3, 4, 5, 6	Coir fiber logs, Brush mattresses
Restorative	Full ecological restoration to reference or baseline condition	All functions	Live stakes, LWD placement

[1] The numbers in this column refer to the functions numbering in Figure 3-1.
[2] Practices are discussed in detail in Section 2.1.1, Table 2-1, and Appendix A.

Due to spreading development and the need to effectively manage natural resources as part of the built environment, the improved and enhanced levels of achievement are the focus of this research. In order to describe damage to stream modification projects, it is necessary to define the criteria used to evaluate damage for projects at both the improved and enhanced levels of achievement.

3.2 – Damage States

The damage states are an assessment tool specifically for modified channels based on widely used stream assessment tools, such as the habitat assessment in the EPA rapid bioassessment protocol (Barbour, et al., 1999) and the channel stability assessment at bridge crossings (Johnson, 2005). The damage states are not intended to be used for monitoring progress in modified channels.

Damage states were developed for improved and enhanced levels of achievement. At each level of achievement a set of damage categories evaluates the functions affected by the stream modification project (Table 3-1). Each category of damage is assessed as being not damaged, moderately damaged, extensively damaged, or completely damaged for the whole project reach. Both improved and enhanced projects target a state of static equilibrium that is evaluated by three categories of damage: *infrastructure protection*, *structural integrity*, and *bank stability and migration*. These three categories of damage address the impact of flow on local property and structures installed in the project reach. They also evaluate the hydraulic and geomorphic parameters of flow dynamics and lateral stability (Figure 2-3). Improved projects have one additional category of damage that further characterizes local impacts and evaluates floodplain connectivity. Enhanced projects have three additional categories of damage that evaluate the hydraulic and geomorphic parameters of floodplain connectivity, sediment transport competency and capacity, large woody debris transport and storage, riparian vegetation, bedform diversity, and bed material characterization.

If available, plan sets that depict the design or as-built conditions are very useful in evaluating multiple categories of damage. Damage assessment is possible without design documents but it would be necessary to contact someone who is knowledgeable of the design and construction of the project. The framework proposed in this study is most useful in projects with limited resources for monitoring and evaluation; this can sometimes mean that the nature of the project did not require as-built documents. Without as-built documents or knowledge of the design, project conditions following construction can only be inferred and damage may be over or under estimated.

3.2.1 – Damage States for Improved Projects

Improved projects directly affect the transport of water in the channel and to the floodplain, targeting a state of static equilibrium. These functions are characterized using measures of flow dynamics, floodplain connectivity, and lateral stability such as stream velocity, shear stress, bank height ratio, entrenchment ratio, bank erosion hazard index, and bank pins (Harman, et al., 2012). Flow dynamics such as shear stress help maintain the state of static equilibrium in the channel. Excessive shear stress leads to erosion of the bed and bank of the modified channel and can damage infrastructure or installed structures. Floodplain connectivity supports numerous other channel functions and is essential in flood transport and storage. Improved projects typically constrain floodplain dispersal to protect assets of the built environment. Any increase in the flood prone area of the channel can endanger these assets. Lateral stability is a characterization of the bank material and energy balance in the modified reach; easily erodible materials combined with excessive energy in the channel can erode valuable property adjacent to the stream.

Stream modification projects at the improved level of achievement are evaluated based on four categories of damage; *infrastructure protection, structural integrity*, *bank stability and migration,* and *flood hazard*. The overall damage state of a project is the maximum rating in the set of damage categories. The set of improved project damage states is provided in Table 3-2. Each category of damage is discussed in turn and the delineations between categories of damage are explained.

Table **3-2**: Damage state descriptions for the categories of damage at the improved level of achievement.

	None	**Moderate**	**Extensive**	**Complete**
Infrastructure Protection	Infrastructure is not in immediate danger of being unintentionally worn by stream flow.	Erosion has left infrastructure (1) nearer stream flow or (2) more surface exposed to stream flow than as-built design.	Infrastructure shows unexpected signs of vulnerability that has the potential to impact the integrity or functioning of the infrastructure. Infrastructure (1) is exposed to stream flow.	The structural integrity of infrastructure is compromised or infrastructure has failed as a result of stream flow.
Structural Integrity	The median of damage scores for structures in the reach is ≤ 1.75.	The median of damage scores for structures in the reach is ≤ 2.5.	The median of damage scores for structures in the reach is ≤ 3.25.	The median of damage scores for structures in the reach is > 3.25.
Bank Stability and Migration	Banks are stable and vegetated.	Isolated instances of bank failures (mass wasting, undercut, etc.) or raw banks affect 5-30% of reach.	Bank failures frequent or raw banks describe 30-60% of reach. Channel migration is evident anywhere in the reach but thalweg is within design channel limits.	Bank failures prevalent or raw banks describe more than 60% of reach. Thalweg has left design channel limits anywhere in reach.
Flood Hazard	Design flow is contained within the channel and flood prone width has not increased.	Occasional unintended obstructions may alter the modified channel capacity.	Moderately frequent unintended obstructions with considerable sediment accumulation. Modified channel capacity has likely been altered.	Unintended obstructions are frequent or have significantly altered the design capacity of the channel. Flooding limits anywhere within the project reach have been exceeded.

Infrastructure Protection (e.g. water and sewer lines, bridges, culverts, etc.)

There are two types of infrastructure to consider in this category: (1) infrastructure that is not meant to be exposed to flow, such as buried utility lines, sewers, and manholes, and (2) infrastructure that is intended to be exposed to flow, such as bridge piers and culverts. Infrastructure that is intended to be exposed to flow must be evaluated by a professional experienced in assessing erosion and damage of the infrastructure. Infrastructure included in this damage category that is not intended to be exposed to stream flow includes any infrastructure or portion of infrastructure within project limits. If project limits are not defined then this category of damage includes all infrastructure in the flood prone area or near enough the channel to be immediately threatened by project conditions. The flood prone area is the area wetted by a flow stage twice the bankfull depth. If a bankfull depth is not defined then the height of the hardened bank may be used instead. Note that channel migration and bank erosion can alter the flood prone area and place infrastructure in more immediate danger from stream flow.

When the structural integrity of any infrastructure has been impacted as a result of stream flow the stream modification project is completely damaged. Any damage to infrastructure of the first type (1) due to stream flow would qualify as complete damage. For infrastructure of the second type (2), damage must be assessed as exceeding that of normal wear and tear. The progression of damage evaluates whether infrastructure (1) is nearer exposure or exposed to stream flow or whether infrastructure (2) is more exposed than intended or showing signs of unexpected vulnerability to stream flow. This can include minor damage or scour (undermining) that does not endanger the structural integrity but could if the damage continues.

Structural Integrity

A score for the structural integrity of the project reach is calculated from individual damage scores for every structure installed as part of the project. Two failure modes for installed structures are addressed in this category of damage, movement of structure components and local erosion leading to detachment from the bank. Structures installed in improved and enhanced projects are meant to be static and unmoving therefore the structure displacement leads to damage. The channel bank in contact with the structure is intended to be static and unmoving as well; structures in improved projects are specifically intended to protect the bank from erosion. Therefore scour of the bank and bed that is in contact with the structure results in damage to the structure. Damage is described for each structure in the project reach based on damage states developed by Miller and Kochel (2013) for rapid field assessment of in-stream structures (Table 3-3). The median of the damage scores for all structures in the reach is used to determine overall damage to the structural integrity of the project. It is important to score all structures that were installed in the reach as part of the design; plan sets may be necessary to identify structures that were washed away or buried.

Table **3-3**: Damage scores for individual structures within a stream modification project.

Damage Score (L)	**Description**
1	Structure and structure components have not been displaced and there is no visible erosion.
2	At least 10% of the structure is displaced from the as-built location. And/ Or Structure is attached to bank but erosion is visible everywhere structure is in contact with bank.
3	25-75% of the structure is displaced from as-built location. And/ Or Structure is partially detached from bank.
4	More than 75% of structure is displaced from as-built location. And/ Or Structure is detached from bank.

The median damage score for structures in the project reach can range from 1 to 4. These scores were evenly distributed between the levels of damage (Table 3-2). Since the set of damage scores for all structures in a single stream modification project is an ordinal data set of variable size, the median is used to indicate the central tendency of structural integrity. The intended functions and functioning of structures are not evaluated in this category of damage. Instead, the hydraulic and geomorphic functioning of the project reach is evaluated in other categories of damage according to the level of achievement of the project.

Bank Stability and Migration

Raw and failing banks can be a symptom of channel migration, widening, or degradation. These large scale adjustments represent a geomorphic imbalance that can degrade local habitat and downstream water quality, endanger infrastructure, erode valuable property, and alter flood routing. Complete damage in the category of bank stability and migration occurs when more than 60% of the banks are raw or have experienced bank failures. The breaks in percent of total bank length that distinguish between moderate, extensive, and complete damage are the same as those used in the bank stability habitat parameter of the rapid bioassessment protocol (Barbour, et al., 1999). In order to reduce subjectivity, terms relating to bank condition are defined. Raw banks, or cut banks, are vertical, non-vegetated surfaces that have undergone recent erosion. Bank failures include instances of mass wasting, block failures, and severe undercutting. Indicators of bank stability or instability include bank height, root depth, root density, bank angle, surface protection, soil stratification, soil coherence, soil texture, tension cracks, overhanging banks, undercutting, and slumping. If streambank vegetation is abundant and thick, bank erosion may be hidden unless the project is evaluated in winter. It is advised to determine whether the obstructing vegetation provides surface protection to the banks or hides raw bank surfaces from view.

In addition to bank erosion throughout the reach, this category of damage also accounts for significant channel migration that may not affect a majority of banks within the channel reach. Complete damage has occurred if the thalweg, or deepest point of a channel cross section, has left the channel boundaries as defined in the design documents. Extensive damage to the project reach has occurred if migration is evident within the channel reach. For extensive damage to occur due to channel migration, one bank must be eroding while the opposite bank is filling. Channel migration is distinct from channel widening and results in a change in channel sinuosity.

The categories of damage are intended to be independent of one another and the bank erosion evaluated in this category of damage should not include scour of the bank that is in contact with installed structures, as identified on the design or as-built documents. Scour of the bank that is in contact with structure components is evaluated with *structural integrity*. Erosion of the bank that is not in contact with structure components and bank erosion that continues after a structure is detached from the bank are counted in this category of damage. This situation is discussed and clarified further in the Spring Creek case study in which the left bank of the modified channel was protected by structures but erosion is prevalent. The Port Matilda case study demonstrates an additional concern regarding this category of damage when the damage evaluation occurs years after a project has been completed. Bank erosion may occur gradually, presenting temporary evidence of bank failure or raw banks, or may have occurred years before the damage evaluation is performed and have healed over. These alterations of the stream bank from as-built documents would not be detected during the evaluation. It is possible that adjustments that have ‘healed’ were stabilizing adjustments and do not indicate widespread instability. While these adjustments may occur in a portion of the project reach where adjustment is acceptable, in areas of concern, such as near infrastructure, it may be necessary to perform a survey of conditions to compare the bank location to as-built conditions.

Flood Hazard

Improved projects harden a single bank, defining a bank height and overtopping flood stage for the bank within the project reach. Although improved projects do not directly affect the transport of sediment and debris within the channel, frequent obstructions in the project reach can alter this bank height and overtopping flood stage, endangering assets of the built environment that are in the floodplain. Complete damage in this category of damage occurs when a flood event exceeds the flooding limits. Alternatively, complete damage can occur when unintended obstructions have altered the channel capacity such that a flood event would exceed flooding limits.

This category of damage addresses unintended channel obstructions that increase the flood hazard within the project reach. The descriptions of damage in this category are adapted from the unstable obstructions indicator for assessing channel stability near bridges (Johnson, 2005). Unintended obstructions that accumulate sediment include logs, rocks, growing depositional bars, and other obstructions that were not part of the project design. The flood hazard is described by the flooding limits of the modified channel as defined in the design documents. In the event that flooding limits or a maximum discharge event are not specified in the project design documents, the flood prone width can be used instead. The flood prone width is the wetted width at a stage twice the bankfull depth. If a bankfull depth is not defined then the height of the hardened bank may be used instead.

Visual assessment can be used to determine the frequency of unintended channel obstructions and whether the obstructions might alter, are likely to alter, or significantly alter the capacity of the modified channel. Survey should be performed and a stage-discharge relationship developed to confirm a visual assessment of complete damage in this category. Note that structures included in the project design are intended obstructions and structures that are not a part of the design would be considered unintended obstructions. Expected deposition and growth of intentional obstructions are only considered damage if they unintentionally increase the flood hazard.

3.2.2 – Damage States for Enhanced Projects

Enhanced projects target static equilibrium and directly affect the transport of water, wood, and sediment to maintain diverse bedforms and floodplain connectivity. Projects at this level of achievement harden entire channel cross sections and lock portions of the planform and profile into place. The functions affected by enhanced projects are characterized using measures of flow dynamics, floodplain connectivity, hyporheic exchange, sediment transport competency and capacity, large woody debris transport and storage, lateral stability, riparian vegetation, bedform diversity, and bed material characterization (Harman, et al., 2012). These function parameters are assessed for damage using six categories of damage: *infrastructure protection*; *structural integrity*; *bank stability and migration*; *degradation; wood, sediment, and debris transport;* and *streambank vegetation*. The overall damage state of a project is the maximum rating in the set of damage categories. The relationship between function parameters and the damage categories of enhanced projects is shown in Table 3-4. Since both improved and enhanced damage states target static equilibrium, the first three categories of damage are the same as those described in the improved damage states.

Hyporheic exchange is the only parameter affected by enhanced projects that is not directly assessed by the enhanced damage states. There are no rapid assessment tools available to assess hyporheic exchange in streams across different regions. Hyporheic exchange can be connected to planform and profile, which are hardened in the design phase of an enhanced project. Depending on the local conditions, effective transport of water through sediments may be partially assessed by *streambank vegetation* and *wood, sediment, and debris transport*.

Table **3-4**: Categories of damage for enhanced damaged states and their relation to functional parameters.

Enhanced Damage Categories	**Hydraulic and Geomorphic Parameters**
Infrastructure Protection	Flow dynamics, Lateral stability
Structural integrity	Flow dynamics, Lateral stability
Bank Stability and Migration	Flow dynamics, Sediment transport competency and capacity, Riparian vegetation, Lateral stability
Degradation	Flow dynamics, Floodplain connectivity, Sediment transport competency and capacity, Bed material characterization
Wood, Sediment, and Debris Transport	Flow dynamics, Sediment transport competency and capacity, Large woody debris transport and storage, Bedform diversity, Bed material characterization
Streambank Vegetation	[Floodplain] flow dynamics, Riparian vegetation, Large woody debris transport and storage,

The enhanced damage states describe basic states of damage to general hydraulic and geomorphic conditions in modified channels. Although some functions, such as bedform maintenance and the transport and storage of large woody debris, are dependent on stream type and local conditions, the death of streambank vegetation and the filling in of pools are general signs of damage. A score indicating no damage in any damage category does not mean that channel functioning is adequate to create and maintain high quality conditions. Evaluations of this type are unique to individual project settings and are left to determine project success rather than damage. The enhanced damage states are shown in Table 3-5.

Table **3-5**: Damage state descriptions for the categories of damage at the enhanced level of achievement.

	None	**Moderate**	**Extensive**	**Complete**
Infrastructure Protection	Infrastructure is not in immediate danger of being unintentionally worn by stream flow.	Erosion has left infrastructure (1) nearer stream flow or (2) more surface exposed to stream flow than as-built design.	Infrastructure shows unexpected signs of vulnerability that has the potential to impact the integrity or functioning of the infrastructure. Infrastructure (1) is exposed to stream flow.	The structural integrity of infrastructure is compromised or infrastructure has failed as a result of stream flow.
Structural Integrity	The median of damage scores for structures in the reach is ≤ 1.75.	The median of damage scores for structures in the reach is ≤ 2.5.	The median of damage scores for structures in the reach is ≤ 3.25.	The median of damage scores for structures in the reach is > 3.25.
Bank Stability and Migration	Banks are stable and vegetated.	Isolated instances of bank failures (mass wasting, undercut, etc.) or raw banks affect 5-30% of reach.	Bank failures frequent or raw banks describe 30-60% of reach. Channel migration is evident anywhere in the reach but thalweg is within design channel limits.	Bank failures prevalent or raw banks describe more than 60% of reach. Thalweg has left design channel limits anywhere in reach.

Table **3-5 Continued**: Damage state descriptions for the categories of damage at the enhanced level of achievement, continued.

	None	**Moderate**	**Extensive**	**Complete**
Degradation	There is evidence of higher flows accessing floodplain.	Evidence of moderate or severe entrenchment affecting 5-30% of project reach.	Evidence of moderate or severe entrenchment affecting 30-60% of project reach.	Evidence of moderate or severe entrenchment affecting >60% of reach. A head cut or knickpoint is present or began within the project reach.
Wood, Sediment, and Debris Transport	Less than half of the bottom is affected by sediment deposition. Pools are not filling in and there are few to no unintended obstructions.	Sediment deposition is affecting 50-80% of the channel bottom or deposition in pools is evident. Occasional unintended obstructions are present.	Sediment deposition is affecting 50-80% of the channel bottom or pool depths have measurably decreased. Moderately frequent unintended obstructions.	Aggradation is evident or sediment deposition affects >80% of the channel bottom. Pools have filled in, creating an unintentionally homogeneous bed. Unintended obstructions are frequent.
Streambank Vegetation	Streambank vegetation is in good condition and showing progress along all streambank surfaces.	50-70% of the bank is covered by vegetation in good condition or showing progress	50-70% of the bank is covered by monostand vegetation or old and dying plants.	Less than 50% of the bank is covered by vegetation or disruption due to grazing and mowing is evident.

