Improving the Success of Stream Restoration Practices – Revised and Expanded

Final Project Report

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Executive Summary

In the United States, stream restoration is currently a billion-dollar industry. Though it is commonly used as a method for stream impact mitigation, sediment and nutrient reductions for Total Maximum Daily Load (TMDL) crediting, and stormwater management, there are few studies defending stream restoration as an effective tool for addressing these issues. In particular, limited research has been conducted with the goal of providing recommendations for future design improvements.

The goal of this research project was to improve our understanding of the conditions under which stream restoration practices “fail,” with the long term goal of improving the overall application, design, and review of stream restoration projects. To achieve the project goal, a selection of 65 completed Maryland stream restoration projects were assessed at the watershed and project level. Watershed, site, and design characteristics were quantified using ArcGIS, restoration design and/or as-built plans, and monitoring reports. Using current literature, stream restoration assessment methodologies were developed to assess geomorphic function and design success both in the field and by reviewing monitoring reports. Multiple linear regression analysis and related methods were then used to identify correlations and relationships between watershed- and project-level characteristics and three measures of stream restoration success.

At the watershed scale, land cover was the factor most strongly related to project success. Increasing agricultural landuse was positively related to improved stream geomorphic function, likely due to the more stable stream hydrology, reduced infrastructure constraints on designs, and less confined floodplains in rural watersheds. At the project level, restored channels with larger width to depth ratios and smaller bed particle sizes relative to the channel size also scored higher on the functional assessment. When buildings and related infrastructure are not present in the floodplain, the channel width, relative to channel depth, can be increased, allowing the stream to inundate the floodplain more frequently. Frequent floodplain inundation reduces the hydraulic stress on the channel and allows the use of smaller rock sizes in stream restoration designs.

Study results clearly demonstrated that the design constraints within urban watersheds limit the restoration of geomorphic/physical functions in stream systems, which ultimately limits the potential recovery of biological function. Therefore, it is recommended that stream restoration projects undertaken to mitigate stream impacts be targeted in watersheds that have similar or less urban land cover as the watershed where the impact occurred. This siting criterion will increase the likelihood that the impacted stream functions can be restored.

Stream restoration is frequently undertaken in urban watersheds to reduce channel erosion and sediment and associated nutrient loads, and to protect infrastructure. However, study results indicated that increased development within the contributing watershed following project construction was correlated with reduced design lifespan, despite the presence of stormwater management practices. Therefore, future development should be considered in stream restoration designs. Additionally, projects in larger watersheds and catchments with higher discharge and specific stream power were less durable, likely due to greater hydraulic forces on the channel and instream structures. This finding was supported by the positive correlation between bed particle size and design success. Therefore, the use of larger rock sizes is important for channel stability in urbanized watersheds where channel migration cannot be allowed to protect infrastructure. Because instream structures limit natural channel migration and are typically constructed with materials of sizes that are not naturally found in these stream systems, existing stream physical processes will not maintain these structures; therefore, organizations should plan for routine monitoring and maintenance of stream restoration projects where instream structures are used.

Study results also demonstrated that the ability to determine project success from standard monitoring reports is limited. Because stream restoration success is multi-faceted and can significantly vary based on assessment method (biological function, geomorphic function, infrastructure protection), it is important that specific, individual goals are stated for each project and that monitoring requirements be targeted to assess each project goal. Clarity of realistic goals and monitoring targeted at goal assessment, however, remain low, so further emphasis should be placed on stream restoration assessment design and reporting in the future. For example, the primary goal of a stream restoration project in a highly urbanized watershed may be to stop bank retreat that is threatening to undermine a roadway. In this situation, monitoring should focus on the elimination of the bank erosion. In contrast, if the goal of a stream restoration project is to mitigate lost ecological function in a headwater stream impacted by new development, the project should be located in a watershed where ecological uplift is not limited by upstream landuse and the monitoring should evaluate indicators of biological function before and after project completion to insure lost function is restored.

In addition to overall project success, the design of instream structures was also evaluated. Instream structures are used to reinforce channel margins, redirect flows, and create habitat, but there is little consensus about their design or whether they function as intended. For this assessment, 536 instream structures in 39 stream restoration projects were assessed to determine the effect of structure-, project-, and watershed-scale factors on performance. Structures were assessed using a 19-point scoring system based on structural stability, sediment transport, and overall function. Structure-scale design variables were related to structure construction, geometry, and placement and differed for each of six structure families: bank protection (BP), full and partial span vanes (FSV), constructed riffles (RF), regenerative stream conveyances, and step pools. Project- and watershed-scale variables were related to flow, erosion resistance, and design approach. Relationships between structure scores and explanatory variables were evaluated using regression analysis.

The structure study results showed structure performance was strongly influenced by the individual project, suggesting that design quality, construction, and maintenance are as important as specific design features. Increased medium density development in a watershed after a restoration project was completed was correlated with lower structure success for all structures, especially rock full span vanes. Residential development in the Maryland Piedmont and western coastal plain typically occurs on rural lands and the increase in impervious surface area causes increased runoff volume and peak flows. Stream restoration projects implemented in watersheds where future development is anticipated will require a higher degree of planning and more robust structure designs.

Overall, imbricated rock walls were more effective than stone toe structures for bank stabilization because these walls are constructed four times taller with boulders that are three times larger, on average, compared to stone toe. As a result, imbricated rock walls have less risk of erosion behind the structure due to overtopping flows and reduced chance of rock movement. While imbricated rock walls are more expensive to construct, they have reduced risk of failure where infrastructure protection is critical. In designs where bank stability is not critical, the use of dense woody vegetation with coir fiber fabric is recommended instead of stone toe, as woody vegetation is less expensive, easier to replace, and has decreasing failure risk as compared to stone toe structures, as vegetation stability and density increase with time as the vegetation grows. More research is needed to quantify the fluvial erosion resistance (i.e. allowable stress) of typical riparian vegetation communities in the mid-Atlantic at different growth stages for use in bank erosion analyses.

Study results also provided design insights for specific instream structures. For single arm vanes, there was evidence that single arm vanes constructed in series were more durable than individual vanes. For full span vanes, the installation of a bank key or cutoff sill at angles between 35° and 90° to the streambank improved structure performance. Several design factors for constructed riffles were correlated with structure success. Constructed riffles were more durable when constructed with downstream grade control, which likely stabilizes the riffle against scour and material migration. Moreover, relatively longer riffles (length:width > 4.5) and those constructed with deeper substrate performed better, as these structures could experience greater material movement before the structure function was compromised. However, given that naturally formed riffles have length:width of less than 2.0 and occur at greater spacings than observed in several stream restoration projects, it is apparent that these longer constructed riffles essentially served as channel armor/riprap instead of replicating natural stream bedforms. More focus should be placed on correctly siting constructed riffles in the planform and designing riffles with length:width of less than 3.0.

Although the results of this study provided insight into design and project features that contribute to structure success, it should be noted that a range of design techniques can be effective and that other factors play significant roles in structure success such as design quality, construction quality, weather conditions during and immediately after construction, and structure maintenance. Development of national design standards (such as by the American Society of Civil Engineers) is recommended to improve structure performance and to minimize liability for professional engineers, as concerns over professional liability can lead to more conservative stream restoration designs and the use of hard materials, such as boulders, since design data are more available for rock than for wood and live vegetation.

Structure evaluation in this project did not assess the ecological function/value of structures, so future studies should explore whether structures, particularly those that have stated habitat functions, such as full span vanes, constructed riffles, and step pools, are ecologically beneficial. Given that stream channels naturally migrate over time and that biological integrity is linked to the inherent diversity and dynamism of natural systems, it should be recognized that the use of instream structures to permanently hold a stream in place will limit ecosystem health. Therefore, it is recommended that instream structures, particularly those constructed of rock, be used only for infrastructure protection or to protect adjacent stream reaches from channel degradation, such as incision caused by knickpoint migration. Additionally, regulatory agencies should allow some degree of channel movement for stream restoration projects where infrastructure protection is not critical. Additional research is needed to define acceptable levels of channel migration in the mid-Atlantic region that do not result in excessive sediment loads or biological impairment.

In addition to the broad evaluation of stream restoration projects overall and a more detailed assessment of instream structure design and siting, a detailed hydraulic analysis was conducted to provide insight into the benefit of using two-dimensional (2D) hydraulic modeling in stream restoration design instead of the more commonly used one-dimensional (1D) modeling. Six stream restoration projects representing a range of channel sizes, project ages and lengths, and structures were modeled in 1D and 2D using HEC-RAS 5.0.7. Study results show that 3-4 cross sections are required for each instream structure to reliably capture structure impacts on stream hydrodynamics. With the increased number of cross sections, the model was able to replicate flow contraction through the structure and the resulting upstream backwater conditions. However, this increased model resolution in the 1D model also resulted in an unrealistically jagged flood extent that would not be suitable for floodplain studies.

In creating a 2D model, there is a tradeoff between a small grid size that provides greater resolution of the model results and the model run time. Grid sizes ranging from 0.8 – 13 ft. and with 0.5 – 8.0 cells per channel width were investigated. Study results indicated that for small streams where stream restoration projects are commonly targeted, the meshes should be set with either a minimum breakline cell size of 3.28 ft. (1 m) or a minimum of two grid cells per channel width.

Comparison of the predicted water surface elevations, velocities, and shear stresses for the 1D and 2D models indicated the 2D model better represented stream hydrodynamics overall. Additionally, the 2D model captured areas of high shear along the channel boundary that could cause structure flanking. Given the improved spatial data tools in HEC-RAS 5.0 and 6.0 and the increased availability of high resolution topographic data, the development of a 2D model was not significantly greater than the time required for a 1D model, although model run times were extended.

In summary, stream restoration is increasing used in Maryland to address stormwater impacts and to improve water quality as part of the watershed implementation plans for the Chesapeake Bay TMDL, particularly in urban watersheds. However, the practice of stream restoration has far outpaced the science, due to limitations of science-based research, such as multiple interdependent variables control stream functions, biological processes cannot be scaled for laboratory studies, and the response time of stream systems is typically much longer than human planning or funding horizons (Shields et al., 2003). This research project evaluated 65 stream restoration projects in Maryland as independent stream restoration “data points” with the goal of improving the overall application, design, and review of stream restoration projects. Overall study results indicate that the multiple constraints in urban watersheds make the restoration of geomorphic processes challenging. Restoration projects should clearly state specific and realistic project goals and post-construction monitoring should be linked to project goals. Given the challenges in urban stream restoration, engineers commonly create conservative restoration designs with hard structures. Additional research is needed to provide engineering design data for materials such as wood and vegetation, to improve restoration design practice. Research is also needed to determine if the use of instream structures provides ecological improvement in stream systems.

1.0 Introduction

A synthesis of stream restoration projects within the US estimated that, on average, at least $1 billion was spent annually between 1990 and 2004 on stream restoration (Bernhardt et al., 2005). Increasingly, stream restoration is used in Maryland to address stormwater impacts and to improve water quality as part of the watershed implementation plans for the Chesapeake Bay TMDL, particularly in urban watersheds. Currently, over 900 miles of stream restoration projects are planned in the Bay watershed by 2025, with an estimated cost of $0.5 billion (Wheeler, 2020).

However, in comparison to upland best management practices, there is relatively little research on the effectiveness of stream restoration to improve the physical, chemical, and/or biological integrity of stream systems. There are many reasons for this lack of science-based research: multiple interdependent variables control stream functions, biological processes cannot be scaled for laboratory studies, and the response time of stream systems is typically much longer than human planning or funding horizons (Shields et al., 2003). All of these factors combined make scientifically defensible stream restoration research difficult and costly. As a result, the practice of stream restoration has far outpaced the science. Practitioners have adapted their design techniques based on personal experience; however, there is little written record of practitioner experience, as this information is frequently guarded as “trade secrets” due to competition among environmental consulting firms (Bennett et al. 2011). Where the knowledge and experience of many stream restoration practitioners has been assessed (e.g. Radspinner et al., 2010), these studies have been predominately qualitative and provided largely anecdotal evidence.

Current stream restoration research typically consists of assessments of existing stream restoration projects and/or practices within a single project. An extensive study of the Minebank Run near Baltimore, MD showed the restoration increased the geomorphic diversity and stability of the channel and decreased lateral erosion (Doheny et al., 2012). Endreny and Soulman (2011) monitored a stream restoration project on Batavia Kill in the Catskill Mountains of New York. The project included 12 cross vanes and 48 j-hook vanes along 19 meander bends. Both aggradation and degradation of pools were observed following construction with the stream trending from a riffle-pool channel to a plane bed/step pool channel. The researchers attributed structure failures to designs that did not follow current guidance, as well as a channel form that was likely not appropriate for the steep mountain stream. Bain et al. (2014) evaluated an urban stream restoration project on Nine Mile Run in Pittsburgh, PA, noting improved fish and benthic macroinvetebrate communities following the restoration project. In contrast, Buchanan et al. (2012) noted some structures in a stream restoration project on Six Mile Creek near Slaterville Springs, NY created fish migration barriers while others focused high velocity cross-stream flows onto downstream structures at high discharges. Similar observations were made by Puckett and Jennings (2006).

Some studies have evaluated multiple projects within a region. Miller and Kochel (2010) assessed 26 projects in North Carolina 1-6 years post construction, noting changes in channel configuration and the performance of instream structures. Their results indicated that major changes in channel geometry and structure failure were associated with channels with a large sediment transport capacity, significant sediment supply, and/or erodible banks. An additional study in North Carolina (Hill et al., 2011) documented an overall success rate of 75% for stream restoration projects; however, the authors noted that the success rate for the Piedmont physiographic region was lower (69%) than that for either the Coastal Plain or Mountain regions (95% and 98%, respectively). In a study of seven compound channel designs in northern California, Tompkins and Kondolf (2007) noted that channels with relatively constrained floodplain widths did not achieve their geomorphic goals. Additionally, urban and suburban streams had few external sources of in-channel complexity (large wood, range of particle sizes, etc.), indicating these elements may need to be included in designs to accelerate the development of channel complexity. Similarly, Doll et al. (2015) quantified overall project success using the Stream Performance Assessment (SPA) method: study results indicated restored streams were similar to reference streams.

While these studies have documented both success and failure of stream restoration projects and practices, they have provided few design recommendations to improve current site selection or design techniques. Systematic, published, post-project appraisals of both successful and failed restoration projects are needed to learn and to inform future projects (Thompkins and Kondolf, 2007; Kondolf et al., 2011). It is a common adage in engineering that we learn more from the bridges that fall down than from those that are still standing. Similarly, Petroski (1992) pointed out that no progress can be made beyond the current state of the art without failures. Ideally, these assessments should be conducted by individuals independent of the design, review, and construction process, to avoid the human tendency to maintain current practices. Objective, structured assessments promote what Downs and Kondolf (2002) referred to as “surprise learning” or new insights. Ultimately, information gleaned from such studies should feed back into design recommendations as part of adaptive management (Johnson et al., 2002; Palmer et al., 2011; Buchanan et al., 2012; Law et al., 2015).

The goal of this project was to improve our understanding of the conditions under which stream restoration practices “fail,” with the long term goal of improving the overall application, design, and review of stream restoration projects. We conducted the study at three scales: watershed, project, and practice. This study provides guidance on landscape-scale and reach-scale factors that indicate the risk of project failure, such as watershed size or impervious landuse or channel specific stream power or relative floodplain width (Chapter 2). At the practice scale, the success of individual stream restoration practices was assessed to evaluate current standards (Chapter 3). In addition to the broad evaluation of stream restoration projects overall, a detailed hydraulic analysis was also conducted to provide insight into the benefit of using two-dimensional (2-D) hydraulic modeling in stream restoration design instead of the more commonly used one-dimensional (1-D) modeling (Chapter 4).

2.0 Linking Stream Restoration Success with Watershed, Practice and Design Characteristics

It is well established that all life depends on water. As such, running waters such as streams and rivers have been called the "lifeblood of a continent" (Karr and Chu,1999). In addition, running waters support a variety of beneficial functions to society such as providing clean drinking water, flood and erosion protection, groundwater recharge, pollution reduction, wildlife habitat, and economic stimulation (EPA, 2013). Though streams and rivers are so important, they have endured "centuries of abuse as humans continue to alter the riverine landscape for a variety of purposes, including farming, logging, mining and development on the floodplain, and the subsequent need for channelization and flood control", resulting in the significant diminishing of the natural functions of stream corridors and the decline of the health of our nation's waters (Karr and Chu, 1999; Harman et al., 2012).