Infrastructure Protection, *Structural Integrity*, and *Bank Stability and Migration*

These damage categories are the same as those described in the improved damage states. For structural integrity, structures used in enhanced projects include structures that span the channel. Erosion of the bed or bank adjacent to structure components results in damage to the structure. Structures that are not in full contact with the bank, i.e. bank armoring, typically have one or multiple components that anchor the structure in the bank. The description of visible erosion where the structure is in contact with the bank refers to erosion of the as-built bankfull streambank in contact with the anchor component(s) nearest the channel. This description does not refer to erosion surrounding the entire length of extended anchor components. Complete detachment from the bank implies that the channel has scoured around all anchor components.

Degradation

Damage in this category occurs when excessive scour of the bed lowers the channel grade below the as-built or expected grade within the project reach. Degradation is a systematic lowering of the channel grade that is different than processes of local scour and bedform maintenance. This type of large scale adjustment represents a state of disequilibrium that will continue to alter the channel form, potentially degrading local habitat and surrounding water quality, endangering infrastructure and property. Channel incision compromises bank stability and lowers the local water table, resulting in damage in other categories and degrading physicochemical and biological functioning. Vulnerability to degradation relies on bed material characteristics and flow dynamics.

The breaks in percent of total reach length affected that distinguish between the scores of damage are the same as those used in the bank stability habitat parameter of the rapid bioassessment protocol (Barbour, et al., 1999). These breaks in percent of affected reach length or bank length distinguish between local instabilities from systematic and progressing instabilities.

Complete damage in this category of damage occurs when degradation has affected more than 60% of the channel bed. The presence of a head cut or knickpoint, an abrupt vertical step in the bed profile, within the reach also indicates complete damage as these features naturally progress and will lead to further damage. Visual assessment can be used to determine the severity of entrenchment within the project reach; evidence of entrenchment includes floodplain abandonment, increased confinement, decreased width depth ratio, and the presence of levees near the channel edge (Johnson, 2005). If possible, a survey of channel conditions compared to as-built conditions should be performed to confirm a visual assessment of complete damage in this category.

Sediment, Wood, and Debris Transport

This category of damage assesses the capabilities of the channel to transport sediment, woody debris, and other debris. Streams that have achieved a state of static or dynamic equilibrium are streams that maintain slow or near zero rates of lateral and vertical change that occur within the context of a balanced sediment regime. A balanced sediment regime maintains bedforms and channel grade, neither degrading nor aggrading the channel with time. Similar to unintended obstructions in the *flood hazard* category of damage for improved damage states, the transport of large wood and other debris is critical to static equilibrium. Channel stability is threatened by the formation and growth of unintended obstructions that accumulate sediment or alter local flow patterns. This category of damage describes deficiencies in the transportation properties of the channel characterized by sediment deposition, bedform maintenance, and unintended obstructions.

Complete damage in this category occurs when any of the following criteria are met: aggradation is evident; sediment deposition affects >80% of the channel bottom; pools have filled in, creating an unintentionally homogeneous bed; or unintended obstructions are frequent.

Sediment deposition can be indicative of an increased sediment load from a disturbed watershed or unstable banks upstream, either within the project reach or upstream of the project reach. Excessive deposition throughout the project reach can lead to aggradation, or raising of the channel bed, which can bury structures and alter the flood hazard of the project reach. Additionally, excessive deposition of fine sediments can decrease hyporheic exchange and smother substrate habitat. The amount of the bed affected by sediment deposition that determines the level of damage match those that describe poor and marginal conditions relating to sediment deposition in the rapid bioassessment protocol (Barbour, et al., 1999). The maintenance of bedforms is characterized by pool formation and only applies to streams in which pools naturally occur; modification of a plane-bed stream should target an intentionally homogenous bed. A homogeneous bed, lacking in variations in depth and velocity, is typically considered unfavorable habitat and can limit hyporheic exchange. Unintended obstructions are described in the *flood hazard* category of damage of the improved damage states. Note that there are structures employed in enhanced projects that intentionally collect debris and encourage sediment deposition, such as groins and cut off sills. Expected deposition and growth of intentional obstructions are only considered damage if they unintentionally increase the flood hazard.

This damage category is a combination of multiple habitat parameters from the rapid bioassessment (Barbour, et al., 1999) and multiple stability indicators from the channel stability assessment at bridge crossings (Johnson, 2005). A score of no damage in this category does not mean that the transport of sediment and wood in the channel is adequate to create and maintain high quality conditions in the stream channel or that bedforms are sufficient to support the life cycle of local aquatic species.

Streambank Vegetation

Depending on the region and stream type, streambank vegetation provides shade, carbon, nutrient processing, groundwater recharge, habitat, wood for recruitment, energy dissipation, flood retention, bank stability, and sediment storage. This category of damage assesses vegetation immediately adjacent to the channel for its role in hydraulic and geomorphic functioning, primarily its role in bank stability and energy dissipation. Healthy streambank vegetation can dissipate erosive flows during overbank flood events and increase cohesion in bank surfaces. Vegetation should be a native composition that mimics stable streams of the same type and order in the region. Woody vegetation contributes to bank stability and energy dissipation more than grasses (Johnson, 2005) but the presence of a mix of trees, shrubs, and non-woody macrophytes can indicate better site conditions (Barbour, et al., 1999).

Damage in this category is based on the percent of total stream bank length that is protected by vegetation and the quality of that vegetation. This includes the stream banks located adjacent to and near in-stream structures. The breaks in percent of total length of streambank affected that distinguish between the scores of damage are the same as those used in the vegetative protection habitat parameter of the rapid bioassessment protocol (Barbour, et al., 1999). Vegetation covering the streambank surfaces is classified as being largely in good condition and showing progress or as sparse vegetation that is either a monostand or old and dying. Where riparian vegetation is planted as a part of the channel modification design, survival rates of vegetation should be monitored and considered when evaluating the progress exhibited by streambank vegetation in this category of damage. Disturbances to streambank vegetation, such as grazing or mowing, inhibit natural bank stability and can cause bank failures. If there is evidence that unnatural disturbances like these are frequent enough to impact the progress of the streambank vegetation then the project is considered completely damaged in this category.

The damage evaluation should consider seasonal characteristics of the vegetation observed. If an assessment is performed in winter, it may be necessary to assess the relative amount of streambank vegetation that would be present during the local season for high flows. In some regions it may be necessary to re-assess this category of damage in the spring. A score of no damage in this category does not mean that the riparian vegetation is adequate to perform all the functions necessary to create and maintain high quality conditions in the stream channel.

3.2.3 – Damage States Discussion

The damage states are a rapid assessment tool for the condition of hydraulic and geomorphic functioning of small stream modification projects. The damage states provide a standard of measure for completed stream modification projects when conditions prior to modification are unknown, no monitoring or post-project assessment was performed, or projects goals were vague or never recorded. All damage scores should be documented with descriptions of site conditions found onsite and photographic documentation of the conditions described. The overall state of damage for a project should be referenced with the category or categories of damage that match the overall state. For example, the Roaring Run bank stabilization project, case study 1, is moderately damaged due to a likely increase in flood hazard, as opposed to another project that may be moderately damaged in all categories of damage. This reduces confusion and communicates more information about the current conditions of the project site. Since every project is unique, there are going to be special considerations and situations that arise. Chapter 4 presents three case studies in which unique conditions are found and resultant damage ratings are fully explained.

The damage states were tested for sensitivity with the help of two volunteer doctoral candidates in the water resources engineering program of Pennsylvania State University. They were provided a brief description of the design of the case studies and Tables 3-2, 3-4, and 3-5. The volunteers visited the case studies during the summer of 2013 and assessed them for damage. Their results were comparable to those presented in Chapter 4, none of their damage category or individual structure damage scores differed from the author's by more than a one rating. Where the ratings did differ, discussion of the results indicated that the differences were due to lack of familiarity with stream modification practices. The similarity in overall project damage and individual damage ratings is a testament to the adequacy of the descriptions and sensitivity of the assessment. The experience also indicated that application of the damage states requires training and should be employed by those familiar with local stream modification practices. These results are discussed further in Chapter 4 of this report.

Similar to bridge damage states, a level of required repair can be associated with the damage states. A rating of no damage in a category would require no action while a rating of moderate or extensive damage in a category would recommend remedial action be taken to restore site functioning. The decision to repair damage rated moderate or extensive would depend on available resources, extent and location of damage, and consequences of further damage. A rating of complete damage in any category would require remedial action appropriate to restore the functions characterized by the damage category (see Table 3-4).

The damage states lend themselves to many applications that can improve the state of practice for stream modification. Given the large amount of uncertainty associated with stream modification, one important application of the damage states explored in this research is risk assessment.

3.3 – Vulnerability-Based Risk Assessment

Significant risk is associated with the practice of stream modification due to limited knowledge of unique environmental systems and naturally stochastic processes. Risk analysis is a critical tool that can identify significant risks and vulnerabilities, aid in selecting risk reducing measures, and inform hazard preparation. Since the data and resources necessary for quantitative risk assessment are not typically available or obtainable for stream modification projects, a semi-quantitative method is proposed. Vulnerability-criticality risk matrices are a semi-quantitative method used by multiple federal agencies to identify relative risk situations. The hazard of interest in this research is widespread damage across the majority of damage states for a modified stream reach. A vulnerability-criticality risk matrix is used to determine the relative risk to static equilibrium and basic functioning. The relative risk of complete damage is a function of the vulnerability, or likelihood of complete damage, and criticality, the consequences of damage.

Stream modification projects are installed to protect physical and environmental assets that are near to or dependent on the natural channel. The proposed risk assessment determines the potential for hydraulic and geomorphic functioning to decline in modified channel reaches and the consequences of damage to the project. The end result is a category of action recommending the further monitoring of damage, more frequent monitoring and preparation of remedial action alternatives, or immediate remedial action.

3.3.1 – Vulnerability

Vulnerability is a feature or attribute that renders an asset, i.e. the channel reach, susceptible to hazard (DHS, 2010a). The hazard considered in this assessment is that of widespread damage that prevents functional lift within the modified reach and extends its damage beyond the project. The vulnerability to widespread damage is determined by the damage state of the project in each category of damage for the level of achievement of the project. The damage states describe deficiencies in hydraulic and geomorphic functions that are altered by the stream modification project. If the hydraulic and geomorphic functions of improved and enhanced projects are extensively or completely damaged then the channel conditions do not support a healthy riverine ecosystem and may have damaged infrastructure near the channel. The more damaged a project is the more vulnerable it is to functional decline within the project reach and damaging other physical and ecological assets.

The damage states for improved and enhanced levels of achievement consist of four and six categories of damage respectively. Each category of damage represents functioning onsite and all damage categories contribute to the vulnerability of the project. The damage scores in all categories of damage are combined using the weighted sum method to produce a relative vulnerability score for the entire project. The weighted sum method is the most common method for combining variables in multi-criteria decision making (Hobbs and Meier, 1994). A similar procedure was applied in assessing risk of stream instability at bridges (Johnson and Whittington, 2011). The relative vulnerability score, *V*, for the project is determined using the following equation:

$$V = \sum_{i=1}^{n} w_i R_i$$

Where *n* is the number of damage categories for the level of achievement, *w* is the weight assigned to the damage category, and *R* is current condition rating for damage. The weights for all categories of damage must sum to one. In order to reduce subjectivity, default weights are assigned for each level of achievement. The categories of damage and corresponding weights for an improved project are shown in Table 3-6.

Improved projects directly affect the transport of water in the channel and to the floodplain, targeting a state of static equilibrium. These natural functions are characterized using measures of flow dynamics, floodplain connectivity, and lateral stability. Deficiencies in flow dynamics could manifest in all four improved categories of damage; floodplain connectivity is assessed in the *flood hazard* damage category and lateral stability is assessed in *bank stability and migration*, *infrastructure protection*, and *structural integrity*. The weights are equally distributed between the four damage categories because each category characterizes stream functions directly affected by improved stream modification projects.

Table **3-6**: Weight distribution for determining relative vulnerability of improved projects. The level of damage for each category is determined from descriptions in Table 3-2.

Category of Damage	**Level of Damage** (R_i)	**Weight** (w_i)
Infrastructure protection	1 – 4	0.25
Structural integrity	1 – 4	0.25
Bank stability and migration	1 – 4	0.25
Flood hazard	1 – 4	0.25
Relative vulnerability	$V = \sum_{i=1}^{4} w_i R_i$	

Enhanced projects directly affect multiple hydraulic and geomorphic functions targeting a state of static equilibrium (Table 3-1). The functions affected by enhanced projects are characterized using measures of flow dynamics, floodplain connectivity, hyporheic exchange, sediment transport competency and capacity, large woody debris transport and storage, lateral stability, riparian vegetation, bedform diversity, and bed material characterization. The weights are equally distributed between the six damage categories as shown in Table 3-7. An equal distribution as used because each category of damage is independent and characterizes stream functions directly affected by enhanced stream modification projects (Table 3-4).

Table **3-7**: Weight distribution for determining relative vulnerability of enhanced projects. The level of damage for each category is determined from descriptions in Table 3-5.

Category of Damage	**Level of Damage** (R_i)	**Weight** (w_i)
Infrastructure protection	1-4	0.167
Structural integrity	1-4	0.167
Bank stability and migration	1-4	0.167
Degradation	1-4	0.167
Sediment, wood and debris transport	1-4	0.167
Streambank vegetation	1-4	0.167
Relative vulnerability	$V = \sum_{i=1}^{6} w_i R_i$	

While the damage states are written to be widely applicable, the recommended set of damage categories will not be applicable to all project reaches. In order to redistribute the weights, stakeholders must agree that the category of damage is not applicable to the project site. For example, if bank stabilization is installed on a channel where there is no infrastructure in the floodplain then stakeholders could agree to set the weight on infrastructure protection to zero and redistribute the weight equally between the remaining three categories. It is important to avoid subjectivity in the process of weighting the damage states and keep near equal weights on all applicable categories of damage. When determining whether to remove categories of damage, it is necessary to keep in mind the relationship between the damage categories and the parameters that assess functional capacity in the channel. It would be a mistake to remove one of the damage categories because a problem is not anticipated in that category. The watersheds of improved and enhanced projects may be undergoing further development that alters flow dynamics, sediment inputs, and other channel conditions.

It is possible for a project that is extensively damaged in multiple categories to be more vulnerable than a project that is completely damaged in one category. Since the damage categories are independent, it is possible for damage to occur in any one category of damage without damage occurring in the other categories. However, it is unlikely for complete damage to occur in a single category without some damage occurring in other categories of damage. Isolated damage is more likely to be locally contained while widespread damage is more likely to indicate instability, prevent functional lift within the modified reach, and export damage to its surrounding. For example, a bank that is migrating toward a sanitary sewer line will register damage in both *bank stability and migration* and *infrastructure protection,* creating a situation that is more serious than if the channel were migrating in open floodplain.

The range of possible relative vulnerability scores is from 1 to 4. An equal division of these scores between four vulnerability ratings would not be sensitive to significant damage within a project. This division would result in extreme vulnerability only for projects that receive a score higher than 3.25 meaning that the project was extensively damaged in most damage categories and completely damaged in at least one. However, widespread damage in a project reach has occurred at a relative vulnerability score of 2.5 as shown in Figure 3-2.

EXTREME VULNERABILITY

Improved Damage Categories:
Infrastructure Protection
Structural Integrity
Bank stability and migration
Flood Hazard

Ex #1	**4**	**4**	1	1
Ex #2	**4**	2	2	2
Ex #3	**4**	**3**	2	1
Ex #4	**3**	**3**	2	2

$$V = \sum_{i=1}^{4} w_i R_i = 2.5$$

Enhanced Damage Categories:
Infrastructure Protection
Structural Integrity
Bank stability and migration
Degradation
Wood, sediment, and debris transport
Streambank vegetation

Ex #1	**4**	**4**	**4**	1	1	1
Ex #2	**4**	**4**	2	2	2	1
Ex #3	**4**	**4**	**3**	2	1	1
Ex #4	**4**	**3**	2	2	2	2
Ex #5	**4**	**3**	**3**	**3**	1	1
Ex #6	**3**	**3**	**3**	2	2	2
Ex #7	**3**	**3**	**3**	**3**	2	1

$$V = \sum_{i=1}^{6} w_i R_i = 2.5$$

Figure **3-2**: Samples of damage scores that indicate extreme vulnerability for improved and enhanced projects. Complete (4) and extensive (3) damage scores are bolded.

Since the hazard considered in this assessment is that of widespread damage across multiple categories of damage for the project's level of achievement, a project is given the highest vulnerability rating when the relative vulnerability score is 2.5 or higher. The values between 1 and 2.5 were equally divided between the other three relative vulnerability ratings. The relative vulnerability score is translated into a vulnerability rating of low, moderate, very high, or extreme, as shown in Table 3-8. Once the method is applied to a large sample of projects across the US and in specific regions, the vulnerability rating distribution, weight assignments, and the weighted-sum method can be examined for sensitivity and these procedures can be optimized.

The hazard considered in this assessment is that of widespread damage that prevents functional lift within the modified reach and extends its damage beyond the project.

Table **3-8**: Relative vulnerability scores and corresponding vulnerability ratings.

Vulnerability Rating	**V**	**Description**
Low (D)	1.0 – 1.4	Widespread damage of the stream modification project is unlikely.
Moderate (C)	1.5 – 1.9	Given continuing channel conditions, widespread damage is more likely to occur than not.
Very High (B)	2.0 – 2.4	Widespread damage is very likely.
Extreme (A)	2.5 – 4.0	Widespread damage has occurred and is likely to prevent functional lift and damage project surroundings.