In response to this degradation, the 1972 amendments to the Federal Water Pollution Control Act of 1948 [commonly known as the Clean Water Act (CWA)] were adopted to restore and maintain the chemical, physical and biological integrity of the Nation's waters. Under the CWA, section 303(d) requires that states generate a list of impaired waters and develop Total Maximum Daily Load (TMDL) plans to address elevated pollutant levels (Clean Water Act, 1972). According to Bernhardt et al. (2005), greater than a third of U.S. waterways are included on this list and require plans to improve impairments.

One such waterway is the Chesapeake Bay, the largest and once most productive estuary in the United states, which Congress has recognized as a "national treasure and resource of worldwide significance," and the cleaning of which has been valued at 130 billion USD annually related to fishing, tourism, property values, and shipping activities. (Chesapeake Bay Foundation, 2019). To address these problems of degrading waterway health, stream and river restoration has increasingly become an accepted and encouraged method of watershed management (Wohl et al., 2005). In the Chesapeake Bay Watershed (CBW) in particular, many states are considering stream restoration as a strategy to meet nutrient and sediment load reduction targets under the Chesapeake Bay TMDL, which is the largest TMDL ever developed, and calls for nutrient and sediment reductions to the Bay (Berg et al, 2014; EPA, 2010). As a result, 3.4 million linear feet of stream restoration were identified to be implemented in the Bay watershed by 2025 (Law et al., 2015).

Not only has stream restoration become a significant physical undertaking, it has become a major economic industry. In a synthesis of over 37,000 stream restoration projects, Bernhardt et al. (2005) found that costs associated with stream restoration have averaged over one billion USD annually since 1990.

Because of the wide breadth of perspectives and disciplines involved in stream restoration, it is inherently difficult to define; however, in general, stream restoration is a term used for the wide range of actions undertaken to improve the geomorphic and ecological function, structure, and integrity of river corridors (Bennett et al., 2011). This wide range of actions can include restoration, rehabilitation, preservation, mitigation, naturalization, creation, enhancement, and reclamation (Shields et al., 2003). The NRCS (2007) provided a definition of ecological restoration, defining it as "the process of returning as closely as possible to pre-disturbance conditions”. As “pre-disturbance” is difficult to determine, others have adapted this definition to be “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.” (Society for Ecological Restoration Science and Policy Working Group, 2004), or “assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system, and replacing lost, damaged, or compromised elements of the natural system” (Wohl et al., 2005).

River manipulation by humans has been happening for centuries (Brookes and Shields, 1996; Wohl et al., 2015). Generally, this management was completed with the intention of improving navigation and reducing the risks of loss of life and property, although exceptions in this practice were made in order to improve the aesthetic and recreational quality of rivers. As a result of this management pattern, river corridors were typically reduced to more uniform, physically simplified, and ecologically less diverse and functional systems.

From the recognition of the extent and consequences of these alterations, river restoration began to become more important during the second half of the 20th century. In the beginning, restoration mostly focused on fish habitat creation through the physical manipulation of channel form, but was expanded to include water quality improvement with the onset of societal concern and water quality regulation (e.g., the CWA in the U.S.A and the Water Framework Directive in the European Union) during the late 1900s. Recently, as a result of pressure from the academic community, restoration prioritizing river function and process (i.e., process-based restoration) has increased in prominence (Wohl et al., 2015). Though this shift in restoration ecology to being informed by scientific research has been pushed more frequently (e.g. Shields et al., 2003), Wohl et al. (2015) remind that ecological restoration first originated not as an academic science, but as a citizen-led undertaking. As such, river restoration should be undertaken in reference to its social context. This social perspective, however, creates problems of its own. For instance, for a project to maintain support, it must retain the interest of the local communities surrounding the river in question (Wohl et al., 2015). Shields et al. (2003) further point out that maintained interest is hindered by lack of landowner compensation, and the complexity of decision-making involved in land management. In addition, social relevance is usually determined by factors other than those valued by ecological science (Wohl et al., 2015). Finally, difficulty in scientific research pertaining to river restoration is further compounded by large spatial and temporal scales, and by gaps pertaining to the many factors and complex relationships that contribute to the behavior of river ecosystems. As a result of these difficulties, the practice of stream restoration has far outpaced the science. Most updates in knowledge have come as a result of personal experience by the “Practitioner”. Little record of this experience is available, however, as most consulting firms wish to guard their “trade secrets” from competition (Bennett et al. 2011).

Current research on stream restoration has usually taken the form of assessment of completed stream restoration projects, but few projects have offered design recommendations to improve the practice. This project serves to provide guidance in stream restoration site selection and design techniques by improving understanding of the impact watershed- and project-level characteristics on stream restoration project success probability.

In particular, the goal of this research is to improve our understanding of the conditions under which stream restoration practices are successful. Specific objectives include the following:

1) Development of a method to assess stream restoration project success, both in the field, and using monitoring reports;
2) Evaluation of watershed-scale factors related to stream restoration success; and,
3) Evaluation of project and reach-scale factors related to stream restoration success.

Through this research the following questions are addressed:

1) Does stream restoration success increase with decreasing watershed size, impervious cover, and slope?
2) Are projects with lower relative flow energy (as indicated by stream channel confinement, specific stream power, floodplain width/bankfull channel width, watershed and channel slope, bankfull discharge/watershed area) more successful?
3) Are projects with low sediment supply (as indicated by watershed geology, watershed slope) or sediment transport capacity (channel slope, width:depth ratio) more successful?

2.1 Literature Review of Stream Restoration Assessment

In their synthesis, Bernhardt et al. (2005) found that the most common goals of stream restoration were to enhance water quality, manage riparian zones, improve in-stream habitat, allow for fish passage, and increase bank stability.

Riparian areas are the lands along watercourses and waterbodies with unique soil and vegetation characteristics. These areas provide many benefits such as nonpoint source pollution control by holding nutrients and filtering sediment, by providing habitat provision for a large diversity of animals, flood reduction, and through baseflow maintenance (NRCS, 1996). According to the U.S Forest Service guidance for restoration techniques, an early necessary step, and often the only necessary action in riparian recovery, is the exclusion of degrading agents such as livestock and wildlife. In cases of more disturbed systems where incision or channelization have altered water table elevations, more intensive restoration is required (Yochum, 2018).

As habitat degradation has been identified as a serious threat to biodiversity (Miller et al., 2010), and U.S. streams have reached an extremely low occurrence (2%) of “high natural quality.” (Benke, 1990), habitat restoration has become a major goal of stream restoration, with 6000 in-stream habitat enhancement projects implemented between 2000 and 2010. Miller et al. (2010) stated the goal of in-stream habitat restoration is typically to increase the diversity, density, and/or biomass of aquatic organisms through enhanced hydraulic and substrate heterogeneity and increased food availability.

According to the National Oceanic and Atmospheric Administration (NOAA) fisheries division, millions of fish migrate each year to native habitats to reproduce. Often, however, they are prevented from completing their journey by barriers such as dams and culverts. When they are prevented from reaching their spawning grounds, they are not able to reproduce and populations may decline, affecting entire ecosystems and economies (NOAA, 2017). In the Chesapeake Bay watershed in particular, fisheries contribute greatly to the economy by supporting almost 34,000 jobs and supplying 3.39 billion USD in sales in Maryland and

Virginia alone (Chesapeake Bay Foundation, 2012). To protect this valuable aspect of the Bay watershed, 1,236 miles of stream were opened to fish passage between 2012 and 2017 (Chesapeake Bay Program, 2019).

Multiple studies of Piedmont streams have shown that bank erosion contributes at least equally and perhaps up to 70% of watershed sediment yields compared to upland and floodplain erosion (Allmendinger et al., 2007; Donovan et al., 2015). Since bank erosion is such a large potential source of sediment to downstream waters, it can be easily seen why bank stabilization is a common goal of stream restoration. Bernhardt and Palmer (2007) showed that simple measures such as planting vegetation increased bank stability. The United States Army Corps of Engineers (USACE) further lists soil bioengineering, structural revetments, live fascines, and vegetated geogrids as methods of bank stabilization (Lake County Stormwater Management Commission, 2002).

2.1.1 Regulatory Drivers

The main regulatory driver for the enhancement of water quality is the Clean Water Act. Sections 303 and 404, in particular, are applicable to stream health. As discussed above, section 303 calls for the development of a list of impaired waters and TMDL plans to reduce pollutant loads. In some watersheds the majority of sediment yield is a result of stream bank erosion (e.g. Donovan et al., 2015; Allmendinger et al., 2007), and as stream restoration is commonly used for erosion reduction, it makes sense that it be considered a strategy for TMDL compliance. Section 404 regulates the discharge of dredged or fill material into waters of the U.S by requiring permits from the USACE to authorize such discharges. Every discharge allowed under these permits must minimize or avoid adverse effects to wetlands and streams. However, for unavoidable impacts, the loss of wetland and aquatic resource functions must be replaced through compensatory mitigation.

Also, under the CWA, The National Pollution Discharge Elimination System (NPDES) regulates point source discharges of pollutants into waters of the U.S. through the issuance of discharge permits. Discharges from municipal separate storm sewer systems (MS4) also require permits, although permits for MS4 discharges do not require a discharge to be compliant with water quality standards. Instead, MS4 permits require permitees to reduce pollutant discharge to the "maximum extent practicable," through the development of stormwater management plans and the implementation of Best Management Practices (BMP; Leo et al., 2018). Under the Chesapeake Bay TMDL, the EPA determined total pollutant reductions required for the Bay, and allocated reduction responsibility to each jurisdiction (Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia and the District of Columbia) within the watershed. Each jurisdiction was required to submit Phase I, II, and III Watershed Implementation Plans (WIPs), detailing actions and controls to be implemented by 2017 and 2025 respectively (EPA, n.d.). Included in Maryland's Phase II WIP, are strategies to meet TMDL reduction requirements while also satisfying MS4 permit requirements. Stream restoration is identified as one of these strategies (Maryland Department of Environment, 2012).

2.1.2 Restoration Assessment

Because stream restoration is a broad field with the possibility for multiple, potentially conflicting goals, qualitative and quantitative project objectives must be clearly stated, not only to guide design, but to allow for post-completion project evaluation (Kondolf, 1995; Kondolf and Micheli, 1995). This need for post project evaluation has been well argued. For instance, Palmer et al. (2005) argued for a definition of restoration success, stating "Without well-accepted [success] criteria that are ultimately supported by funding and implementing agencies, there is little incentive for practitioners to assess and report restoration outcomes." Others concur that post-project assessment is necessary for the advancement of the field through lessons from successes and failures (Kondolf and Micheli,1995; Morandi et al., 2014)

As discussed above, a definition of restoration success is necessary for the evaluation of projects and the progress of the field; however, because of the diverse goals and site conditions of restoration, a universal definition of success is difficult to agree upon, and probably not possible (Kondolf and Micheli, 1995). This difficulty is improved somewhat if clear and quantifiable goals are specified for each project, as there is a clear end-point which can be objectively evaluated. To increase the likelihood of project goals being achieved, Kondolf and Micheli (1995) advise that due to the experimental nature of restoration practices and the dynamism of aquatic systems, a range of acceptable variation may be required for defining success criteria.

Multiple studies have shown that physical channel stability as evaluated according to Pfankuch (1975) correlates with biological indices of stream health such as benthic diversity, and wildlife populations (Collier, 1992). As stability and geomorphology are linked, these findings lend themselves to success evaluation based on geomorphic characteristics of streams. Kondolf and Micheli's (1995) opinion mirrors this, arguing that channel geomorphology is the framework upon which ecological systems are developed, and that project evaluation techniques should be developed with geomorphic cross sections as their foundation. In her Ph.D. dissertation, Doll (2013) identified seven key elements of stream restoration design, all of which can be related to geomorphology: channel bedform, channel pattern, in-stream habitat, sediment transport, streambank condition, streambank vegetation, and floodplain function. Morandi et al. (2014) show that others agree with this conclusion, as they found that hydromorphology was the most frequently evaluated project component in a study of 44 French restoration projects.

Similarly, others argue that a functional viewpoint is beneficial, because it is derived from the recognition that healthy watersheds support ecosystem components that interact in complex ways and maintain functions that contribute to the continual dynamic development/evolution of the watershed (Fischenich, 2006). Fischenich (2006) used this idea to develop a set of functional objectives for stream restoration which includes system dynamics, hydrologic balance, sediment processes and character, biological support, and chemical processes and landscape pathways.

Harman et al. (2012) utilized these functional objectives to develop a "stream functions pyramid," which hierarchically ranks the stream functions of hydrology, hydraulics, geomorphology, physicochemistry, and biology. They argue that this pyramid can be used as a tool to develop assessments of restoration that focus on functional lift.

Other authors argue that stream restoration success should be defined with respect to ecological integrity. For instance, Palmer and Bernhardt (2006) state that "ecological restoration of rivers should result in a watershed's improved capacity to provide clean water, consumable fish, wildlife habitat, and healthier coastal water." Further, Palmer et al. (2005), recommended five criteria for evaluating ecological success: a guiding image exists, ecological conditions (physicochemical, biological) of the river are measurably enhanced toward the guiding image, resilience (ability to self-sustain) is increased, no lasting harm is done, and ecological assessment is completed. These authors further discuss stakeholder success, which includes aesthetics, economic benefits, recreation, and education; and learning success, which calls for scientific contribution, management experience and improved methods.

It is well established that pre- and post-restoration assessment are necessary for the progress of the field; however, it has also been shown that there is a widespread lack of monitoring (Kondolf and Micheli, 1995; Bernhardt et al., 2005). Kondolf and Micheli (1995) suggested this systematic lack of evaluation may be a result of the difficulty of defining and measuring steam restoration success. Because of this difficulty, Kondolf (1995) offered a starting point for improved evaluations and further conversation by specifying five elements for effective evaluation of stream restoration. These five elements are: 1) clear objectives; 2) baseline data; 3) good study design; 4) commitment to the long term; and 5) willingness to acknowledge failure. He also stated that project success can be evaluated only in the context of quantifiable change.

Many assessment methods have been developed which can be adapted and organized to fit within Kondolf's suggestion. These assessment methods are summarized below and in Table 2.1. Select examples of data sheets used to conduct these assessments are in Appendix A.

2.1.2.1 Stream Visual Assessment Protocol

The Stream Visual Assessment Protocol (SVAP) was developed to provide a basic level of stream health evaluation that can be applied by conservationists with little biological or hydrological training (USDA-NRCS, 1998). The protocol consists of scoring up to 15 assessment elements, depending on which are applicable to the reach in question (Table A.1). The fifteen elements are: channel condition, hydrologic alteration, riparian zone, bank stability, water appearance, nutrient enrichment, barriers to fish movement, in-stream fish cover, pools, invertebrate habitat, canopy cover, manure presence, salinity, riffle embeddedness, and macroinvertebrates observed. Each element is rated from 1 to 10 and an overall assessment score is determined by summing the scores for each element and dividing by the number of elements assessed.

2.1.2.2 Stream Quantification Tool

The stream quantification tool (SQT) was developed by Harman et al. (2017) and utilizes a spreadsheet-format as a simple calculator for use in determining numerical functional lift. The tool is based on the stream functions pyramid developed by Harman et al. (2012) and builds from the pyramid framework to develop function-based parameters, measurement methods, and performance standards. Performance standards provide the basis for the final project score, as each functional component at both the reach- and catchment-level are given a designation of functioning, functioning at risk, or not functioning. The SQT was developed primarily for projects completed for mitigation and has been adapted for use in the states of North Carolina, Tennessee, South Carolina, Georgia, Colorado, and Wyoming. Due to the length of this assessment, it was not included in Appendix A.

2.1.2.2 Pfankuch Channel Stability Evaluation

The Pfankuch channel stability evaluation was developed to "systemize measurements and evaluations of the resistive capacities of mountain streams to adjust and recover from potential changes in flow and/or increases in sediment production" *(*Pfankuch, 1975*).* It isolates three portions of a stream (upper bank, lower bank, channel bottom) and assesses characteristics of each, ranking them as excellent, good, fair or poor (Table A.2). The upper channel banks are assessed for bank slope, mass wasting hazard, debris jam potential, and vegetative bank protection. The lower channel banks are assessed for channel capacity, bank rock content, obstructions and flow deflectors, cutting, and deposition. Finally, the channel bottom is assessed for rock angularity, brightness, consolidation, size distribution, and scouring/deposition.

2.1.2.2 Bank Erosion Hazard Index

The Bank Erosion Hazard Index (BEHI) was developed as part of the Bank Assessment of Nonpoint Consequences of Sediment (BANCS) model to assess the susceptibility of stream banks to erosion based on seven characteristics: study bank-height ratio, root depth ratio, weighted root density, bank angle, surface protection, bank material, and stratification of bank material (Table A.3; Rosgen, 2006).