3.3.2 – Criticality

To complete a vulnerability-criticality risk-logic matrix, the consequences of damage to a stream modification project must be considered. Criticality is a function of the immediate, short-term, long-term, direct, and indirect consequences of damage to the project. According to the

Vulnerability Self-Assessment Tool (VSAT) for water and wastewater infrastructure, consequence reduction is the most effective method for reducing risk (EPA, 2010).

The consequences of damage to stream modification projects include an array of potential negative impacts. This research describes the financial costs, potential costs to society, and environmental impacts of project damage using seven criticality factors. The economic impact of damage to a project includes the project cost, infrastructure repair cost, and the economic impact of streambank erosion. The consequences to society are quantified by two factors: loss of infrastructure service and the injury potential. Criticality factors that quantify the environmental consequences include impacts to the local habitat and the pollution that could be released into waters from project damage. The criticality factors presented in Table 3-9 are not exhaustive and it is strongly recommended that project managers and stake holders consider additional factors related to local conditions and priorities.

Table **3-9**: Criticality factors that assess economic, societal, and environmental impacts of damage.

Criticality Category	**Criticality Factor**
Economic	Project replacement cost
	Infrastructure repair
	Eroded streambank value
Societal	Infrastructure service impact
	Injury potential
Environmental	Habitat impact
	Pollution source

In applying this methodology to compare stream modification projects within a region or to individual projects, each criticality factor should be assessed for whether it is applicable and then weighted in accordance with a relative ranking of importance. The set of criticality factors applicable to the current project are combined using the weighted sum method to calculate a relative criticality score, *C*. While there is no limit on the number of criticality factors, the sum of the weights of all of the criticality factors must equal one. The process of selecting and weighting criticality factors should be carried out with input from all project stakeholders.

The rating assigned to each criticality factor is a severity rating, *S*, with a value of 4 assigned to project that would incur the most severe consequences and a value of 1 assigned to a project that would lead to the least severe consequences in that factor. The delineation between severity ratings should be non-arbitrary determinations that reflect the range of severity appropriate for the projects being considered. Each criticality factor in Table 3-9 is explained and the severity ratings are defined.

Economic Factors

The economic impact factors reflect the financial costs associated with damage of the stream modification project. The factors that contribute to the economic impact include the cost to replace or repair the project, the cost to replace or repair damaged infrastructure, and the value of eroded streambank property. It is possible that damage to stream modification projects on large rivers, fifth order and higher streams, could alter flood hazard on a large scale and change the regional economic impact. This research focuses on projects on smaller streams whose impacts on large scale flood hazard is negligible. Table 3-10 defines the severity categories for each of the economic criticality factors: project replacement cost, infrastructure repair, and eroded streambank value.

Project Replacement Cost

Damage of the project could entail repair or complete replacement of the channel modification project. If a project is performed for mitigation credit, then project damage can result in the retraction of these credits or a refusal to release them. In the worst case scenario, the project would require full redesign and construction in order to meet project goals or gain mitigation credit. While it is possible for a redesign and repair to cost more than the initial project, the relative severity of financial impact is assumed to be related to the total cost of the damaged project.

In the current study, the values that delineate between severity categories were determined using data from the National River Restoration Science Synthesis (NRRSS). The NRRSS had over 37,000 project records from stream restoration projects in the United States by 2004 (Bernhardt, et al., 2005). Approximately 58% of the project records collected included the overall cost of the project and these data were published according to pre-determined project goal categories. The project goal categories included bank stabilization, in-stream habitat improvement, and stormwater management, among others. The median cost for floodplain reconnection, $207,000, was the highest of the channel modification categories. Bank stabilization projects had a median cost of $42,000 and the median cost for channel reconfiguration was $120,000. Since these were median costs from the period of 1990-2004, reasonable values for the delineation between severity categories were determined to be $60,000, $175,000, and $300,000 after adjusting for inflation from 1998 values.

Infrastructure Repair

This factor applies to all infrastructure examined for damage in the vulnerability analysis. This includes infrastructure exposed to stream flow within the project and any infrastructure or portion of infrastructure within project limits or in the flood prone area likely to be affected by project damage.

The cost to repair the infrastructure will depend on the type and amount of infrastructure present on the project site and the degree of damage. Some projects will have no infrastructure onsite or no infrastructure damaged, while other projects may damage multiple infrastructure assets sufficiently to require replacement. Infrastructure that may be located near a stream channel includes bridges, roads, culverts, water lines, sewer lines, gas lines, and utility lines. The costs to repair or replace these systems falls into a wide range of values, with costs as low as $2,500 to replace 100m of underground utility line (Morrison, et al., 2005) and $2.3 million to install a mile of sewer (Hashemi, 2008). Therefore, the delineation between severity categories is logarithmic. The infrastructure repair costs are most easily calculated by contacting the infrastructure owners or the agencies responsible for maintenance and repair.

Eroded Streambank Value

One of the failure modes for both improved and enhanced stream modification projects is bank erosion and channel migration. The economic impact of eroded streambank includes the financial and cultural value of land highly vulnerable to streambank erosion within the project reach. The value of the property lost to streambank erosion varies based on local property values and land use. Since property values can vary widely throughout the country, the eroded streambank value primarily considers the land use of the streambank, placing higher value on land that provides value to the owner. The categories of land use considered in this criticality factor include agriculture land use designations for crop production, forestry, or animal production. Lands that produce value directly, such as crop production and forestry, are more valuable than land that produces value indirectly, such as through animal production. Public and privately owned land maintained for recreation and aesthetics are also considered for relative value. Expensive property whose worth is directly dependent on the presence and aesthetics of the stream is given higher value than other maintained land such as parks and yards. The highest severity rating is reserved for the most valuable land, based on land development or other cultural value. The lowest severity rating is reserved for land where bank erosion is tolerable and the river has room to move, such as designated riparian buffer zones, right-of-ways, or naturally managed lands.

Table **3-10**: Severity rating distributions for economic criticality factors.

S	Project Cost	Infrastructure Repair	Eroded Streambank Value
1	< $60,000	< $10,000	Designated riparian buffer, stream or utility right-of-way, or other natural land.
2	$60,000 - $175,000	$10,000 - $100,000	Land maintained for aesthetics, recreation, or animal production.
3	$175,001 - $300,000	$100,001 - $1,000,000	Productive land used for crop production or forestry.
4	> $300,000	> $1,000,000	Expensive or culturally valuable land.

Societal

The societal criticality factors reflect the potential costs to the health and well-being of the public caused by damage of a stream modification project. These factors include the loss of service of infrastructure and the injury potential of the project. Table 3-11 defines the severity categories for both of the societal criticality factors: infrastructure service impact and injury potential.

Infrastructure Service Impact

In addition to the financial costs incurred by infrastructure damage, the loss of service is taken into account. Infrastructure that may be located near a stream channel includes bridges, roads, culverts, water lines, sewer lines, gas lines, and utility lines. The loss of any of these infrastructure could result in impacts ranging from inconvenient to serious consequences to society. Depending on the infrastructure function and the facilities served by the infrastructure, damage could increase local commute times or leave hospital patients without power or water. Given the variety of infrastructure that could be present within a stream modification project site, the severity of consequences in this criticality factor are determined by the number of people served by the system or asset. The range of population served can range from service to a single household, a whole town, or heavy commuter traffic from across the state. The bridges in two of the case studies have an average daily traffic around 900 vehicles, while the Spring Creek case study has only a dirt parking lot utilized by fisherman. Drinking water supply systems in Centre County, Pennsylvania serve as few as 32 people in a mobile home community or as many as 47,000 in the State College Borough (SDWIS, 2013). The delineation between severity categories matches the size classification used by the EPA for water distribution systems (SDWIS, 2013): very small water systems serve 500 people or fewer, small systems serve 501 – 3,300 people, and medium systems serve 3,301 – 10,000 people.

Injury Potential

When stream modification projects are performed on channels utilized for recreation they can create slipping, falling, entrapment, or boat flipping hazards to fisherman, swimmers or boaters (Cramer, 2012). Damage to these stream modification projects can further compound these problems or create them where they did not exist, creating steeper and less stable banks or displacing large structure components to create submerged hazards. While one stream modification project may be located behind a fence with restricted access another project may be used daily for kayaking, swimming, and fishing. If the modified reach is frequently or easily accessed then conditions created by project damage could lead to injuries. In order to determine the severity of consequences in this category, the frequency and relative ease of access of the channel is considered. The most severe consequences exist in a reach that is accessed frequently;

these are typically frequented by recreational users or individuals whose work requires interaction with the stream. The remaining severity ratings distinguish between ease of access for channel reaches that are not accessed frequently if they are visited at all.

Table **3-11**: Severity rating distributions for societal criticality factors.

S	Infrastructure Service Impact	Injury Potential
1	Between 0 and 500 people are served by the infrastructure onsite.	Accessing the project reach is prohibited or very difficult.
2	Between 501 and 3,300 people are served by the infrastructure onsite.	The project reach is not accessed frequently if at all and access is moderately difficult.
3	Between 3,301 and 10,000 people are served by the infrastructure onsite.	The project reach is not accessed frequently if at all but access is not difficult.
4	More than 10,000 people are served by the infrastructure onsite.	The project reach is accessed frequently.

Environmental Factors

While stream modification projects purposefully alter local hydraulic and geomorphic channel functions, the impacts of damage can affect hydraulic, geomorphic, physicochemical, and biologic functioning within the project reach and in any connected waters and ecosystems. Damage to stream modification projects can negatively impact the riparian cover, alter hyporheic exchange, release pollutants from the floodplain and streambanks, or otherwise directly or indirectly degrade the environment. While the environmental impacts of project damage are best determined by comparing measurements to previously recorded values within the project reach, this research focuses on smaller projects that often lack detailed monitoring. Therefore, the environmental criticality factors judge the relative amount of damage that could be done within the project reach, habitat impact, and to connected waters, pollution source.

In this research the environmental consequences of project damage are quantified by impacts to the habitat of the project reach and the magnitude of sediment and other pollutants that could be released by project damage. The factors presented here are not an exhaustive set of environmental consequences of project damage. It is recommended that project managers consider additional factors related to local conditions and stakeholder concerns. The factors presented here are intended to be widely applicable across different regions. Table 3-12 defines the severity categories for both of the environmental impact criticality factors: habitat impact and pollution source.

Habitat Impact

The biological communities and habitat of stream channels are greatly diverse across the United States and can vary between stream order and type within a region. The habitat of the project reach and connected waters is characterized by the species able to survive in the environment that is created by the water quality and other physical conditions. While the physical conditions of habitat are modified by the stream modification project, the water quality and biological communities feel the effect of these physical changes. Collecting water quality and biological data is resource intensive and infrequently or inconsistently performed before or after construction of stream modification projects. Therefore, this criticality factor focuses on species of notable concern near the project and the water quality associated with the protected use of the stream channel.

Preferably, stream modification projects would not impact rare, threatened, or endangered (RTE) species or their habitat. However, some stream modification projects may be required near critical habitat or undertaken in order to create, enhance, or protect RTE habitat. Species classified as listed endangered or listed threatened under the US Endangered Species Act (ESA) are federally protected (USFWS, 2013). Rare species, or species of special concern, are identified by state governments as populations that are to be protected or monitored but are not nationally recognized as threatened or endangered. Project managers should contact the local department of natural resources or natural heritage program for a complete list of protected species that can be found locally. The presence of a protected species on or near the project site indicates that the consequences of damage to the stream modification project are very serious. Construction permits require determinations of whether ESA listed species are present on or near project sites.

Consequences of project damage are also considered very serious when the stream reach being modified qualifies as high quality waters. High quality waters are defined as waters given Tier 2 and Tier 3 protection by the federal Antidegradation Policy (40 CFR 131.12). These include waters whose condition warrants the high quality classification, Tier 2, and Outstanding National Resource Waters, Tier 3. Tier 1 protection is given to all waters of the United States and requires water quality in a stream reach to support the documented existing uses of the channel. Federally required existing uses include: public water supplies, propagation of fish and wildlife, recreation, agriculture, industrial, and navigation. State regulations will declare water quality standards that are to be applied to unclassified streams. The most stringent water quality standards are typically applied to potable water supplies and waters that support cold water species, requiring higher concentrations of dissolved oxygen and lower temperatures. Depending on the state, waters designated for cold water aquatic species also have higher standards for turbidity, pH, or specific conductivity. There may also be stricter standards for specific cold water game species such as salmonids or trout. The EPA receives reports from every state on the quality of the surface waters within the state (EPA, 2013c) that declare whether the waters are in good condition and support the existing uses or are impaired and do not support the existing uses. Although any degradation in water quality within a project reach is undesirable, streams in good condition before project construction are valued more than projects that are impaired prior to modification. The physicochemical properties of water directly impact the health of local species dependent on the water within the modified reach; deteriorating water quality can increase susceptibility to disease or death.

Pollution Source

Federal regulations require that limits be set on the amount of pollution to impaired waters, total maximum daily loads (TMDLs). Damage to stream modification projects can directly contribute to TMDLs for sediment. Large amounts of sediment can be released by degradation and streambank erosion, contributing to the widespread and severe impacts to the biological condition of streams in the United States due to excess sediment (EPA, 2013b). Improved projects specifically stabilize stream banks and practices implemented in enhanced projects can provide grade control to prevent degradation and protect banks through stabilization or flow deflection. This criticality factor assesses the environmental impacts of project damage by determining the relative quantity of sediment that could be released by project damage.

The Bank Erosion Hazard Index (BEHI) (Rosgen, 1996) uses bank characteristics to determine whether the bank erosion potential is very low, low, moderate, high, very high, or extreme. Relative determinations regarding the potential magnitude of pollution that could be released due to project damage are made based on the BEHI rating of the majority of the project reach. If a project is already damaged, the severity of the consequences in this criticality factor should be assessed according to the damaged conditions. A stream that has degraded has also increased the amount of sediment readily available for transport in addition to increasing the level of damage of the project. Stretches of bank that are stabilized or hardened are to be given a BEHI rating and considered in the total bank length of the project reach. This accounts for the sediment source behind the stabilization practice that could be released following damage to the structural integrity of the project.

Table **3-12**: Severity rating distributions for environmental criticality factors.

S	Habitat Impact	Pollution Source
1	Project damage is not likely to degrade high quality waters or cold water fisheries.	Less than half of the reach is characterized as a high bank erosion hazard or worse.
2	Project damage is likely to degrade impaired cold water fisheries.	At least half of the project reach is characterized as a high bank erosion hazard or worse.
3	Project damage is likely to degrade cold water fisheries in good condition.	At least half of the project reach is characterized as a very high bank erosion hazard or worse.
4	Project damage is likely to degrade high quality waters or RTE habitat.	At least half of the project reach is characterized as an extreme bank erosion hazard.

Relative Criticality Score

The criticality dimension is essential to the vulnerability-based risk assessment in which the potential for damage to modified channel reaches and the consequences of such damage is assessed. The end result of the risk analysis is a category of action that describes whether immediate action is required, recommended, or not needed. As such, it provides a basis for making decisions regarding the need for additional maintenance or the level of impact caused by unexpected damage. In this section, a method is developed to determine whether the consequences of damage to a stream modification project are not serious, moderate, serious, or very serious.

It is encouraged to select criticality factors and weights for the criticality factors that represent local conditions and priorities. It is important to note that projects with different criticality factors or weights would not be directly comparable. Therefore, determinations of factors and weights should be carried out at a scale appropriate to the scope of the study. For this research, improved and enhanced stream modification projects are being considered; therefore, the set of criticality factors is limited to the seven presented in Table 3-13.

The weight distribution provided in Table 3-13 is based on generalized objectives for improved and enhanced projects that value static equilibrium over environmental impact. The project cost is given the most weight, followed by the societal factors since safety is a primary concern of projects located in or near population centers. The environmental factors are given the least weight since in constrained environments, the capacity for functional lift may be limited.

Table **3-13**: Criticality factors and proposed weights for improved and enhanced projects.

Criticality Factor	**Rating** (S_i)	**Weight** (w_i)
Project replacement cost	1-4	0.20
Infrastructure financial impact	1-4	0.12
Eroded streambank value	1-4	0.12
Infrastructure service impact	1-4	0.18
Injury potential	1-4	0.18
Habitat impact	1-4	0.10
Pollution source	1-4	0.10
Relative Criticality	$C = \sum_{i=1}^{9} w_i S_i$	

The range of possible relative criticality scores is from 1 to 4. The relative criticality score is translated into a criticality rating of not serious, moderate, serious, or very serious as shown in Table 3-14. The possible scores for relative criticality are equally divided between the four categories. Other distributions are possible to determine the criticality rating but the severity rating, *S*, and weights, *w*, for a given level of achievement take the importance of each criticality factor into account.

Table **3-14**: Relative criticality scores and corresponding criticality ratings.

Criticality Rating	**C**	**Description**
Very Serious (1)	3.3 – 4.0	Consequences of damage are very serious. Overall losses would be unacceptable and remedial action would be required immediately.
Serious (2)	2.6 – 3.2	Consequences of damage are serious. Overall losses are high and remedial action will be required.
Moderate (3)	1.8 – 2.5	Consequences of damage are moderate, the impact would be noticeable and are likely to require repair.
Not Serious (4)	1.0 – 1.7	Consequences of damage are not severe enough to warrant any action or further investigation.

The method proposed in this research includes nine criticality factors that are widely applicable. It is appropriate, and encouraged, to consider additional criticality factors and to prioritize applicable factors. However, it is important to note that analyses that utilize different sets of factors and weights are not comparable. The practice of developing a set of criticality factors for every stream modification project is not recommended. Rather, the scope of the risk analysis should be determined and an appropriate set of factors and weights decided for use. The scope of a risk analysis consists of comparing relative risk for projects throughout a city, county, state, or region. This framework could be applied to compare relative risk of all mitigation projects by one owner or to compare a few alternatives for a single mitigation project. The choice of criticality factors and weights allows for customization to local conditions and priorities.