2.1.2.2 Geo-hydraulic Diversity Index

The Geohydraulic Diversity Index (GDI) was developed to assess the sustainability of environmentally-aligned river channel management schemes through the calculation of their geomorphic and hydraulic diversity (Skinner et al., 1998*)*. In particular, the authors cite diversity of depth and velocity as being important characteristics contributing to habitat quality of streams. To assess velocity and depth variability, the same reach-averaged variability equation is used, which for velocity takes the form:

$$R_v = \frac{V_{98} - V_{02}}{V_{50}} \qquad (2\text{-}1)$$

where R_v is the reach velocity variability, and V_{02}, V_{50}, and V_{98} are the 2nd, 50th and 98th percentile velocities, respectively, measured throughout a reach. Depth is substituted into this equation to calculate reach depth variability.

2.1.2.2 Rapid Stream Assessment Tool

In response to a "growing need to identify existing channel erosion areas and systematically evaluate general stream quality condition on a watershed-wide scale" The Rapid Stream Assessment Technique (RSAT) was developed by the Metropolitan Washington Council of Governments (COG) to provide a simple, rapid reconnaissance-level assessment of stream quality conditions (Galli, 1996). The RSAT was derived from a synthesis of USEPA's Rapid Bioassessment protocols, and considers the categories of channel stability, channel scouring/sediment deposition, physical in-stream habitat, water quality, riparian habitat conditions, and biological indicators at approximately 400-ft. intervals along the stream. Categories are given a score corresponding to ratings of poor, fair, good and excellent. Due to the length of this assessment, it was not included in Appendix A.

2.1.2.2 Riparian, Channel, and Environmental Inventory

The Riparian, Channel, and Environmental Inventory (RCE) was developed to assess the physical and biological condition of small streams (<10 ft. wide) in lowland, agricultural landscapes. The RCE consists of sixteen characteristics which define the structure of the riparian zone, stream channel morphology, and the biological condition in both habitats (Petersen, 1992*)*. Each characteristic is assigned one of four possible conditions, which corresponds to a score. The lowest possible score is 1, while the highest possible score ranges from 15 to 30 depending on the importance of the characteristic and the ease of accurate measurement (Table A.4). RCE categories include: land use pattern beyond the immediate riparian zone, width of the riparian zone from stream edge to field, completeness of the riparian zone, vegetation of riparian zone within 33 ft. of the channel, retention devices, channel structure, channel sediments, streambank structure, bank undercutting, and stony substrate feel and appearance.

2.1.2.2 Stream Performance Assessment

The Stream Performance Assessment (SPA) was developed based to be a systematic method that can be implemented by a single assessor with substantial training and experience in stream morphology and ecology *(*Doll, 2013). The assessment takes the seven categories of channel bedform, channel pattern, in-stream habitat, sediment transport, streambank condition, streambank vegetation, and floodplain function and breaks them down into sub-variables for a total of 17 components which are individually ranked and summed to develop a total score (Table A.5).

2.1.2.2 USEPA Rapid Bioassessment Protocols for use in streams and wadable rivers

The USEPA Rapid Bioassessment Protocols (RBPs) were developed in response to a need realized in the 1980s for cost-effective biological survey techniques to fill the gap of rapidly dwindling resources for monitoring and assessment and the extensive miles of un-assessed stream miles in the United States (Barbour et al., 1999). The RBPs advocate for an integrated assessment, comparing habitat (e.g., physical structure, flow regime), water quality, and biological measures with empirically defined reference conditions. Four protocols were developed, one each for habitat assessment and physicochemical parameters, periphyton, benthic macroinvertebrates, and fish. The first, focusing on habitat assessment and physicochemical parameters, is the most applicable to stream restoration and requires visual observation of many stream characteristics to assign scores associated with optimal, suboptimal, marginal and poor stream and habitat health (Table A.6). These characteristics are epifaunal substrate/available cover, embeddedness, pool substrate, velocity/depth combinations, pool variability, sediment deposition, channel flow status, channel alteration, frequency of riffles, channel sinuosity, bank stability, bank vegetative protection, and riparian vegetation zone width. Different assessments were developed for high and low gradient streams.

2.1.2.2 Eco-geomorphological Assessment

The Eco-geomorphological assessment (EGA) was developed specifically to be a rapid assessment of restored stream reaches conducted by trained evaluators (NCSU Water Quality Group, 2006; Doll, 2013). The assessment consists of four main sections: channel condition, bank and riparian condition, aquatic insect community structure, and an evaluation of instream structure condition and function. Channel condition is further broken down into bedform, dominant substrate material, and cover/refuge. Bank and riparian habitat include streambank stability, riparian vegetation, and floodplain/floodplain soil condition. Scores are determined for each section and summed to develop a final score. The EGA was also not included in Appendix A due to the length of the assessment.

Table 2.1 Summary of parameters included in the stream assessment methods where ✓ indicates the protocol has one or more measures of assessment group and X indicates the protocol has no measure of assessment group. Adapted from Akinola, A., unpublished material.

Assessment group ↓	Assessment Protocol									
	SVAP[1]	SQT[2]	Pfankuch[3]	BEHI[4]	GDI[5]	RSAT[6]	RCE[7]	SPA[8]	USEPA RBP[9]	EGA[10]
Bank Stability	✓	✓	✓	✓	X	✓	✓	✓	✓	✓
Bed Material evaluation	✓	✓	✓	✓	X	✓	✓	X	✓	✓
Riparian zone	✓	✓	X	X	X	✓	✓	X	✓	✓
Channel Pattern	X	✓	X	X	X	X	✓	✓	✓	X
Flood Plain	✓	✓	X	X	X	X	X	✓	X	✓
Bedform	✓	✓	✓	X	X	✓	✓	✓	✓	✓
Cross Section Survey	X	X	✓	X	X	✓	✓	X	X	✓

[1] Stream Visual Assessment Protocol

[2] Stream Quantification Tool

[3] Pfankuch Channel Stability Index

[4] Bank Erosion Hazard Index

[5] Geo-hydraulic Diversity Index

[6] Rapid Stream Assessment Tool

[7] Riparian, Channel, and Environmental Inventory

[8] Stream Performance Assessment

[9] USEPA Rapid Bioassessment Protocol

[10] Eco-geomorphological Assessment

2.1.3 Results of Stream Restoration Assessments

Many studies have shown both the success and failure of stream restoration activities, some even within the same project. For example, Buchanan et al. (2012) found that 2.5 yr after construction, restoration of Six Mile Creek in central New York was only marginally successful. Their assessment of restoration goals through "(i) longitudinal and cross-sectional channel surveys; (ii) hydraulic modelling; (iii) vane stability, flow competence and permissible shear stress analyses; (iv) scour–fill mass balance; (v) pebble counts; and (vi) qualitative channel/floodplain condition surveys [i.e. stream visual assessment protocol (SVAP) and Pfankuch surveys]" showed that stability goals were not met. Successful establishment of adequate pool habitat, however was apparent. In addition, the project continued to become more successful with time, as Buchanan et al. (2014) showed consistent reduction in channel deformation and bed adjustment and substantial coarsening of bed sediment two years later. These findings indicated the same channel was stabilizing.

Improvement with time was also shown by Purcell et al. (2002), who documented progressively improved biological and habitat quality by comparing unrestored, restored, and 12-year restored streams in Northern California. The authors assessed each stream with a visually based habitat assessment, an assessment of water quality using biological indicators, and a survey of neighborhood residents to gauge public perceptions.

Many studies have also evaluated the effectiveness of in-stream structures. For example, Buchanan et al. (2012; 2014) assessed structures for the quality of created habitat, the degree of upstream/downstream bank erosion, the physical stability and/or degree of morphological deformation, the degree of excess scour, and the functionality of the structure over a range of flows, finding that multiple problems were apparent. For example, in their first post-project-assessment (PPA), they found that barriers to fish passage were formed by grade control structures. Additionally, in their second PPA (2 yr later), they found that 8 out of 34 instream structures experienced destabilization of one or more stones, and 13 of 34 structures were listed as either impaired or failed.