3.3.3 – Relative Risk

The previous sections described how to assess the vulnerability of a stream modification project and how to evaluate the criticality of damage. The final step in this semi-quantitative risk assessment is to combine vulnerability and criticality in a risk-logic matrix to evaluate the relative risk of the project. The end result is a category of recommended action, ranging from immediate remedial actions to monitoring the damage onsite. This final risk categorization will assist project managers in identifying significant risks and vulnerabilities, aiding in the selection of risk reducing measures, and informing hazard preparation.

The vulnerability rating (A, B, C, or D) and the criticality rating (1, 2, 3, or 4) are entered into the risk matrix shown in Figure 3-3. The risk matrix is divided into three zones, identical to those used by the Federal Aviation Administration (FAA) in risk assessment (FAA, 2000). In this risk analysis for stream modification projects the zones represent three zones of recommended action. The white shaded zone in the matrix (1A, 1B, 1C, 2A, 2B, and 3A) represents risks that are unacceptable and must be avoided or eliminated. Projects in this risk category are the highest priority and immediate remedial action that repairs the damage or reduces the consequences is recommended. The striped zone (3D, 4A, 4B, 4C, and 4D) represents risks that are acceptable, damage should be reviewed and noted but the risk is low enough that action need not be imminent. The remaining boxes in the risk matrix, the grey zone (1D, 2C, 2D, 3B, and 3C), represent risks that should be unacceptable. For projects in these zones the recommended action is to perform regular damage assessment and consider remedial action plans.

The vulnerability-criticality framework for risk assessment can be useful to planners, designers, and other stakeholders in natural resource preservation and management. The risk matrix can be applied to any collection of projects to identify projects that have a higher risk and require immediate resources within the scope of the analysis. A comparative risk assessment could be performed on various damage scenarios to compare project design alternatives and eliminate alternatives that present more risk. Additionally, the information gathered in performing this risk assessment can aid communities in planning for large scale flood events.

Vulnerability \ Criticality		1	2	3	4
		Very serious	Serious	Moderately serious	Not serious
A	Very high probability	1A	2A	3A	4A
B	High probability	1B	2B	3B	4B
C	Moderate probability	1C	2C	3C	4C
D	Low probability	1D	2D	3D	4D

Unacceptable Risks	Remedial actions should be taken immediately
Monitored Risks	Monitor damage regularly and prepare remedial action plans.
Acceptable Risks	Monitor and record damage.

Figure **3-3**: Vulnerability-criticality risk matrix and recommended action categories.

There is one other dimension in addition to vulnerability and criticality that, if the information is available, can contribute significantly to risk assessment. When performing analysis on water and wastewater systems VSAT considers three dimensions in their risk determination: vulnerability, consequence, and threat (EPA, 2010). The threat likelihood is the probability of occurrence of widespread damage to a stream modification project. Damage to a project can be caused by flow events or human intervention. Human intervention is not a negligible threat to the system but it is difficult to quantify. High, low, and moderate flow events occur daily in perennial streams and the likelihood of threat occurrence is quantifiable in gaged streams. Damage can be expected during a large flow event or damage can occur unexpectedly during relatively low flow events. The probability of widespread damage that prevents functional lift and damages other aquatic resources can best be determined by estimating the discharge in the channel that caused the present state of damage. This value could be higher than the maximum design flow or this value could be lower than the maximum design flow. A project that is moderately damaged after a 2-year flow event has higher threat likelihood than a project that is only slightly damaged after a 10-year event. A quantitative analysis is not straightforward as many watersheds are ungauged and historical analyses of flow recurrence may be inaccurate due to changing land use and climate. The local property owners may be a good source of information for relative flows but this would introduce uncertainty unless verified by precipitation or other recorded data. When possible, a consideration of the threat will enhance the risk analysis proposed in this research.

3.4 – References

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Chapter 4

Case Studies

The proposed framework for assessing damage to basic channel functioning of stream modification projects is demonstrated in three case studies. Three stream modification projects located in the Ridge and Valley region of central Pennsylvania were evaluated. The first case study is a project at the improved level of achievement upstream of a bridge along a rural highway. The remaining two case studies are enhanced level of achievement projects, one which was stabilized in place and the other in which a channel was shaped and hardened after a dam removal. These case studies are diverse in age, motivation for modification, practices implemented, type of damage, and level of damage. The damage to each project was evaluated in the summer of 2013 and each project is discussed in the following sections. Appendix B contains photographs taken of site conditions at each project in the summer of 2013 and historic aerial images of the case study project reaches.

The damage states were tested for sensitivity with the help of two volunteers, doctoral candidates in the water resources engineering program of Pennsylvania State University. These students had no previous experience with stream modification or familiarity with in-channel structures. They were provided a brief description of the design of each case study, maps of the project sites, lists of structures installed, and Tables 3-2, 3-4, and 3-5. Questions about the damage state descriptions were answered prior to evaluating any site. The volunteers visited the three case studies during the summer of 2013 and assessed them for damage. Their results were comparable to those reported in this chapter and discussed where they differed. None of their damage states or individual structure damage scores differed from those reported by more than a one rating. Recommendation from this experience suggest that future applications of the damage states should be preceded by a formal training that includes a further explanation of the damage descriptions, figures to exemplify common damage, and recommendations of how to track damage throughout longer project reaches. The damage states are intended to be simple to apply and require minimal training for those familiar with local stream modification practices. The results of this trial application of the damage states provided insight into necessary training and demonstrated the stability of the damage state framework.

Damage states are a tool for rapid assessment of damage to stream modification projects and are not intended for monitoring or for use in determining project success or failure. For projects without measurable and unambiguous goals the damage assessment can be used to determine the amount of damage to the hydraulic and geomorphic functioning of the modified channel. Design documents were not available, do not exist, or were incomplete for all three case studies. The case studies are not monitored and no criteria for success or failure of the projects have been defined. In each case individuals who were involved with the project design or present during project construction were consulted for project information. The overall level of damage for each project is determined using the damage state framework.

In addition to damage, the relative risk to static equilibrium and physical channel functions is also determined for each of the case studies using the vulnerability-criticality risk matrix. The risk associated with the case studies is determined relative to one another using the generalized criteria for improved and enhanced projects presented in Section 3.3 of this research.

4.1 – Case Study 1: Roaring Run at State Route 445

As part of Pennsylvania State Route 445, a concrete bridge was installed over Roaring Run in 2000. As shown in Figure 4-1, the bridge is southwest of Lamar and 5 miles north of Madisonburg, Pennsylvania. Roaring Run approaches the bridge heading north and takes a sharp turn to the east, cutting under State Route 445. In 2000, riprap was installed immediately upstream of the bridge along the left channel bank to cut off the old channel and force Roaring Run under the bridge. Personal communication with engineers involved in the project revealed that in 2006 the original riprap failed during a high flow event. Water overtopped the road creating dangerous driving conditions around the old, abandoned channel. Following this failure, a culvert was installed in the abandoned channel and a stream modification project was performed in the channel upstream of the bridge.

Figure **4-1**: PA State Route 445 over Roaring Run. Aerial Photograph of Roaring Run at bridge crossing and culvert location in abandoned channel. Images from Google earth (2012a). Flow direction is east, left to right in the above images.

Roaring Run is a second order stream nestled in the ridges of the ridge and valley region. The watershed for Roaring Run is naturally forested with little development. In the vicinity of the bridge crossing, Roaring Run is a relatively uniform step-pool channel with gravel, cobbles, and boulders as bed material (Johnson, 2006). The original riprap on the left bank (LB) consisted of

70^{o} angle riprap wall with a median size of 152-229mm (Figure 4-2, [a, b]) (Johnson, 2006). The project was evaluated in 2006 and it was determined that this riprap was undersized and failure was evident from the stone deposited in the channel (Johnson, 2006). Following a large flow event and further damage to the riprap along the left bank (LB), repair work was performed using stone up to 1.2 m in size (Figure 4-2 [c]) and the channel along the right bank (RB) upstream of the bridge was shaped with an elevated floodplain in channel (Figure 4-2 [d]).

[a] [b]

[c] [d]

Figure **4-2**: [a] and [b] Original riprap placed in 2000, images from FHWA report (Johnson, 2006). [c] and [d] Photographs of repair work taken during 2013 damage evaluation. [a] and [c] are taken looking upstream from bridge and [b] and [d] are taken looking downstream at bridge.

4.1.1 – Damage to the Roaring Run Case Study

The stream modification project in Roaring Run was evaluated for damage in June, 2013. The project reach consists of the modified stretch of channel upstream of the State Route 445 bridge that was performed in 2006. The project hardened the left bank of the channel upstream of the State Route 445 bridge and is classified as an improved level of achievement. In personal communication with DOT, the structure on the right bank of the channel was described as an elevated floodplain installed 0.15 meters (6 inch) above bed elevation in the channel. Adjacent to the right bank in the channel, this structure was intended to repair over-widened conditions seen in Figure 4-2[b]. The design mimics gravel bars that occur naturally elsewhere in Roaring Run and the size of the riprap used suggests that this practice was not intended to hard armor the right bank. The practice leaves the right bank of the channel relatively free to adjust to disturbances while static conditions are expected where large riprap lines the left bank of the modified reach.

In order to determine damage, the project was evaluated in the four categories of damage for improved projects: *infrastructure protection*, *structural integrity*, *bank stability and migration*, and *flood hazard*. The infrastructure affected by the project includes the State Route 445 bridge across Roaring Run, the culvert in the abandoned channel, and the portion of State Route 445 vulnerable to being overtopped. The extents of the latter are shown in the inset of Figure 4-1, spanning east of the culvert to just south of the bridge. The structural integrity of the riprap on the left bank and the elevated floodplain in the channel were evaluated. Bank stability and flood hazard were evaluated throughout the length of the modified reach, from the upstream extents of the left bank riprap to the upstream end of the abutment protection on the downstream side of the bridge.

In addition to the two structures, large boulders were placed along the abutment of the bridge and downstream of the bridge to shield the abutment. This riprap was not considered as part of the project reach as the structures do not take natural stream processes into account and were installed solely to protect the abutment of the bridge. This damage evaluation only considered the work that hardened and shaped the channel upstream of the bridge.

Infrastructure Protection

The road surface of State Route 445 and the culvert in the abandoned channel show no signs of being worn or damaged due to stream flow. It appeared that the only flow through the culvert was due to rain events and a small amount of backwater from the confluence of the abandoned channel with Roaring Run.

In order to determine whether any damage to the bridge due to stream flow exceeds that of normal wear and tear, the most recent bridge inspection for the State Route 445 bridge was consulted (FHWA, 2012). The Pennsylvania Department of Transportation (DOT) inspects bridges regularly and records conditions in the National Bridge Inventory (NBI). The 2012 DOT inspection gave no indication that the bridge was damaged due to stream flow. The items related to the channel and bridge components include the substructure, channel and channel protection, and scour critical bridges (FHWA, 1995); each were evaluated as in very good condition, receiving an 8 out of 9. This evaluation was performed a year prior to this damage assessment but the bridge showed no sign of excessive wear due to channel flow at the time of the assessment.

Structural Integrity

There were two structures installed in this improved stream modification project; a large riprap lining along the left bank of the channel and an elevated floodplain feature in the channel adjacent to the right bank. Without a plan set or as-built survey, which was not performed, it is difficult to tell how much of the structures have remained in place. The riprap on the left bank is largely intact, with less than 10% of the structure displaced. There is no erosion evident behind the riprap but a few components of the riprap have been dislocated as can be seen in Figure 4-3. The elevated floodplain in the right portion of the channel is intact, vegetated and appears stable; it is possible that the gravel bar may have grown from the as-built conditions. The damage scores for the structures in the Roaring Run modification project are provided in Table 4-1. The median damage score of the individual structures was 1.0 which means the structural integrity for the project is not damaged.

Table **4-1**: Damage scores for structures in the Roaring Run stream modification project.

Structure	**Location**	**Score**	**Description of damage**
Riprap	LB	1	Less than 10% of structure components are displaced.
Elevated Floodplain	In the channel on Right	1	No damage.

Bank Stability and Migration

There were no instances of bank failures or raw banks within the project reach. Since the left bank is entirely protected by the riprap structure, damage to bank stability would only be possible after components were detached from the bank. Few components were displaced and there was no evidence observed of bank erosion behind these displaced components. The gravel bar shows no sign of erosion or instability and the right bank above the gravel bar appeared stable and vegetated.

Figure **4-3**: Riprap on the left bank, photograph looking upstream from bridge.

Flood Hazard

The waterway adequacy was evaluated in the 2012 DOT bridge inspection and the roadway approaches were given a slight chance of overtopping but the bridge deck was not (FHWA, 2012). There were no unstable, unintended obstructions in the channel present during the damage evaluation. The displaced riprap components were minor obstructions but showed no signs of being unstable and are not likely to impact the flooding limits. The gravel bar is an intended obstruction that affects the majority of the project reach; the project design purposefully left an elevated floodplain in the channel approximately 0.15m above the channel bed. Growth of intentional obstructions is only considered damage if the structure unintentionally increases the flood hazard. Significant growth of this gravel bar could endanger the infrastructure onsite and lead to further damage. While it appears that the bar has grown in height from as-built conditions, there is no evidence that the flood hazard has definitely increased. As intended in the design, the bar is low enough to be inundated in high flow conditions (Figure 4-4).

Figure **4-4**: Elevated floodplain structure, photograph taken looking downstream.

This evaluation determined that the growth of the gravel bar may have altered the flood hazard, which indicates a moderate level of damage. One of two volunteers who evaluated this project for damage determined that the channel capacity was likely not increased. This can be attributed to the stable appearance of the bar at a height significantly lower than the left bank of the modified reach. Also, it may have been unclear that the growth of intended obstructions causes damage in this category. Survey of current conditions is not within the scope of this evaluation but the bar height was estimated as at least triple the installed height of 0.15 meters, a survey could indicate an increased flood hazard. If the obstruction continues to grow then the flood hazard will be impacted and the project would become more damaged.

Damage Summary

The Roaring Run bank stabilization project was evaluated in the four categories of damage for improved level of achievement projects. The ratings in each category of damage are given in Table 4-2. The overall level of damage of the project, equal to the highest damage score, was evaluated as moderately damaged. The damage score was due to a likely increase in the flood hazard throughout the project reach. The elevated floodplain structure was built to be 0.15m above the channel bed and has approximately tripled in height since construction was completed. A survey of the current channel conditions and the development of a stage-discharge relationship would need to be performed and compared to the intended capacity of the bridge to confirm that the flood hazard has been increased. There was no damage observed in the categories of *infrastructure protection*, *structural integrity*, and *bank stability and migration*.

Table **4-2**: Categories of damage for improved projects and scores for Roaring Run stream modification project evaluated in June, 2013.

Damage Category	**Score**
Infrastructure protection	1 – None
Structural integrity	1 – None
Bank stability and migration	1 – None
Flood hazard	2 – Moderate

4.1.2 – Risk of the Roaring Run Case Study

A vulnerability-criticality risk matrix was used to determine the risk associated with the Roaring Run stream modification project. The vulnerability of the project is expressed by the current state of damage of the project in every category of damage for the level of achievement. The second dimension to the semi-quantitative risk analysis is criticality, the consequences of damage to the Roaring Run stream modification project. Consequences are considered with respect to the financial cost, societal impacts, and environmental impacts of damage to the project.

The Roaring Run stream modification project was evaluated in the four categories of damage for projects at the improved level of achievement. The damage scores and weights for each of the improved categories of damage are shown in Table 4-3. The relative vulnerability score was calculated to be 1.25 which equates to a low vulnerability rating (Table 3-8). Widespread damage of the Roaring Run stream modification project is unlikely.

Table **4-3**: Relative vulnerability for the Roaring Run stream modification project

Category of Damage	**Level of Damage** (R_i)	**Weight** (w_i)
Infrastructure protection	1	0.25
Structural integrity	1	0.25
Bank stability and migration	1	0.25
Flood hazard	2	0.25
Relative vulnerability	$V = \sum_{i=1}^{4} w_i R_i$ = 1.25	

The consequences of damage to the Roaring Run stream modification project were evaluated using seven factors: project replacement cost, infrastructure repair, eroded streambank value, infrastructure service impact, injury potential, habitat impact, and pollution source.

Personal communication with DOT estimated that project cost was around $30,000 in 2006, and that cost included the work performed on the culvert. DOT estimated the current cost for replacing the bridge would be around $1,000,000 in addition to any expenses to repair the roadway and the culvert. The stream banks consist of state-owned land that is naturally managed and therefore not of high value. The severity ratings for the economic impacts factors was determined using Table 3-10. The infrastructure service impact can be estimated by the average daily traffic on the bridge which was reported as 899 in 2012 (FHWA, 2012). The injury potential of the modified stream reach is serious since the reach is easily accessed from the road but it is not accessed frequently. The severity ratings for the societal factors were determined using Table 3-11. Roaring Run in Centre County is a high quality cold water fishery and therefore the consequences of damage could be very serious to the local habitat. The BEHI was evaluated for both the left and the right banks onsite and was low or moderate throughout the project reach. The bankfull elevation was assumed to be the crest of the elevated floodplain structure near the top of the reach since this structure has been shaped by high flows. Since the left bank is composed of boulders, the erosion potential is low and the right bank at the top of the reach also has a low erosion potential. As you near the bridge, the bank height increases and the right bank has a moderate erosion potential. The severity ratings for the environmental factors were determined using Table 3-12. The scores for each criticality factor, associated weights, and resulting relative criticality score are summarized in Table 4-4.

The weights used for the criticality factors are the default weights presented in this research. The relative criticality score of 2.2 equates to a moderate criticality rating (Table 3-14), the impact of damage would be noticeable and is likely to require repair.

The vulnerability-criticality risk matrix, shown in Figure 3-3, shows that a low vulnerability score and moderate criticality score equate to an acceptable level of risk. The recommended action is to record any damage that was observed at the site and monitor periodically for further damage; immediate action is not necessary.

Table **4-4**: Criticality for the Roaring Run stream modification project

Criticality Factor	**Rating** (S_i)	**Weight** (w_i)
Project replacement cost	1	0.20
Infrastructure financial impact	4	0.12
Eroded streambank value	1	0.12
Infrastructure service impact	2	0.18
Injury potential	3	0.18
Habitat impact	4	0.10
Pollution source	1	0.10
Relative Criticality	$C = \sum_{i=1}^{7} w_i S_i$ = 2.2	

4.1.3 – Discussion of the Roaring Run Case Study

The Roaring Run stream modification project is an improved project that hardened the left bank of the channel on the approach to a bridge. The only damage to the project is the possible increase in flood hazard due to the growth of an intended obstruction in the channel. Since the damage states are a rapid damage assessment framework, survey is outside the scope of the evaluation. This means that the only way to evaluate complete damage in the category of flood hazard would be to observe high water indicators that indicated an increased flood hazard. Extensive damage in the category of flood hazard at this site would be indicated by the encroachment of the bar further into the channel accompanied by a growth in height or the formation of unstable, unintended obstructions in the channel. These conditions would indicate that the flood hazard has likely been increased. One of the volunteers who assessed the project for damage did not note any damage in this category which demonstrates some subjectivity of the *flood hazard* damage category evaluation. Employing evaluators familiar with flow dynamics at bridge crossings would decrease subjectivity in this category of damage.

A risk assessment of current conditions determined that the relative risk of the Roaring Run stream modification project is low and no immediate action is necessary. Damage is isolated to one category and potentially stable in that further damage may not occur. It is likely that hydraulic and geomorphic functioning is supports physicochemical and biological functioning within Roaring Run. In terms of criticality, the project was not contracted out for design or construction and was therefore much less expensive than it would be if DOT had to put the project out to bid in case of replacement. The BEHI was estimated for both banks on the project site which included a BEHI estimate for the bank protected by riprap.

The Roaring Run streambank stabilization project is an example of limited damage to an improved level of achievement stream modification project. Pictures of conditions found onsite during the damage assessment in June, 2013 are included in Appendix B.

4.2 – Case Study 2: Bald Eagle Creek at Port Matilda

In 2003 a stream restoration project was completed to mitigate for impacts incidental to the realignment of a section of US Highway 220 near Port Matilda, Pennsylvania. The project implemented a holistic approach, utilizing public education, cattle and pasture management, and stream modifications to restore 6,400 meters (4 miles) of Bald Eagle Creek in Centre County, Pennsylvania (Perdikakis, 2010). The channel modifications performed as part of this project included the stretch of Bald Eagle Creek near the Port Matilda Community Park (Figure 4-5). This case study will consider the 400 meters of stream modification performed on Bald Eagle

Creek between the pedestrian bridge in the community park (upstream) and the PA State Route 3017 bridge on South High Street (downstream), shown in Figure 4-6. The section of the stream modification project between the two bridges, where the vast majority of the modifications were performed, was chosen for its demonstrative value in applying the damage assessment framework to an enhanced stream modification project.

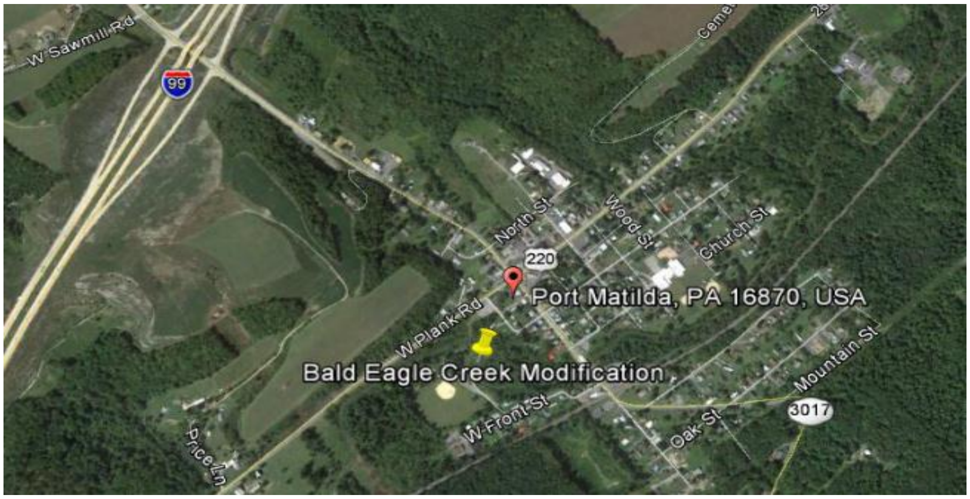

Figure **4-5**: Location map for Bald Eagle Creek stream modification (Google earth, 2012b).

Figure **4-6**: Aerial view of Bald Eagle Creek project reach evaluated in this case study (Google earth, 2012b). The black circles indicate the location of the J-Hook structures. Flow proceeds from the pedestrian bridge (west) toward the South Higher Street Bridge (east).

The watershed for Bald Eagle Creek consists primarily of forested land, particularly on the steep slopes of the ridges. However, there are small, scattered portions of the watershed used for commercial, residential, agricultural, or otherwise developed land uses (Sherwin, et al., 2009). Bald Eagle Creek is a larger stream, fourth order, with a gentle slope in a valley of the ridge and valley region. The Centre County Pennsylvania Senior Environmental Corps has been performing physical, chemical, and biological monitoring just upstream of a pedestrian bridge since 2002. The water quality and biosurvey data at this site, including the most recent survey from May, 2013, report good conditions (CCPASEC, 2013). The stream modifications installed in Bald Eagle Creek near the Community Park consisted of imbricated riprap and J-Hook structures that stabilized in-place the channel planform, profile, and cross sections. Historical images, provided in Appendix B, show that channel planform has been relatively stable throughout at least the last 20 years and that the installed structures did not alter the channel pattern.

4.2.1 – Damage to the Bald Eagle Creek Case Study

The Bald Eagle Creek stream modification project at the Port Matilda community park was evaluated for damage in June, 2013. The stream modification performed in 200 consisted of six J-Hook structures placed on meanders that deflect flow away from the outer bank of the meander bend. There were also two long imbricated riprap walls installed at the top of the project reach, arresting bank erosion and protecting infrastructure. These structures were installed to the stream modification performed on Bald Eagle Creek is an enhanced level of achievement project due to multiple hardened cross sections that armor the planform and profile of the reach in place.

The project was assessed for damage in the six categories of damage applicable for enhanced projects: *infrastructure*; *structural integrity*; *bank stability and migration*; *degradation*; *sediment, wood, and debris transport*; and *streambank vegetation*. There were four unidentified structures that spanned the channel, perpendicular to flow across channel cross sections. These structures were not part of the original stream modification design and have most likely been constructed by the public to attract fish. Since these structures were not a part of the original design they are not evaluated for structural integrity, they are assessed as unintended obstructions and considered in another category of damage.

Infrastructure

The infrastructure that could be impacted by this project includes the pedestrian bridge at the upstream end of the reach, a two lane bridge for local traffic at the downstream end of the reach, a community park with a dirt access road (Park Street) and parking area, and a hydrant. The pedestrian bridge spans the channel with riprap protecting the bank directly under the bridge. The riprap is set back from the edges of the channel, there is ample vegetation surrounding the riprap, and no damage is visible on the bridge or its supports, as shown in Figure 4-7. The dirt road and parking area are visible in the southwest corner of Figure 4-6, located on a stretch of the right bank of the reach. The hydrant is between the parking area and the channel, shown in Figure 4-7. This infrastructure was undamaged and the two-tiered imbricated riprap wall protecting this infrastructure is also undamaged; the infrastructure is no nearer to being exposed to stream flow than as-built conditions.

Figure **4-7**: Undamaged infrastructure near Bald Eagle Creek. The right bank of the pedestrian bridge (left) and the hydrant between dirt parking area and the stream channel (right).

The PA State Route 3017 (SR 3017) bridge over Bald Eagle Creek is located at the downstream end of the project reach. The most recent DOT inspection for the bridge was performed in 2012 (FHWA, 2012) following the replacement of the bridge in 2011. The items related to the channel and bridge components include the substructure, channel and channel protection, and scour critical bridges. All of these were in excellent condition in the 2012 site inspection (Figure 4-8). In the evaluation of site conditions prior to bridge replacement (FHWA, 2011) only the scour critical bridges item received a good score. The substructure was determined to be poor and the channel and channel protection was described as:

> "Bank is beginning to slump. River control devices and embankment protection have widespread minor damage. There is minor streambed movement evident. Debris is restricting the channel slightly." (FHWA, 1995, pp. 56)

The bridge inspection record from 2011 reported that the bridge was built in 1930 and while the maintenance record is not known, an evaluation of the bridge prior to replacement described the bridge site as "low" vulnerability due to an otherwise stable channel, good waterway adequacy, and no scour (Johnson and Whittington, 2011).

Figure **4-8**: Embankment of SR-3017 bridge from June, 2013. Bridge was replaced in 2011.

Structural Integrity

Within the reach, there are two imbricated riprap walls and six J-hooks. The locations of the six J-Hooks in the project reach are indicated in Figure 4-6 and will be discussed in order from upstream to downstream. The outside of the first meander bend, the left bank (LB) of the channel following the pedestrian bridge, is lined with imbricated riprap. The first J-Hook comes out of the imbricated riprap wall at the apex of this meander. The large rocks in both the imbricated riprap and the J-Hook may have slightly shifted but no components are displaced (Figure 4-9). At the end of the riprap wall, there is a short straight section with a completely submerged but otherwise undamaged J-Hook.

Figure **4-9**: Looking upstream at imbricated riprap wall on the left bank of the channel and the first J-Hook.

Continuing downstream, the channel is near the dirt road, parking area, and hydrant which are protected by a two-tiered imbricated riprap wall on the right bank (RB) of the channel (Figure 4-10). While some components have shifted and settled, there is no evidence of erosion and no components are displaced from this riprap wall.

Figure **4-10**: Two-tiered imbricated riprap on the right bank.

Figure **4-11**: The extensively damaged fourth J-Hook with displaced components and partial detachment from the bank.

Following the two-tiered imbricated riprap wall, there are two damaged J-Hooks coming from the right bank of the channel. The end of the third J-Hook in the reach is likely present but buried. A connection to the left bank of the channel has been made with bits of concrete and bricks, creating an unintended channel obstruction. There is some minor erosion and piping occurring on the right bank where the J-Hook ties in to the bank, but it is not sufficient to indicate moderate damage. The fourth J-Hook is the only structure in the reach with displaced components. A portion of the arm of the fourth J-Hook has fallen into the channel and erosion around the bank tie-in has partially detached the structure from the bank indicating extensive damage (Figure 4-11). The throat of this J-Hook was not displaced but completely submerged.

Proceeding downstream, the fifth J-Hook in the reach comes from the left bank and is undamaged but submerged. The furthest downstream meander in the project reach turns the channel for a straight approach to the SR 3017 bridge. The final J-Hook is located on the right bank of this meander. The arm of this J-Hook ties into the right bank is completely buried and the other side of the structure ends in the middle of the channel, suggesting channel migration.

Damage scores for every structure are provided in Table 4-5 along with a description of any damage observed during the June, 2013 damage evaluation. The median of the damage scores for each individual structure was 1.0 indicating that the structural integrity of the project has not been damaged.

Table **4-5**: Damage scores for structures in the Bald Eagle Creek stream modification project. Structures are listed in order of occurrence in the project reach, upstream to downstream.

Structure	**Location**	**Score**	**Description of damage**
Imbricated Riprap	LB	1	No damage.
J-Hook	LB – coming from riprap	1	No damage.
J-Hook	RB	1	No damage.
Two-tier Imbricated Riprap	RB	1	No damage.
J-Hook	RB	1	Minor erosion between structure and RB, piping is occurring through arm.
J-Hook	RB	2	Arm components have been dislocated and erosion has partially detached structure from bank.
J-Hook	LB	1	No damage.
J-Hook	RB	1	No damage.

Bank Stability and Migration

There were no instances of recent bank failure and few reaches of raw banks evident in the reach during the damage assessment of June, 2013. Dense vegetation obscures the streambanks along much of the channel reach. However, there is evidence that the channel is migrating from as-built conditions and that bank erosion has occurred or is occurring in a few areas on the left bank within the project reach. There is a stretch of short, raw banks between the fourth and fifth J-Hook structures. In this region, channel flow has detached one of the channel-spanning, unintended obstructions from the left bank and the left bank upstream of the fifth J-hook is recessed from the bank adjacent to the structure arm. More extensive damage is evident near the sixth J-Hook structure. The arm of this J-Hook that ties in to the right bank is buried while the other end of the structure is in the middle of the channel (Figure 4-12). Since J-Hook structures are intended to span the channel cross section, the channel has evidently migrated from as-built conditions. Further evidence of this migration is visible in a large area of terrace erosion on the left bank of the last meander before the SR 3017 bridge. This eroding area is visible in the aerial image of the project reach in Figure 4-6.

Figure **4-12**: Looking upstream at the fifth J-Hook (left) that ends in the middle of the channel. Terrace erosion on left bank (right) across from fifth J-Hook.

There is evidence to suggest that the bank has eroded along more than 5% of the bank of the project reach but less than 30%. These conditions alone would indicate moderate damage in this category but there is sufficient evidence to conclude that the channel is migrating near the sixth J-Hook, extensively damaging the project reach. The channel cross section is nearly flat, such that the location of the thalweg in relation to design channel limits is not evident, otherwise the damage may have been complete.

Degradation

There is no evidence of degradation within the project reach and there is ample evidence of high flows accessing the floodplain. On the inside of meander bends throughout the project there are recently deposited sediments, vegetation bent by flowing water, and rafted debris against sturdier vegetation. There is terrace erosion in two locations along the project reach, where flow is accessing the floodplain at erosive velocities providing further evidence that the channel is not degraded.

Sediment, Wood, and Debris Transport

This category of damage evaluates bedform maintenance, sediment deposition, and unintended obstructions to determine deficiencies in the transportation properties of the channel characterized. Bedforms are present within the reach and a heterogeneous velocity-depth regime is present throughout. Shallow pools were observed along the outside bank of meander bends and there were deep pools downstream of a few of the J-Hook structures. Although the bed was not homogenous during the damage assessment in June, 2013, there was significant damage observed due to sediment deposition and unintended obstructions.

There were fine sediment deposits across from the imbricated riprap walls and downstream of terrace erosion and deposition of larger sediments is widespread throughout the reach. Many of the J-Hook structures are completely submerged and high flow events have caused significant erosion on the left terrace in two locations. The first section is at the beginning of the reach, above the imbricated riprap wall on the left bank of the channel. The second area of terrace erosion is across from where the channel is migrating. These areas of terrace erosion may be indicative of a local increase in bed elevation which has decreased channel capacity. A survey of the current channel profile would be needed and compared to as-built conditions in order to determine the extent and magnitude of deposition. The presence of mid-channel and side bars, unintended obstructions, also indicate sediment deposition. It is estimated that sediment deposition has affected between 50 and 80% of the channel bottom.

Unintended obstructions within the project reach consisted of bars within the channel and four unidentified channel-spanning structures that were man-made, but not part of the stream modification plan (Figure 4-13). These man-made unintended obstructions affect flow within the channel; the structure upstream from the fifth J-hook has deflected flow toward the bank. These obstructions have also accumulated some debris and have contributed to observed deposition throughout the reach. Channel bars were vegetated and only one of the channel bars, upstream of the SR 3017 bridge, was significantly affecting channel flow (Figure 4-14). Unintended obstructions are moderately frequent within the reach.

Figure **4-13**: Unintended obstructions in the channel.

The frequency of unintended obstructions and extents of sediment deposition throughout the project reach have extensively damaged the Bald Eagle Creek stream modification project in the category of *wood, sediment, and debris transport*. One of the two volunteers that evaluated this project for damage determined that the project was completely damaged in this category of damage. This can likely be attributed to expectations and impressions of damage. The bed is not homogeneous and without As-built plan sets, there is no evidence that pools have filled in or that the majority of the reach. Also without As-built plan sets, determining whether more than 80% of the bed within the project reach has been affected is an impression of conditions onsite. The disagreement could also be due to the distinction between moderately frequent and frequent unintended obstructions. While there are more than a handful of unintended obstructions, there are significant stretches without unintended obstructions within the project reach.

Figure **4-14**: Channel bar constricting flow within the channel immediately upstream of SR 3017 bridge. Left picture is taken looking downstream at bridge and the right picture is taken looking upstream from the bridge.

Streambank Vegetation

The streambank vegetation is obstructing access to and the view of streambank surfaces throughout much of the reach. Although there are a few small stretches that primarily consist of grasses where recent erosion has occurred (Figure 4-11), the vegetation is largely in good condition and showing progress along the vast majority of streambank surfaces (Figure 4-9, 4-12, 4-13, and 4-14). Nowhere in the project was the stream completely shaded, but the riparian vegetation provided shade to approximately one quarter of the project reach near the banks.

Damage Summary

The Bald Eagle Creek stream stabilization project was evaluated in the six categories of damage for enhanced level of achievement projects. The ratings in each category of damage are given in Table 4-6. The project was evaluated as extensively damaged in June, 2013 due to significant evidence of channel migration, the prevalence of sediment deposition, and the frequency of unintended obstructions in the channel. The migration of the channel at the downstream end of the reach will change the approach angle of the channel to the SR 3017 bridge, potentially endangering the bridge. The channel migration may also lead to significant bank erosion along the right bank of the channel. The sediment deposition and unintended obstructions have already altered the flooding hazard of the project reach and led to some local bank erosion. The channel adjustments are likely to continue and prevent static equilibrium within the project reach. There was no damage observed in the categories of *infrastructure protection*, *structural integrity*, *degradation*, and *streambank vegetation*.