Dave (2018) and Endreny and Soulman (2011) also documented structure failures. Dave assessed the effectiveness of streambank stabilization structures by quantifying stream bank retreat using aerial imagery before and after restoration projects for 18 stream banks of the Cedar River in Nebraska that were stabilized using jetties, rock toe protection, slope reduction/gravel bank, a retaining wall, rock vanes, or tree revetments. A dam break during her study simulated a large flood. While showing that showing that stabilized banks were more effective at controlling erosion than control sites, she observed multiple failures of rock vanes and jetties. Rock vanes in particular exhibited poor performance, as they failed during the flood. Jetties proved to be the most effective stabilization measure; a 70% success rate was observed. Endreny and Soulman (2011) assessed a New York project designed using the Natural Channel design (NCD) method by surveying 35 monumented cross sections and 12 cross-vane structures. HEC-RAS 1D flow modelling was used to simulate channel conveyance. The surveys showed that vane geometry no longer aligned with design standards, and improper flow direction by cross vanes resulted in aggradation in meander bend pools and below structures. Roper et al. (1998) on the other hand, showed structure durability in restored Pacific Northwest streams was high, as less than 20% of 3,946 assessed instream structures were removed after experiencing floods that exceeded a 5-yr return interval.

Others (e.g. Bain et al. 2014; Doll et al., 2015) showed that restored streams successfully exhibit improved stream health and function. Bain et al. assessed a large stream restoration project in Pittsburgh, PA using surface water quality sampling, fish assemblage surveys, benthic invertebrate sampling and cross section surveys. They found "continual and substantial" improvement in the fish community post-restoration, and evidence of a healthier, more diverse benthic macroinvertebrate fauna. Doll et al. assessed 156 streams throughout the state of North Carolina (93 restored, 21 impaired, 29 reference and 13 reference with some incision) using the SPA methodology. Principal component analysis (PCA) showed that restored streams aligned closely with reference reaches in terms of geomorphic condition, and even exhibited a greater range of bedform and habitat condition variability. They concluded that stream design and construction by practitioners restores streams to conditions similar to reference reaches.

Finally, in a study of 79 stream mitigation projects in NC assessed against regulatory requirements, Hill et al. (2011) found that 75% of the assessed projects were successful. Piedmont streams, however, had a lower success rate than mountain and coastal plain streams.

2.2 Methods for Watershed- and Project-Scale Assessments

Research regarding stream restoration can be challenging due to socio-economic structures, and the complexity of relationships between variables governing stream system behavior, but by treating completed stream restoration projects as experiments, and controlling for variability through site selection criteria and the use of dimensionless variables, relationships can be determined between watershed- and project-level variables and project success. Regression analysis was used to determine correlation between these variables.

A large number of stream restoration projects have been completed in Maryland, making it an ideal location to conduct this research project. Projects and information were provided by five western shore Maryland counties and the Maryland Department of Transportation State Highways Administration (MD-SHA). All projects were located in either Anne Arundel, Baltimore, Calvert, Frederick, Harford, Howard, Montgomery or Prince Georges counties. Projects were chosen to ensure the inclusion of broad ranges in age, location, watershed size, and project characteristics. Locations of projects used in this study are shown in Figure 2.1. Documents such as design plans and reports, as-built plans, and monitoring reports were provided to the extent they were available. If a project design included a significant tributary, the tributary was separated from the project mainstem and considered as its own individual project, due to differences in the contributing watersheds between the main stem and the tributary.

2.2.1 Project Assessments

To assess project success, two main questions were considered:

1. Is the stream functioning geomorphically (i.e., is it transporting water and sediment, and supporting physical stream functions)?
2. Are the design elements still intact?

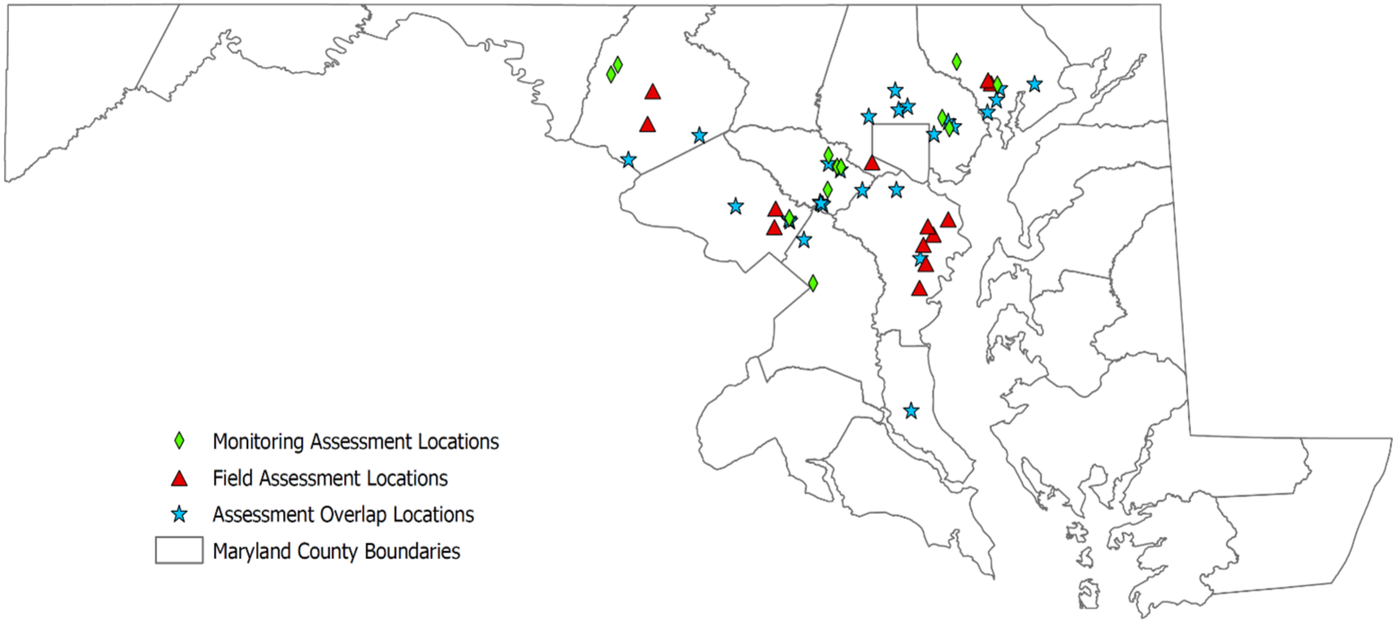


Figure 2.1 Locations of assessed stream restoration projects.

To address these questions, three assessment methods were developed:

1. A field-based rapid geomorphic assessment;
2. A field-based design assessment; and,
3. A monitoring report-based assessment of geomorphic function and design success.

2.2.1.1 Geomorphic Function Assessment

To assess the geomorphic function of each project, a rapid, field-based assessment was developed based on the literature reviewed. Six characteristics were evaluated and scored from 1 to 4 based on the observed extent of each process or feature in each stream project. The primary indicators of geomorphic function used in the function assessment were the presence of appropriate bedforms and bed sediment for a particular physiographic province, stable banks, native riparian vegetation, and evidence of floodplain access, such as sediment or debris deposits on the floodplain. Additionally, the presence of a diversity of velocity, depth, and physical structure that would provide habitat for aquatic organisms was evaluated.

In fluvial geomorphology, stability is usually viewed in terms of channel equilibrium, in which natural cycles of scour and fill cause stream form to fluctuate about an average condition (Charlton, 2008; Wohl, 2014). These cycles of scour and fill, resulting from sediment transport dynamics, tend to develop bedforms in channel beds. Thus, when a stream develops this dynamic equilibrium state, bedform type and spacing become characteristic of the stream type (Montgomery and Buffington, 1997). Thus, the type and location of bedforms, as a function of bed sediment and physiographic province, were visually evaluated in the field.

Another natural adjustment of stream beds in response to flow regime and sediment supply is the sorting of sediment by size. Integral to the maintenance of equilibrium and resulting stability is the necessity of a channel to balance sediment entrainment and deposition. Interruptions in the balance between flow and sediment, such as an introduction of excess fine sediment, can cause a change in bed substrate composition (EPA, n.d.).

Although the main focus of the field function assessment was evidence of geomorphic processes, the presence of cover and refuge areas and a diversity of flow types (fast and shallow, slow and deep, etc.) were used as additional indicators of region-appropriate bedforms and channel form. Uniform channels with little variation in flow depth or velocity indicate an imbalance in geomorphic processes.

Channel migration is a natural fluvial process that requires the erosion of one bank and the aggradation of the opposite bank. However, extensive bank erosion indicates the flow energy has exceeded the supplied bedload and/or bank erosion resistance has been reduced. Bank resistance can be reduced due to vegetation removal, a lack of diverse riparian vegetation, or increased stream temperatures (Wohl, 2014; Allen et al., 2018; Hoomehr et al., 2018). Therefore, overall bank stability is a logical indicator of balanced fluvial processes.