Table **4-6**: Categories of damage for enhanced projects and scores for the Bald Eagle Creek stream modification project evaluated in June, 2013.

Damage Category	**Score**
Infrastructure protection	1 – None
Structural integrity	1 – None
Bank stability and migration	3 – Extensive
Degradation	1 – None
Sediment, wood, and debris transport	3 – Extensive
Streambank vegetation	1 – None

4.2.2 – Risk of the Bald Eagle Creek Case Study

A vulnerability-criticality risk matrix was used to determine the risk associated with the Bald Eagle Creek stream modification project. The vulnerability of the project is expressed by the current state of damage of the project in every category of damage for the level of achievement. The second dimension to the semi-quantitative risk analysis is criticality, the consequences of damage to the Bald Eagle Creek stream modification project. Consequences are considered with respect to the financial cost, societal impacts, and environmental impacts of damage to the project.

The Bald Eagle Creek stream modification project was evaluated in the six categories of damage for projects at the enhanced level of achievement. The damage scores and weights for each of the enhanced categories of damage are shown in Table 4-7. The relative vulnerability score was calculated to be 1.67 which equates to a moderate vulnerability rating (Table 3-8). Widespread damage of the Bald Eagle Creek stream modification project is moderately likely, or more likely than not to occur. It is important to note that although there was some disagreement between the volunteers who also evaluated damage in this project, their damage scores resulted in the same vulnerability rating.

Table **4-7**: Relative vulnerability for the Bald Eagle Creek stream modification project.

Category of Damage	**Level of Damage** (R_i)	**Weight** (w_i)
Infrastructure protection	1	0.167
Structural integrity	1	0.167
Bank stability and migration	3	0.167
Degradation	1	0.167
Sediment, wood, and debris transport	3	0.167
Streambank vegetation	1	0.167
Relative vulnerability	$V = \sum_{i=1}^{6} w_i R_i$ = 1.67	

The consequences of damage to the Bald Eagle Creek stream modification project were evaluated using seven factors: project replacement cost, infrastructure repair, eroded streambank value, infrastructure service impact, injury potential, habitat impact, and pollution source. The cost information for this project was unavailable and was assumed to be between $175,001 and $300,000. The replacement for the cost for SR 3017 bridge alone exceeds $1,000,000. The riparian land is owned by the Port Matilda Borough and the banks are maintained for recreation and aesthetics. The severity ratings for the economic impacts factors was determined using Table 3-10. The infrastructure service impact can be estimated by the average daily traffic on the SR 3017 bridge which was reported as 945 in 2012 (FHWA, 2012). The average daily use of the park is unknown but is not likely to bring the service impact over 3,300 people. The injury potential of the modified stream reach is very serious since the reach is frequently accessed for fishing and wading by park goers. The severity ratings for the societal factors were determined using Table 3-11. Bald Eagle Creek near Port Matilda is a cold water fishery in good condition (Sherwin, et al., 2009). The BEHI was evaluated onsite and under 61 meters (200 feet) of bank total were evaluated as high erosion hazard, nowhere in the reach was very high or extreme. The severity ratings for the environmental factors were determined using Table 3-12. The scores for each criticality factor, associated weights, and resulting relative criticality score are summarized in Table 4-8.

The weights used for the criticality factors are the default weights presented in this research. The relative criticality score of 2.8 equates to a serious criticality rating (Table 3-14), the impact of damage would be serious and would require remedial action.

Table **4-8**: Criticality for the Bald Eagle Creek stream modification project

Criticality Factor	**Rating** (S_i)	**Weight** (w_i)
Project replacement cost	3	0.20
Infrastructure financial impact	4	0.12
Eroded streambank value	2	0.12
Infrastructure service impact	2	0.18
Injury potential	4	0.18
Habitat impact	3	0.10
Pollution source	1	0.10
Relative Criticality	$C = \sum_{i=1}^{7} w_i S_i$ = 2.8	

The vulnerability-criticality risk matrix, shown in Figure 3-3, shows that a moderate vulnerability score and serious criticality score equate to risks that should be unacceptable. The recommended action is to monitor the project regularly and consider options for remedial action plans in case conditions onsite degrade further.

4.2.3 – Discussion of the Bald Eagle Creek Case Study

The Bald Eagle Creek stream modification project stabilized in-place a portion of the stream that runs through the Port Matilda Community Park. The project installed two long imbricated riprap walls and six J-Hooks to maintain dynamic equilibrium in the channel. The hydraulic and geomorphic functions of the channel are extensively damaged due to channel migration and significant deposition. Although extensively damaged, the project is only moderately vulnerable to widespread damage that prevents functional lift within the modified reach and extends its damage beyond the project. Both the channel migration and deposition threaten the state of static equilibrium within the project reach. The deposition is also indicative of a sediment or energy imbalance that is affecting functioning within the project reach that could impact ecological conditions, preventing functional lift or degrading current functions.

This case study highlights the independence of the damage categories and the sensitivity of relative vulnerability ratings to isolated damage versus larger instabilities. In the vulnerability analysis, widespread damage refers to a vulnerability score of 2.5 or greater. This means that if project conditions degrade to complete damage of *sediment, wood, and debris transport* and *bank stability and migration* while the other four categories remain undamaged, the project would not be extremely vulnerable. Until infrastructure, structures, or streambank vegetation are also damaged, the damage from the project is contained to the channel and the channel may still support functional lift. Additionally, although the two volunteers disagreed about the severity of damage regarding sediment transport, their ratings were similar to those presented and the vulnerability rating was not sensitive to their slight differences in ratings.

The lack of design documents, as-built survey, or communication with an individual who participated in the design of this project was prohibitive. The thick vegetation obscured the banks of the project and the extent of bank erosion was not evident. While there is no doubt as to the presence of a sediment imbalance, likely due to local scour and deposition, the extent to which pools may be filling in is not evident without knowledge of the as-built conditions. Since there were multiple deep pools present within the reach, the fact that some J-Hook structures did not have pools immediately downstream was not considered damage. Regarding criticality, although the streambanks are both maintained by the park for access, they are managed differently. The left streambank is naturally managed while the riparian buffer on the right bank is limited in width with mowed grass on the other side of the riparian buffer. There are trails through the buffer in multiple locations to provide access. The banks were considered managed for aesthetics and recreation since the right stream bank is valuable to the community park.

The Bald Eagle Creek stabilization is an example of an extensively damaged enhanced level of achievement stream modification project. The project was determined to have moderate risk, and therefore represents a more beneficial use of Centre County resources than monitoring or repair of the Roaring Run case study. Pictures of conditions found onsite during the damage assessment in June, 2013 are included in Appendix B.

4.3 – Case Study 3: Spring Creek at Bellefonte

In 2007 the McCoy-Linn Dam was removed from Spring Creek and in 2009 the dam removal was followed up with a habitat enhancement project that adjusted the stream channel dimensions and installed habitat improvement structures. The McCoy-Linn Dam was located in between Bellefonte and Milesburg, Pennsylvania, just upstream of the USGS gage on Spring Creek at Milesburg (Figure 4-15). The dam was 3.7 meters high and impounded approximately

600 meters of Spring Creek. When the dam was removed, water cut a channel into the impounded sediments and the previously inundated floodplain was completely exposed and easily eroded (Figure 4-16). A local non-profit group was involved with restoring the surrounding riparian corridor and wetland while a local company was hired to modify the previously impounded section of Spring Creek (Omblaski, 2013). Spring Creek is a popular trout fishing stream in Centre County so the modification focused on creating a stable channel that would attract fish and fisherman.

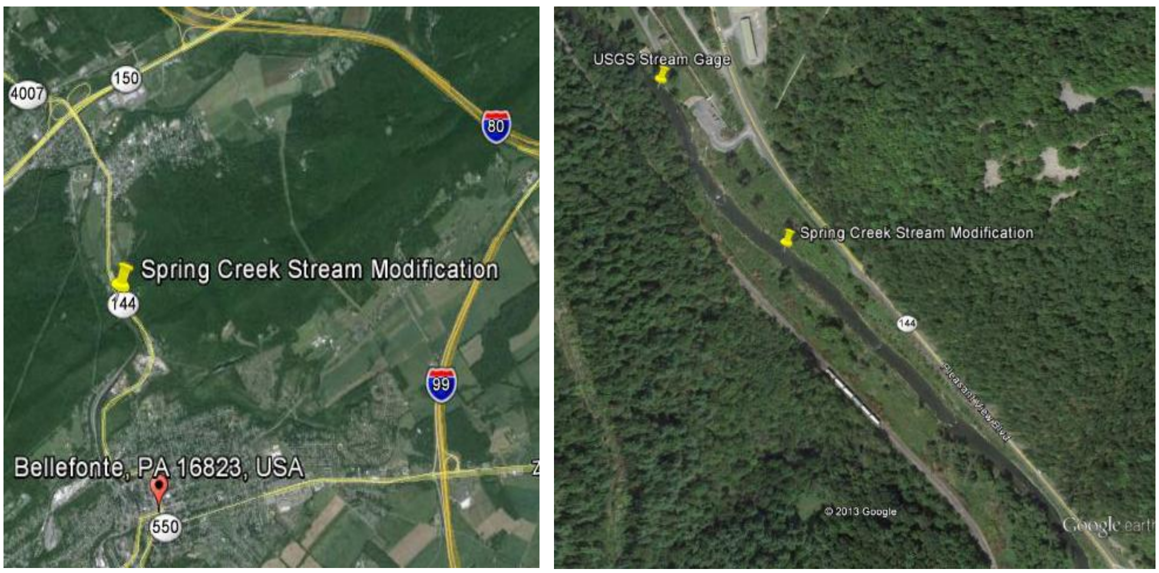

Figure **4-15**: Location map (left) for Spring Creek stream modification project. Aerial view of Spring Creek stream modification project extents (right). Images from Google earth (2012c). Flow direction is northwest.

The Spring Creek watershed is only 39.4% forested with the majority of land in the watershed is used for agriculture (USGS, 2013). The stream receives significant groundwater input, keeping the waters cold and making it one of the best Class A wild trout streams in the state of Pennsylvania (PFBC, 2013). The stream modification project was approximately 670 meters long and was designed to enhance the local fish habitat and stabilize the banks of the channel (Detar, et al., 2011).

Figure **4-16**: Historic photographs of the McCoy Linn Dam (top), the post-dam removal but pre-modified channel (middle), and the modified channel. Images from Google earth (2012c, 2008, 1994).

4.3.1 – Damage to the Spring Creek Case Study

The Spring Creek stream modification project was assessed for damage in May, 2013. The stream modification performed on Spring Creek in Bellefonte is an enhanced level of achievement project due to multiple hardened cross sections that armor the planform and profile of the reach in place. The project was assessed for damage in the six categories applicable for enhanced projects: *infrastructure*; *structural integrity*; *bank stability and migration*; *degradation*; *sediment, wood, and debris transport*; and *streambank vegetation*. The project floodplain is confined on either side by infrastructure. Although fewer structures were initially planned, thirty-three structures were installed in Spring Creek in order to meet the project goals, including cross vanes, log vanes, lunkers (mud sills), and rootwad-log vanes. These practices affect how the reach transports water in the channel, to the floodplain and through sediments. By using practices that deflect and concentrate flow, the stream modification project also affects the transport of wood and sediment in the channel to create diverse bedforms and maintain the desired state of static equilibrium. All thirty-three structures were evaluated for *structural integrity* and the extents of the project reach were evaluated for *degradation*, *sediment, wood, and debris transport*, and *streambank vegetation*.

Infrastructure

Although there is no infrastructure in the channel there is infrastructure near the site that could be impacted by project damage that include a wall from the old dam, a dirt parking lot at the downstream end of the reach, and a stretch of PA Route 144 near the channel at the upstream end of the reach. At the downstream extents of the project reach there is an old wall near the left bank of the channel left over from the removal of the dam (visible in Figure 4-17). While the structure shows signs of deterioration, the damage to the structure appears to be due to age rather than stream flow. The dirt parking lot is owned by the Pennsylvania Fish and Boat Commission and provides access for fisherman to the channel. At the upstream extents of the reach PA Route 144 and a few telephone poles are within 10 meters of the channel (seen in Figure 4-16) but over 5 meters higher than the bankfull elevation. This infrastructure shows no signs of damage from high flows and there is no evidence of erosion from as-built conditions that would put this infrastructure nearer to danger.

Telephone poles, the remainder of PA Route 144, and an active railroad are near the site but outside of project limits and well above the flood prone area of the modified channel. These infrastructure are located a minimum of 1.5 meters above the bankfull elevation and located at least 20 meters from the channel bank.

Figure **4-17**: Infrastructure near the channel include telephone poles, railroad tracks (left), and a remaining dam wall (right).

Structural Integrity

Within the project reach there are 2 log vanes, 4 rock cross vanes, 8 rootwad-log vanes, 8 rock vanes, 2 lunkers, 2 stretches of riprap, and multiple stretches of boulder revetment. The majority of these structures have remained in their as-built positions, there are few instances of component displacement. Most damage to structures within the project reach is due to local bank scour adjacent to structure components.

The boulder revetment consisted of multiple stretches of large boulders along the left bank of the project reach. This structure was evaluated as six boulder revetment structures, four of these stretches were isolated in between other structures. The two stretches of boulder revetment at the downstream end of the reach were continuous through the rootwad log-vane structures and evaluated as one stretch. The condition for these structures were similar throughout the reach, there are multiple components of the boulder revetment displaced, although less than 25% of the total structure in each case. Most of the components of the boulder revetment have evident scour above and behind all components with some either completely detached from the bank or partially detached (Figure 4-18).

Figure **4-18**: One stretch of boulder revetment along the left bank. Mild to extensive scour has detached components from the bank and some components have been displaced.

Eight rootwad-log vanes were installed along the left bank of the channel. The rootwad component of one rootwad-log vane structure was been displaced, extensively damaging the structure. Two other rootwad-log vanes were moderately damaged due to scour surrounding the entire contact area between the structure and the bank that exposed the top of the structure as depicted in Figure 4-19.

Figure **4-19**: Moderately damaged rootwad-log vane.

There were two stretches of riprap along the right bank of the project reach. The downstream reach of riprap is near the parking lot at the fishing access site. This riprap exhibits some minor erosion but was largely undamaged. The other stretch of riprap, immediately upstream of the third rock cross vane, was partially detached from the bank. The upstream end of this riprap structure, approximately a third of this structure, is completely detached from the bank (Figure 4-20).

There were eight rock vanes within the project reach, five of which are located at the downstream end of the reach. These five rock vanes exhibited some scour; the scour around two of these structures was sufficient to indicate moderate damage. Additionally, two of these rock vanes appeared distinctly shorter than other structures in the reach. It is possible structure components on these two vanes were displaced but without as As-built plan set, this could not be verified. The remaining three rock vanes were completely or partially detached from the bank. Figure 4-20 shows one of these rock vanes and the stretch of riprap detached from the bank.

Figure **4-20**: Structures detached from the right bank. One of two rock vanes completely detached from the right bank (left) and the detached stretch of riprap (right; visible on the right edge of the right photograph).

The two log vanes at the upstream end of the project reach are undamaged, likely protected by a large downed tree just upstream of the project extents (Figure 4-21). The two lunkers installed toward the upstream end of the project reach exhibit erosion surrounding the contact area with the bank, the logs of one of the structures were displaced, sinking, and most of the rocks that were placed on top of the logs of both structures were gone (Figure 4-22).

Finally, the largest structures were four rock cross vanes with very long arms that tie-in high into the floodplain. These structures were stable with some erosion adjacent to the structure, on two of these vanes the scour was sufficient to moderately damage the structures.

Figure **4-21**: Obstruction upstream of project reach and undamaged log vane structures.

Figure **4-22**: Damaged lunker structures. Second half of upstream lunker has fallen in (left); the rock cover on the downstream lunker has washed away (right).

Damage scores for every structure are provided in Table 4-9 along with a description of damage observed during the May, 2013 damage assessment. The median of the damage scores for each individual structure was 2.0, implying that the structural integrity of structures onsite was moderately damaged. The two volunteers who also evaluated current damage of this project underestimated the damage of the structures on the left bank. Due to the size of this case study and rapid flow conditions on the day of evaluation, they were not able to access the left bank of the channel and performed all evaluations from the right bank. This vantage point made the evaluation of scour surrounding any structure tie-ins difficult. Where the volunteers did differ from the reported damage ratings, it was not by more than one rating.

Table **4-9**: Damage scores for structures in the Spring Creek stream modification project. Structures are listed in order from upstream to downstream. Stationing is estimated based on the design plan sheet.

Structure	**Location**	**Score**	**Description of damage**
Log Vane	LB 6+15	1	No damage.
Log Vane	LB 6+85	1	No damage.
Rock Vane	LB 8+00	2	Components displaced and some minor erosion around bank tie-in.
Rock Cross Vane	9+00	1	Erosion along both right and left banks adjacent to structure components.
Boulder Revetment	LB 10+00	2	Components displaced and bank scour evident everywhere components in contact with the bank.
Lunker	LB 10+50	2	A portion of the logs are no longer in place and the rocks on top of the logs are missing.
Lunker	LB 11+75	2	Erosion above logs, rock cover is displaced.
Boulder Revetment	LB 12+00	2	Bank scour evident everywhere components in contact with the bank.
Rock Cross Vane	12+50	1	No damage.
Rootwad-Log Vane	LB 13+75	1	Some scour evident.
Rootwad-Log Vane	LB 14+50	3	Rootwad is missing, log vane is stable.
Rock Vane	RB 15+00	4	Structure is detached from bank.
Rootwad-Log Vane	LB 15+25	1	Some scour evident.

Structure	**Location**	**Score**	**Description of damage**
Boulder Revetment	LB 15+50	2	Components displaced and bank scour evident everywhere components in contact with the bank.
Rootwad-Log Vane	LB 15+75	1	No damage.
Rootwad-Log Vane	LB 16+00	1	No damage.
Riprap	RB 16+00	3	Riprap is partially detached from bank, components displaced.
Boulder Revetment	LB 16+50	3	Scour around all components, some components detached from bank.
Rock Cross Vane	17+00	1	Minor erosion on right bank.
Boulder Revetment	LB 17+75 to 21+25	3	Scour around all components, some components detached from bank and some displaced.
Rootwad-Log Vane	LB 18+25	1	Some scour around log.
Rootwad-Log Vane	LB 18+75	2	Scour around entire structure, rootwad is damaged.
Rock Vane	RB 18+75	4	Structure is detached from bank.
Rootwad-Log Vane	LB 20+00	2	Scour around entire contact area with bank.
Rock Cross Vane	21+50	2	Scour adjacent to structure on both banks.
Rock Vane	RB 21+50	1	Components have shifted slightly and end components may be missing.
Rock Vane	LB 21+25	1	End components may be missing.
Boulder Revetment	LB 21+75	3	Scour around all components, some components detached from bank and some displaced.
Rock Vane	RB 22+00	2	Bank scour surrounding all components.
Rock Vane	LB 22+25	2	Bank scour surrounding all components.
Riprap	RB 23+00	1	No damage.
Rock Vane	LB 24+00	1	No damage.

Bank Stability and Migration

There were many instances of raw banks and bank failures within the project reach, affecting between 30 and 60% of the banks within the reach. The majority of the left bank within project limits was protected by a boulder revetment (Figure 4-18) or was adjacent to other structures such as rootwad-log vanes (Figure 4-19) or rock cross vanes. Where there were instances of raw or failing banks on the left bank of the channel, erosion had continued after structure components were detached. More than half of the right bank exhibited raw surfaces or recent bank failures. While the third rock cross vane, counting from upstream to downstream, is stable, immediately upstream of this structure is a stretch of riprap is partially detached from the bank and erosion behind and upstream of this riprap is extensive (Figure 4-20). The damage to the banks within the channel reach is extensive, affecting an estimated 40% of streambank surfaces. A survey of current conditions compared to as-built conditions would further define the extents of bank erosion within the project.

Degradation

There is limited evidence of severe or moderate entrenchment evident within the project reach. While there is a portions of the banks that are near vertical, these banks are largely less than a few feet tall, there is no evidence of structure undermining, and no other indication that the bed level of the stream is decreasing. On the right bank there is infrequent evidence that high flows access the floodplain, such as small rafter debris. On the left bank, there is little to no evidence of high flows accessing the floodplain. Both volunteers who assessed the project damage rated that the project was moderately damaged in this category for this reason. However, there is no evidence that the height of banks within the reach have significantly increased from the as-built condition.

Sediment, Wood, and Debris Transport

There was a noticeable coat of fine sediments visible on the bed material throughout most of the reach, likely from the ongoing bank erosion. This deposition affects over half of the reach, moderately damaging the stream modification project. There were a few small woody debris obstructions present within the reach during the damage assessment but these obstructions did not appear unstable as they were likely to be transported at the next high flow event. There was one significant obstruction outside of the project reach, upstream of the log vanes, which should be monitored for instability. A large tree has fallen into the channel from the left bank (Figure 4-21). The right bank at this section of the channel is steep and near PA Route 144 and channel migration around this obstruction could endanger the road or cause instabilities within the project reach in the future.

Due to the prevalence of fine sediment on the channel bottom, the project was evaluated as moderately damaged in this category of damage. One of the two volunteers who assessed the site for damage rated the project as moderately damaged in this category while the other rated it as undamaged in this category of damage. The stream is relatively large and deep throughout and only the edges of the channel bed were visible from the right bank where the evaluators assessed damage from. There was abundant fine sediment deposition occurring on the left bank in between the rootwad-log vanes structures. The rating of no damage was due to uncertainty regarding deposition of fines across the majority of the bed. Observation of the stream at lower flow conditions confirms that roughly half the bed experiences deposition of fine sediments.

Streambank Vegetation

Grasses are prevalent on both the right and left bank of the project reach, covering most streambank surfaces. Vegetation along the right bank was planted following construction of the stream modification project. The planted trees and shrubs appear to be showing progress although there are sections of bank where only the grasses are present. The survival rates of planted vegetation are unknown but it is likely that some of the planted vegetation has been lost due to extensive bank erosion. Although minimal stability is being provided by the streambank vegetation more than 70% of the streambank is vegetated and the Spring Creek stream modification project is not damaged in this category. There was little to no canopy cover provided to the stream by the streambank vegetation throughout the project reach.

Damage Summary

The Spring Creek stream modification project was evaluated for damage in the six categories of damage for enhanced level of achievement projects. The ratings in each category of damage are given in Table 4-10. The project was evaluated as extensively damaged in May, 2013 due to frequent raw banks and bank failures throughout the project reach. This bank erosion is causing fine sediment deposition throughout the reach and detaching the installed structures from the bank, further damaging the project. The damage of structures and deposition of fine sediments can degrade the habitat within the project reach, affecting the trout that utilize the stream. The bank erosion is likely to continue, potentially degrading habitat and preventing static equilibrium within the project reach. There was no damage observed in the categories of *infrastructure protection*, *degradation*, and *streambank vegetation*.

Table **4-10**: Categories of damage for enhanced projects and scores for the Spring Creek stream modification project evaluated in May, 2013.

Damage Category	**Score**
Infrastructure protection	1 – None
Structural integrity	2 – Moderate
Bank stability and migration	3 – Extensive
Degradation	1 – None
Sediment, wood, and debris transport	2 – Moderate
Streambank vegetation	1 – None

4.3.2 – Risk of the Spring Creek Case Study

A vulnerability-criticality risk matrix was used to determine the risk associated with the Spring Creek stream modification project. The vulnerability of the project is expressed by the current state of damage of the project in every category of damage for the level of achievement. The second dimension to the semi-quantitative risk analysis is criticality, the consequences of damage to the Bald Eagle Creek stream modification project. Consequences are considered with respect to the financial cost, societal impacts, and environmental impacts of damage to the project.

The Spring Creek stream modification project was evaluated in the six categories of damage for projects at the enhanced level of achievement. The damage scores and weights for each of the enhanced categories of damage are shown in Table 4-11. The relative vulnerability score was calculated to be 1.67 which equates to a moderate vulnerability rating (Table 3-8). Widespread damage of the Spring Creek stream modification project is moderately likely, or more likely than not to occur. It is important to note that although there was some disagreement between the volunteers who also evaluated damage in this project, their damage scores resulted in the same vulnerability rating.

Table **4-11**: Relative vulnerability for the Spring Creek stream modification project.

Category of Damage	**Level of Damage** (R_i)	**Weight** (w_i)
Infrastructure protection	1	0.167
Structural integrity	2	0.167
Bank stability and migration	3	0.167
Degradation	1	0.167
Sediment, wood, and debris transport	2	0.167
Streambank vegetation	1	0.167
Relative vulnerability	$V = \sum_{i=1}^{6} w_i R_i$ = 1.67	

The consequences of damage to the Bald Eagle Creek stream modification project were evaluated using seven factors: project replacement cost, infrastructure repair, eroded streambank value, infrastructure service impact, injury potential, habitat impact, and pollution source. Personal communication with the PA Fish and Boat Commission (FBC) and the local non-profit involved with the work indicated that the project cost was roughly $270,000. It cost FBC under $100,000 to install the parking lot and they maintain the stretch of bank adjacent to the parking lot every month. Other than the short reach of bank adjacent to the parking lot, the riparian land and the banks are naturally managed. The severity ratings for the economic impacts factors was determined using Table 3-10. The parking lot can hold up to 28 cars, with usually anywhere from 5-10 cars and up to 15 on busy days. The average daily traffic for PA Route 144 was assumed to be 12,207, equivalent to average daily traffic on the bridge on PA Route 144 that is 0.8 miles down the highway from the parking lot at the downstream end of the project reach (FHWA, 2012). The injury potential of the modified stream reach is very serious since the reach is frequently accessed for fishing and kayaking. The severity ratings for the societal factors were determined using Table 3-11. The stream receives significant groundwater input, keeping the waters cold and making it one of the best Class A wild trout streams in the state of Pennsylvania (PFBC, 2013). The BEHI was evaluated onsite and under 183 meters (600 feet) of bank total were evaluated as high, nowhere in the reach was very high or extreme. The severity ratings for the environmental factors were determined using Table 3-12. The scores for each criticality factor, associated weights, and resulting relative criticality score are summarized in Table 4-12.

The weights used for the criticality factors are the default weights presented in this research. The relative criticality score of 3.0 equates to a serious criticality rating (Table 3-14), overall losses are high and remedial action would be required.

Table **4-12**: Criticality for the Spring Creek stream modification project

Criticality Factor	**Rating** (S_i)	**Weight** (w_i)
Project replacement cost	3	0.20
Infrastructure financial impact	3	0.12
Eroded streambank value	1	0.12
Infrastructure service impact	4	0.18
Injury potential	4	0.18
Habitat impact	4	0.10
Pollution source	1	0.10
Relative Criticality	$C = \sum_{i=1}^{7} w_i S_i$ = 3.02	

The vulnerability-criticality risk matrix, shown in Figure 3-3, shows that a moderate vulnerability score and serious criticality score equate to risks that should be unacceptable. The recommended action is to monitor the project regularly and consider options for remedial action plans in case conditions onsite degrade further.

4.3.3 – Discussion of the Spring Creek Case Study

The Spring Creek stream modification project was performed to enhance the local fish habitat and stabilize the banks of a newly formed channel. When the project was constructed, a dam had recently been removed and the creek flow was cutting a channel into the deposited sediment that had accumulated behind the dam. This project involved some streambank shaping on the right bank, the excavation of a few pools, and many structures intended to both to lock the channel in-place and enhance in-stream habitat. It is important to note the presence of the infrastructure in close proximity to the channel that is currently outside of the flood prone area of the channel. Bank migration or significant erosion could place this infrastructure within the flood prone area.

The project was extensively damaged due to frequent evidence of bank erosion within the project reach. The hydraulic and geomorphic functions of the channel are extensively damaged due to prevalent bank erosion. Although extensively damaged, the project is only moderately vulnerable to widespread damage that would prevent functional lift and damage connected waters. Bank erosion threatens the state of static equilibrium within the project reach and has led to damage in a significant number of the structures in the project and is likely the source for the fine sediments deposited on the channel bed. This damage is likely to impact ecological conditions, preventing functional lift or degrading current functions in Spring Creek. The Bald Eagle Creek case study was also extensively damaged due to bank instability but with very different site conditions. While the projects have the same relative vulnerability score, the damage to the banks at Bald Eagle Creek was isolated to two categories of damage and no other damage categories were even slightly damaged. In this case study, the banks are significantly unstable and threatening more deposition, the streambank vegetation, and further structural damage.

This case study was the most difficult for the two volunteers who assessed the project for damage. It was their first exposure to stream modification and site conditions were not optimal. The evaluation had to be performed from the right bank as the flow was too quick and deep to cross Spring Creek on the day of the visit. This led to underestimation of scour surrounding structures on the left bank of the channel. Additionally, one or both of the volunteers assessed damage in the *degradation, bank stability and migration,* and *sediment, wood, and debris transport* categories differently than the final evaluation. These differences may be attributed to lack of familiarity with stream modification; while the stream may be entrenched compared to natural channels there was no evidence that the bed has degraded since construction was completed. The differences in expectations and impressions are likely the cause of disagreement in evaluating *bank stability and migration,* and *sediment, wood, and debris transport*. Both of these evaluations are based on percentage of channel affected and the length of this project reach was significant. While maps of the project site were provided to the evaluators to aid in noting the overall extents of damage in these categories they were not utilized.

The Spring Creek stream modification is an example of an extensively damaged enhanced level of achievement stream modification project. The project was determined to have moderate risk, therefore is equal in priority to Bald Eagle Creek near the Port Matilda Community Park. Pictures of conditions found onsite during the damage assessment in May, 2013 are included in Appendix B.

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Chapter 5

Conclusions

This research provides a tool for assessing damage to stream modification projects and determining whether or not the observed level of damage is acceptable. Widely accepted stream assessment tools were used to create damage states for basic functions of modified stream channels in constrained environments. The damage categories and scores can be used to calculate relative vulnerability and, when combined with criticality, the relative risk associated with stream modification projects. The tools presented in this research inform decision making and can be used to improve the results of stream modification in urban and agriculture settings in protecting both physical assets and aquatic functions.

The damage states focus on damage to hydraulic and geomorphic parameters that describe basic stream functioning and support higher level functioning. Evaluating projects based on stream functions affected by modification design provides an objective characterization of post-construction project performance that is separate from the sometimes subjective determination of project success or failure. Improved projects focus on bank stabilization or protection without hardening an entire cross section in the modified channel and are evaluated for damage in the categories of *infrastructure protection*, *structural integrity*, *bank stability and migration,* and *flood hazard*. Enhanced projects harden entire cross sections of the channel within the project reach and are evaluated for damage in the following categories: *infrastructure protection*; *structural integrity*; *bank stability and migration*; *degradation; wood, sediment, and debris transport;* and *streambank vegetation*. A continuum of damage ranging from no damage to complete damage is described for each category in each level of achievement. The overall damage of the project is described as the highest level of damage in any of the damage categories for a projects level of achievement. The individual damage scores in the damage categories can be used to calculate a relative vulnerability score to be entered into the vulnerability-criticality risk matrix. The risk matrix is a semi-quantitative risk assessment that combines vulnerability and criticality to determine the level of suggested action for the current conditions of a project. A set of criticality factors is presented for general use for comparing improved and enhanced stream modification projects but stakeholders are encouraged to develop their own set of criticality factors that can be used for their specific area of study.

The damage states can be used in decision making as a systematic method to determine the need for repair and further improvement. Project regulators and designers can identify channel functions that are not supporting the local environment and target their design or remedial action to address specific deficiencies. It can also be used to systematically determine the level of damage in discussions and legal processes that involve accountability for project damage. Vague project objectives can be superseded by the condition of channel functions that were altered by the stream modification design at improved or enhanced levels of achievement. System response to modification may be difficult to predict but the semi-quantitative risk assessment presented in this research provides insight into relative risk and can inform risk reducing actions. Risk assessment can be used to concentrate resources on high priority risks and appropriate risk-reducing measures in preparation for hazards and disturbance. Decision makers such as city, county, or state planners can use it to identify and prioritize risks and vulnerabilities, implement risk-reducing measures, and prepare for failure or hazards.

Like any rapid assessment tool, there are limitations to the application of the damage states framework. Implementing the damage states requires training to familiarize assessors with the intent of the damage descriptions. Additionally, the evaluator should be knowledgeable of the various aspects and disciplines related to stream modification work and be familiar with local stream modification practices. One important limitation of this research is the need for information pertaining to the design and as-built condition of the project being evaluated. As-built conditions may not have been surveyed and individuals who participated in the design and construction may not be available in all situations. In this case, the damage evaluation would be based on subjective assumptions made by the evaluator. On a similar note, the subjectivity of the damage evaluation has been minimized by providing clear and detailed descriptions of damage and explanation of the case studies but it has not been eliminated. It was apparent from the damage assessments performed by two volunteers that subjectivity was not eliminated, although their assessment also proved that the vulnerability ratings resulting from the damage assessment are not sensitive to these types of uncertainty. It is appropriate to confirm damage scores, especially visual assessments of the likely extent of damage, with a survey of site conditions when possible before remedial action is taken. Additionally there are physical limitations of the damage states that require further research, such as the focus on small streams rather than large rivers and the geographic homogeneity of all the case studies used to apply the methodology. One important limitation of the damage states regards their intent in evaluating project damage to basic channel functions. The damage states are not intended to evaluate project success or failure, but rather a continuum of damage states between those two end points. The evaluation of success and failure must be tied to local environmental and social settings through monitoring and assessment of whether the project has attained its specific goals.

This research was primarily focused on developing the damage assessment framework and risk assessment tool. Due to the variety of environments found across the United States and the rapid evolution of stream modification practice, further study is recommended to validate and improve the tools presented in this research by applying them to a wide variety and large number of projects. A large data set will determine statistical strength and weaknesses across physiographic regions and enable sensitivity analyses on the numerical criteria applied in the damage and risk frameworks. A large data set would also allow optimization of selection processes such as the criticality factors. The process of choosing criticality factors is intended to allow regional decision-makers to identify local priorities, however there may be an optimal number of criticality factors or a maximum number of factors. Future study will also concentrate on developing tools to evaluate superior level of achievement projects.

Stochastic processes and intricately connected stream functions make evaluation of stream modification projects difficult to standardize and the uncertainty associated with predicting channel response to modification is significant. Performance standards are necessary to prevent the degradation of aquatic resources and risk should not be neglected when important assets are at stake. The damage and risk framework presented in this research can improve the results of the practice of stream modification in constrained environments by providing performance standards and enabling risk assessment.

Appendix A

Stream Modification Practices

This table is not an exhaustive list of stream modification practices. Practices are listed in no particular order. Note that different manuals have slightly different definitions and construction methods. Practices that are grouped together in this table are largely similar although may not be exactly the same. References for the practices are in Section 2.4 of this document.