Healthy riparian areas are important to stream ecology, providing stream shading, nutrient cycling and food chain and habitat support through the supply of woody debris. Riparian vegetation further contributes to channel stability, both through the protection of banks, and the facilitation of sediment deposition about the channel (Wohl, 2014). In particular, high vegetation biodiversity has been shown to correlate with decreased erosion rates (Allen et al., 2018). As biological invasions have been shown to decrease the abundance and biodiversity of resident species (e.g., Vilá et al., 2011), invasive species can prove a detriment to stream stability. Given that the climate in the mid-Atlantic United States is favorable for dense vegetation growth and streambank stability and that all evaluated projects were at least three years old, the presence of dense native vegetation was considered important for geomorphic function.

The connection of the floodplain to the channel is also critical both for ecologic and geomorphic function (Loos and Shader, 2016; Hupp et al., 2009). The average boundary shear stress within a channel is a function of the wetted perimeter. As water flows onto the floodplain, a significant increase in the wetted perimeter results for a unit increase in discharge, leading to a decrease in the boundary shear stress and the potential for channel degradation. Additionally, the roughness of vegetated floodplains is significantly greater than the roughness of the main channel, as such, flow velocities on the floodplain are significantly lower than those in the main channel. Channel access to the floodplain was evaluated in the field using evidence such as the presence of fresh sediment deposits and flood debris in riparian vegetation.

The overall project score was calculated by adding the scores for each category assuming equal weighting. Further adjustment to the final score was made if invasive plant species were found on site. If some were found, half a point was subtracted from the total function score, but if invasive species were prominent, a whole point was subtracted. With six categories and scores of one to four for each category, the highest score possible for the geomorphic function assessment was 24. To be able to relate variables to a probability of success, each function score was converted to a percent of the perfect score. The field form used to assess geomorphic function is found in Table 2.2.

2.2.1.2 Design Assessment

The goal of the design assessment was to quantify how much of the original design was still present and functioning in the project reach. These assessments were completed in the field by evaluating individual design components (e.g., structures, pools, etc.). A component that was present and functioning as intended was given a count of one, while a missing design component was scored as 0.0 and a component that was present but not functioning as intended was given a score of 0.5. The scores for each design component were then summed and divided by the total number of design elements and multiplied by 100 to indicate the percent of the original design that was still functional.

2.2.1.3 Monitoring Assessment

Due to time constraints, many projects could not be visited in the field, so an additional assessment was developed to evaluate the geomorphic function of stream restoration projects based on the information provided in post-construction monitoring reports, typically for years 1-3. The goal of the monitoring assessment was to assess both the design success (were the design elements still present and functioning) and geomorphic function. Four categories were assessed using monitoring reports: bed aggradation/degradation, bank stability, riparian vegetation, and in-stream structures. The form utilized in the monitoring assessment is shown in Table 2.2.

In accordance with the assumption that three years gives a high probability of sufficient time for a restoration project to establish vegetation and to experience an elevated flow event, Year 3 monitoring reports were used in this analysis. If the Year 3 report was not available, the Year 2 or later monitoring report was used. Cross-sectional and longitudinal profile surveys, vegetation inspections, structure assessments and photographs were project components commonly included in monitoring reports. If sufficient information to

Table 2.2 Geomorphic function assessment.

	1	**2**	**3**	**4**
Bedform location	<25% of bed features in proper geomorphic locations along reach	25-50% of bed features in proper geomorphic locations along reach	50-75% of bed features in proper geomorphic locations along reach	>75% of bed features in proper geomorphic locations along reach
Substrate	Significant embedded areas, poor gradation, loose, soft areas prominent in >75% of bed	Well graded particle size distribution, minimal embeddedness in 25-50% of bed	Well graded particle size distribution, minimal embeddedness in 50-75% of bed	Well graded particle size distribution, minimal embeddedness in >75% of bed
Cover/ refuge	Presence of refuge areas of few types in <25% of reach	Presence of refuge areas of diverse types in 25-50% of reach	Presence of refuge areas of diverse types in 50-75% of reach	Presence of plentiful refuge areas of diverse types in >75% of reach
Bank stability	High bank slopes, <25% of reach has good vegetation cover and no evidence of mass wasting	Low bank slopes, 25-50% of reach has good vegetation cover and no evidence of mass wasting	Low bank slopes, good vegetation cover and no evidence of mass wasting in 50-75% of reach	Low bank slopes, good vegetation cover and no evidence of mass wasting in >75% of reach
Riparian vegetation cover	<25% of riparian area covered in native vegetation	25-50% of riparian area covered in native vegetation	50-75% of riparian area covered in native vegetation	>75% of riparian area covered in native vegetation
Invasive note				
Floodplain	Evidence of flow access, sediment deposition along <25% of reach	Evidence of flow access, sediment deposition along 25-50% of reach	Evidence of flow access, sediment deposition along 50-75% of reach	Evidence of flow access, sediment deposition along >75% of reach

score an assessment category was not provided in the monitoring report text, photographs were used to estimate a score.

2.2.2 Explanatory Variables

As described above, data collection for predictive characteristics was completed at both the watershed and project scale. Explanatory variables were chosen to reflect the potential applied fluvial stress on a stream reach (i.e. flow energy), and the channel resistance to erosion and degradation. For a description of all variables considered, see Figure 2.22, Table 2.4 and Table 2.5.

Table 2.3 Monitoring assessment form.

	1	2	3
Bed aggradation or degradation	Riffle scour or pools filling at >10% of stations	Riffle scour or pools filling at <10% of stations	No riffle scour or filling of pools
Bank stability	Bank scour >10% of stations, bank failure at any location	Bank scour <10% of stations	No bank scour noted
Riparian veg cover	>10% of project length with problem vegetation growth, heavy invasive growth	<10% of project length with problem vegetation growth, light invasive vegetation	Good vegetation cover, no problem areas, no invasive species
Structures	Problems noted with >10% of structures	Problems noted with <10% of structures	No problems with structures noted

2.2.2.1 Watershed-Scale Variables

Watershed-level data were collected using ArcMAP (ESRI, Redlands, WA). All feature classes and raster files were projected to the coordinate system NAD 1983 Maryland Stateplane FIPS 1900 (meters). Shapefiles of watersheds for each project were created using the procedure described below and were then used to extract/clip datasets for all further watershed analysis.

High resolution Lidar-derived digital elevation models (DEMs) of each county were downloaded from the Maryland iMap database so watershed delineation could be completed. Characteristics of these DEMs are shown in Table 2.6.

To ensure consistency in watershed analysis between counties, each DEM was resampled to 6.6-ft. (2-m) resolution. To reduce the county-level DEMs to a size which could reasonably processed, a rough watershed area was derived from USGS StreamStats analysis tool (U.S. Geological Survey, 2016) buffered by 3280 ft. (1000 m) and used to clip the county DEM to a more focused area. Digital dams in the DEMs were removed by burning lines though conveyance structures such as bridges and culverts which were concealed by Lidar data collection. Watershed delineation was completed using the hydrology toolbox in ArcMAP. Latitudinal and longitudinal coordinates of all restoration outlet locations were found by studying project plan sets, identifying the farthest downstream limits of construction, and matching the project limit with a pin on Google Maps. These points were used as the outlets from which watersheds were delineated. Watershed area was considered as a variable in this analysis, because it provides information on the hydrology typical of each stream restoration project. In particular, it can provide insight into the characteristic discharge and the flashiness of flows, both of which have implications for the geomorphology and stability of the channel.