Unnatural Rigid Design		
Practice	**Explanation**	**References**
Riprap Boulder revetment Riprap revetment	Rock armoring usually placed on top of a filter layer of gravel or fabric. Rocks are sized to resist mobilization.	MDE, 2000; VA DCR, 2004; Cramer, 2002; Schueler and Brown, 2004;
Imbricated riprap Stacked stone	A wall consisting of large, interlocking boulders.	MDE, 2000; VA DCR, 2004; Schueler and Brown, 2004;
Rock toe Roughened rock toe	Rock or log armoring for the bottom portion of the streambank.	VA DCR, 2004; Cramer, 2002;
Gabion baskets Gabions	Stone filled wire baskets used for armoring.	MDE, 2000;
Geobags Sandbags	Sand filled geotextile bags	Akter, et al., 2012;
A-jacks Interlocking concrete jacks	Three-dimensional, pre-fabricated concrete shapes used to armor the bed or bank toe. Other shapes include dolos, toskanes, tetrapods, and tetrahedrons.	Cramer, 2002; Schueler and Brown, 2004; VA DCR, 2004; Lagasse, et al., 2009;
Live crib walls Log cribwalls	Logs are anchored together to form a box filled with soil, rock, and branch layers (live fascines). Crib walls function as degradable retaining walls for steep slopes.	MDE, 2000; VA DCR, 2004; Cramer, 2002; Schueler and Brown, 2004;
Semi-Natural Form Design		
Practice	**Explanation**	**References**
Vanes (log or rock) Barbs Bendway weirs	Linear roughness elements angled upstream that extend into the channel, meeting bankfull elevation at the bank and nearing the bed elevation at the tip.	MDE, 2000; VA DCR, 2004; Cramer, 2002; Schueler and Brown, 2004;

	Can be made of logs or rock.	
J-hook vanes	Vanes that extend into the center of the channel forming a hook to promote scour.	MDE, 2000; VA DCR, 2004; Schueler and Brown, 2004; Lutz, 2007;
Rock cross vanes U-, A-, V-, W-weirs Drop structures Notched log drops V-log drops Log cross vanes	Channel-spanning structures that consist of vanes coming from each bank that connect in the center of the channel. Can be made of logs or rock.	MDE, 2000; VA DCR, 2004; Cramer, 2002; Schueler and Brown, 2004; Mooney, et al., 2007a; Lutz, 2007;
Rock vortex weirs Porous weirs	Similar to rock cross vanes but the rocks in the center of the channel have gaps between them and protrude above the bed elevation.	MDE, 2000; VA DCR, 2004; Schueler and Brown, 2004; Cramer, 2002;
Groins Spur dikes Engineered log jams	High profile (above high water surface elevation) roughness elements that extend into the channel. Can be made of rock, large woody debris, or pilings.	Cramer, 2002; FEMA, 2009;
Woody debris catcher	Porous engineered log jams.	FEMA, 2009
Buried groins Rock trenches Transverse dikes	Groins embedded in the ground rather than in the channel to prevent future erosion.	Cramer, 2002;
Step pools Regenerative stormwater conveyance	Series of low elevation rock weirs and plunge pools.	MDE, 2000; VA DCR, 2004; Schueler and Brown, 2004; Cramer, 2012; Mooney, et al., 2007b; CWP, 2012;
Constructed riffles Rock ramps Roughened channels	Immobile rock armoring of a reach of the channel bed that mimics a natural riffle.	Cramer, 2012; Mooney, et al., 2007b;
Wing deflectors Frame deflectors	Low profile triangular or trapezoidal structures that extend from the bank. Frames can consist of log or rock.	MDE, 2000; VA DCR, 2004; Schueler and Brown, 2004; Lutz, 2007;
Rock sills Cut off sills Linear deflectors	Low profile empty frames that extend into stream channel and promote sediment deposition.	VA DCR, 2004; Schueler and Brown, 2004;
Lunkers Mud sills	Shelves installed extending from channel banks below water surface elevation creating cover.	Schueler and Brown, 2004; Lutz, 2007;
Erosion control fabrics Turf reinforcement mats Manufactured retention system	Non-degradable surface installed over streambank surface.	Schueler and Brown, 2004; Cramer, 2002; Miller, et al., 2012;
Structural earth wall Soil lifts Vegetated geogrid Soil reinforcement	Stream banks consisting of soil layers (or lifts) wrapped in non-degradable fabrics.	Cramer, 2002; Schueler and Brown, 2004; Miller, et al., 2012; Sotir and Fischenich, 2003;

Natural Process Design		
Practice	**Explanation**	**References**
Bank vegetation establishment	Planting of riparian and/or streambank surface vegetation.	Cramer, 2002; FEMA, 2009; Schueler and Brown, 2004;
Channel modifications Channel relocation Streambank shaping	Manually shaping aspects of the channel form, cross section, or profile.	Schueler and Brown, 2004; Cramer, 2002; FEMA, 2009;
Rootwad revetment	The lower trunk of a tree is installed in the stream bank with the root fan protruding into the channel.	Schueler and Brown, 2004; VA DCR, 2004;
Roughness trees Tree revetment Cedar tree revetment	Trunk and rootwad of tree installed parallel to bank with rootwad facing upstream.	Cramer, 2002; VA DCR, 2004; FEMA, 2009;
Coir fiber logs Biodegradable rolled erosion control product Natural fiber rolls	Rolls of degradable fabric secured to streambank surfaces, can be used as toe protection	MDE, 2000; VA DCR, 2004; Cramer, 2002; Schueler and Brown, 2004; Miller, et al., 2012;
Live soil lifts	Stream banks consisting of soil layers (or lifts) wrapped in degradable fabrics with plantings inside of them.	VA DCR, 2004; Cramer, 2002;
Natural fiber matting Brush mattresses Biodegradable erosion control fabrics	Degradable surface installed over streambank surface. Can consist of fabric, matting, a mattress of branches, etc.	VA DCR, 2004; MDE, 2000; Schueler and Brown, 2004; Miller, et al., 2012;
Live fascines	Rolls of dormant cuttings from tree species that are secured to angled streambank surfaces.	VA DCR, 2004; MDE, 2000; Schueler and Brown, 2004;
Live stakes Pole plantings Dormant woody cuttings	Dormant cuttings of tree and shrub species that are driven into stream bank surfaces	VA DCR, 2004; MDE, 2000; Schueler and Brown, 2004; FEMA, 2009;
Branch layering Brush layering	Dormant cuttings of tree and shrub species between soil lifts.	VA DCR, 2004; MDE, 2000; Cramer, 2002;
Random boulders Boulder placement Boulder clusters	Placement of isolated or groups of large boulders in the channel.	MDE, 2000; Cramer, 2012; Schueler and Brown, 2004; Mooney, et al., 2007b; Lutz, 2007;
LWD placement	Placement of large woody debris in the channel.	Schueler and Brown, 2004; Cramer, 2002; FEMA, 2009;

Appendix B

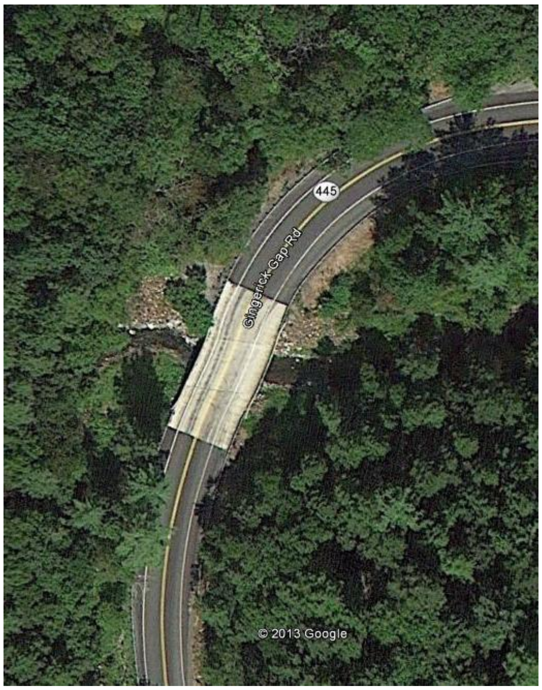
Images and Photographs of Case Studies

This appendix contains images of the case studies discussed in Chapter 4 of this report. The images of damage at these studies are also used to exemplify damage descriptions discussed in Sections 3.2.1 and 3.2.2. Images are labeled with the case study and date the image they were taken and the source if the image is not a photograph. Images are grouped into the following categories:

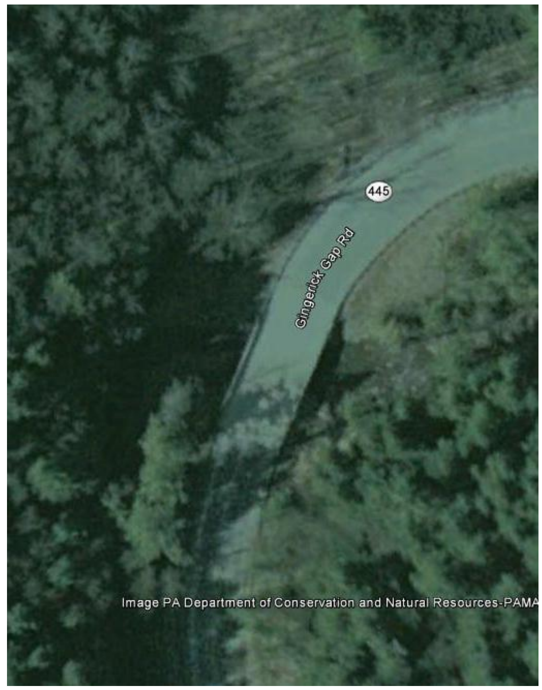
Historical Images

Roaring Run under Pennsylvania State Route 445

August, 2012 [1]



April, 2005 [2]



[1] Google earth. (August 30, 2012). Centre County, Pennsylvania. 40° 58' 51.49" N, 77° 32' 39.46" W, PA Department of Conservation and Natural Resources. http://www.earth.google.com [June 10, 2013].

[2] Google earth. (March 31, 2005). Centre County, Pennsylvania. 40° 58' 51.49" N, 77° 32' 39.46" W, PA Department of Conservation and Natural Resources. http://www.earth.google.com [June 10, 2013].

Bald Eagle Creek at Port Matilda

August, 2012 [3]

September, 2010 [4]

October, 2006 [5]

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[3] Google earth. (August 30, 2012). Centre County, Pennsylvania. 40° 47' 51.83" N, 78° 03' 14.55" W, USDA Farm Service Agency. http://www.earth.google.com [July 12, 2013].

[4] Google earth. (May 9, 2010). Centre County, Pennsylvania. 40° 47' 51.83" N, 78° 03' 14.55" W, USDA Farm Service Agency. http://www.earth.google.com [July 12, 2013].

[5] Google earth. (May 27, 2006). Centre County, Pennsylvania. 40° 47' 51.83" N, 78° 03' 14.55" W, USDA Farm Service Agency. http://www.earth.google.com [July 12, 2013].

September, 2005 [6]

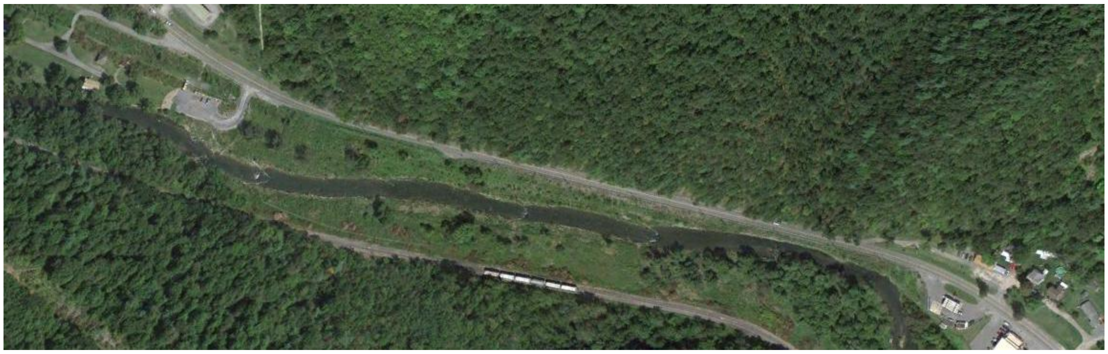
April, 1993 [7]

[6] Google earth. (June 6, 2005). Centre County, Pennsylvania. 40^o 47’ 51.83” N, 78^o 03’ 14.55” W, USDA Farm Service Agency. http://www.earth.google.com [July 12, 2013].

[7] Google earth. (April 17, 1993). Centre County, Pennsylvania. 40^o 47’ 51.83” N, 78^o 03’ 14.55” W, USGS. http://www.earth.google.com [July 12, 2013].

Spring Creek between Bellefonte and Milesburg, Pennsylvania

August, 2012 [8]



September, 2010 [9]

March, 2008 [10]

[8] Google earth. (August 30, 2012). Centre County, Pennsylvania. 40º 55' 46.64" N, 77º 46' 57.91" W, USDA Farm Service Agency. http://www.earth.google.com [June 10, 2013].
[9] Google earth. (September 1, 2010). Centre County, Pennsylvania. 40º 55' 46.64" N, 77º 46' 57.91" W, USDA Farm Service Agency. http://www.earth.google.com [June 10, 2013].
[10] Google earth. (August 30, 2008). Centre County, Pennsylvania. 40º 55' 46.64" N, 77º 46' 57.91" W, USDA Farm Service Agency. http://www.earth.google.com [June 10, 2013].

September, 2005 [11]

April, 1994 [12]

[11] Google earth. (September 20, 2005). Centre County, Pennsylvania. 40° 55' 46.64" N, 77° 46' 57.91" W, USDA Farm Service Agency. http://www.earth.google.com [June 10, 2013].

[12] Google earth. (April 17, 1994). Centre County, Pennsylvania. . 40° 55' 46.64" N, 77° 46' 57.91" W, USGS. http://www.earth.google.com [July 12, 2013].

Examples of Bank Conditions

Raw banks were present at both the Spring Creek case study (left) and Bald Eagle Creek case study (right). Raw banks, or cut banks, are vertical, non-vegetated surfaces that have undergone recent erosion.

Bank failures include instances of mass wasting, block failures, and severe undercutting. There were no instances of severe undercutting at the case study sites. There was evidence of block failures and mass wasting at the Spring Creek site.

Regarding structures, the *bank stability and migration* category of damage accounts for erosion of the bank that was not in contact with structure components when construction of the project was completed and bank erosion that continues after a structure is detached from the bank. Erosion immediately adjacent to structures or structure components are counted as structure damage. Examples are provided in the next section of the Appendix.

Examples of Modification Practices

All photographs were taken in the summer of 2013 in Centre County, Pennsylvania. The practices shown include: lunkers, riprap, rock cross vanes, rootwad-log vanes, rock vanes, J-Hooks, and a rootwad.

Lunkers

The following images are of the lunkers (aka mud sills) installed on Spring Creek. Usually, the logs are underneath rock and earth, hiding the lunkers from sight. These lunkers are damaged due to displacement of structure components. The lunker on the left that is sinking has experienced more displacement and is extensively damaged while the other (two photos on the right) is only moderately damaged.



Riprap

The following images depict riprap at the Roaring Run case study, left, and the Spring Creek case study, right. The large riprap at Roaring Run has a few displaced components (one that is evident in the photo below and one that is evident in the next set of photos) but less than 10% of structure has been displaced and is therefore undamaged. The riprap at Spring Creek may be experiencing some scour but it is similarly insufficient to indicate damage.


The following images depict a displaced footer rock at the Roaring Run case study, left, and detached portion of riprap at the Spring Creek case study, right. The riprap shown on the right in Spring Creek is the upstream extent of the structure which extends significantly downstream, out of the photograph. This structure is partially detached and extensively damaged. Also, since the structure is detached from the bank, the raw banks visible in this photo count contribute toward damage in the b*ank stability and migration* category of damage.


Examples of undamaged imbricated riprap can be found in the Spring Creek case study, Section 4.3.1.

Rock cross vane

There were four large rock cross vanes installed in the Spring Creek stream modification project. The following images depict the parabolic shape and drop in head that occurs across these rock cross vanes.


One of these rock cross vanes exhibited scour surrounding structure components on both banks and was therefore moderately damaged. The following images depict scour surrounding the bank tie-in components that led to the evaluation of structure damage. The components shown on the right are the end of the structure arm and intended to be buried or flush with the ground.


Rootwad-Log Vane

Photographs of various rootwad-log vanes on Spring Creek in Centre County, Pennsylvania. The most damaged rootwad-log vane missing the rootwad while moderately damaged structures showed signs of scour everywhere the structure was in contact with the bank (the top right and lower left photographs).

Rock Vanes

The following image depicts two rock vanes on Spring Creek, one coming from each bank.

Rock vanes on Spring Creek did not experience component displacement, although without As-built plans it would be difficult to determine whether the end of the structure is intact. Moderately damaged rock vanes experienced scour everywhere the structure was in contact with the bank (left). There were two rock vanes that were completely detached from the bank and therefore completely damaged (right). This structure is completely detached from the bank and the raw banks visible in this photo count contribute to damage in the b*ank stability and migration* category of damage.

J-Hooks

J-Hook vanes are channel-spanning structures similar to rock cross vanes with only one bank tie-in. These structure were used on Bald Eagle Creek in Port Matilda, Pennsylvania. These structures were very low and submerged during most site visits but the following images show the shape of typical J-Hooks. The structures installed in Bald Eagle Creek were undamaged except for one that is shown in Figure 4-11 of the report.

Rootwad

The following photograph is of rootwads on Spring Creek in Centre Country, Pennsylvania. Rootwads are oriented facing upstream to dissipate energy. These rootwad has undergone some damage from passing flows. While the rootwad-log vanes in Spring Creek were intended to be permanent, rootwads can also be installed independently of log vanes and degradation may be expected and intended.