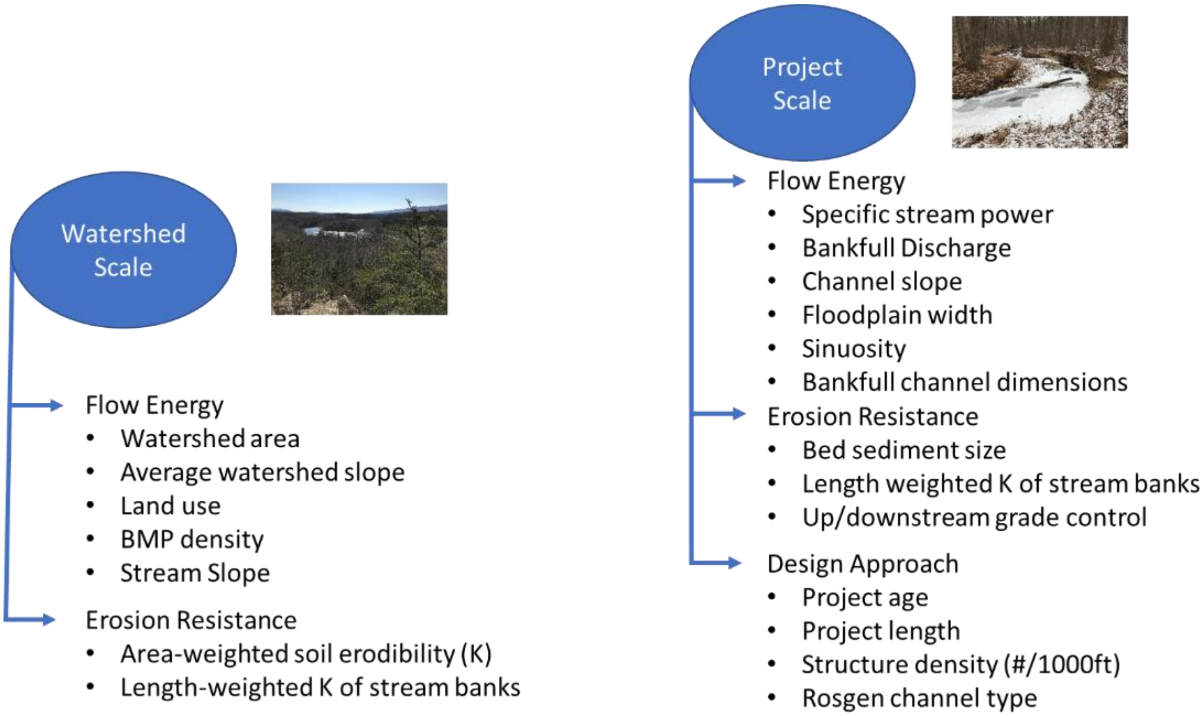


Figure 2.2 Schematic of explanatory variables included in analysis.

Using the output of the flow accumulation tool used in watershed delineation, the network of streams contributing to each project reach was delineated. To identify the extent of the stream network, the symbology of the flow accumulation raster file was adjusted to visually isolate cells with accumulation values of greater than a certain number. This number was changed until the stream network aligned with that observed from aerial imagery on Google Earth. A raster calculation was completed to separate the identified accumulation cells. This raster was then converted to a polyline shapefile.

Watershed land cover was considered, because it provides insight into the behavior of stormwater runoff. For instance, higher density urban development is assumed to have a higher prevalence of impervious surfaces and will produce higher, flashier flows, while a forested watershed will retain more precipitation and result in a less flashy hydrograph. These hydrologic characteristics are important indicators of stream geomorphology and stability. To assess land cover and land cover change throughout the project watersheds, two data sets were used for comparison from 1992 to 2016 to compare land cover changes in data sets that were developed using the same methodology. The Chesapeake Bay Land Cover Dataset series (CBLCD) was used to assess changes in watershed land cover from 1992 to 2001 (Irani and Claggett, 2010). These data

Table 2.4 Watershed-level variables included in analysis.

Explanatory variable	**Scale**	**Units**	**Category**	**Data Source**
Watershed area	watershed	mi^2	flow energy	GIS hydrologic analysis
High density development	watershed	percent	flow energy	GIS land use analysis
Medium density development	watershed	percent	flow energy	GIS land use analysis
Low density development	watershed	percent	flow energy	GIS land use analysis
Agriculture	watershed	percent	flow energy	GIS land use analysis
Forest	watershed	percent	flow energy	GIS land use analysis
BMP density	watershed	$\#/mi^2$	flow energy	GIS BMP analysis
Average watershed slope	watershed	percent	flow energy	GIS slope analysis
Watershed soil erodibility	watershed	unitless	erosion resistance	GIS soil analysis
Streambank soil erodibility	watershed	unitless	erosion resistance	GIS soil analysis
Soil erodibility ratio	watershed	unitless	erosion resistance	GIS soil analysis
Longest channel slope	watershed	ft./ft.	flow energy	GIS slope analysis

Table 2.5 Project-level variables included in analysis.

Explanatory variable	Scale	Units	Category	Data Source
Year completed	project	year	design approach	Monitoring reports
Project length	project	ft.	design approach	Design plans
Project slope	project	ft./ft.	flow energy	Design plans
Flood prone width	project	ft.	flow energy	GIS terrain analysis
Bankfull width	project	ft.	flow energy	Design plans
Entrenchment ratio	project	unitless	flow energy	Design plans
Design discharge	project	cfs	flow energy	Design reports
Ratio of discharge to watershed area	project	(cfs)/mi^2	flow energy	Design reports
Bankfull depth	project	ft.	flow energy	Design plans
Width to depth ratio	project	unitless	flow energy	Design plans
Sinuosity	project	unitless	flow energy	Design plans
Soil erodibility of project banks	project	unitless	erosion resistance	GIS soil analysis
Number of structures per 1000 ft.	project	#/ft.	design approach	Design plans
Design approach	project	N/A	design approach	Design plans
Distance from upstream end of project to upstream grade control	project	ft.	erosion resistance	Google Maps
Distance from downstream end of project to downstream grade control	project	ft.	erosion resistance	Google Maps

Table 2.6 Digital elevation model (DEM) specifications.

County	Horizontal Accuracy (in.)	Vertical Accuracy (in.)	Year Collected	Resolution (ft.)
Anne Arundel	N/A	3.2	2017	1.0
Baltimore	10.6	2.7	2015	2.3
Frederick	N/A	3.9	2012	3.3
Harford	N/A	2.7	2013	4.9
Howard	N/A	7.3	2011	6.6
Montgomery	N/A	3.5	2013	3.3
Calvert	1.2	4.8	2017	6.6
Prince Georges	N/A	3.9	2018	2.3

were retrieved from the USGS ScienceBase Catalog. The National Land Cover Database (NLCD) was used to compare land cover changes from 2001, 2006, 2011, and 2016 (Jin et al., 2019). These data were retrieved from the Multi-Resolution Land Characteristics Consortium (MRLC). Both data sets were developed using the same schema and land cover classifications and were in the form of a raster dataset with a 98-ft. (30-m) resolution. The land cover classifications provided by these data sets were then reclassified based on their description into the six categories used for this study: high density development, medium density development, low density development, forest, agriculture, and water/wetland. Descriptions of each land cover category are provided in Table 2.7. The current project land cover was estimated using the 2016 data, while land cover changes since project construction were determined by comparing the total area of each land cover in each project watershed for the project completion date and the 2016 data set. Linear interpolation was used to estimate land cover for completion dates that did not occur in a year when land cover was determined.

Table 2.7 Maryland 2008 land cover category descriptions (Maryland Department of Planning, 2010).

High density development	Areas of more than 90 % high-density residential units, with more than eight dwelling units per acre, areas used primarily for the sale of products and services, schools, military installations, churches, medical facilities, correctional facilities, government offices, and miscellaneous transportation features
Medium density development	Areas of more than 90% single-family/duplex units and attached single-unit row housing, with lot sizes of less than 1/2 acre but at least 1/8 acre (two dwelling units/acre to eight dwelling units/acre)
Low density development	Areas of more than 90% single-family/duplex dwelling units, with lot sizes of less than five acres but at least 1/2 acre (0.2 dwelling units/acre to two dwelling units/acre)
Forest	Deciduous forest evergreen forest, and/or brush
Agriculture	Cropland, pasture, orchards, vineyards, horticulture, and/or feeding operations
Water/Wetland	Rivers, waterways, reservoirs, ponds, bays, estuaries, forested or non-forested wetlands, including tidal flats, tidal and non-tidal marshes, and upland swamps and wet areas

As stormwater infrastructure is designed to control runoff, it is expected that flow energy in streams should decrease with increased BMP density. Maryland has steadily increased stormwater regulation requirements since 1984 (Stewart Comstock, MDE, personal communication, 13 Aug 2018), so the effect of these practices on stream stability was assessed. The MDE county BMP geodatabases (e.g., Baltimore BMP geodatabase) included BMP locations, types, and ages throughout individual Maryland counties. These geodatabases were used to assess the prevalence of stormwater infrastructure in each watershed. The density of stormwater BMPs in each watershed was determined by dividing the number of BMPs by area of high and medium-density development in square kilometers. Given that stormwater management has evolved from the use of single large structures, such as regional ponds, to smaller, more distributed practices, it was anticipated that watersheds with a high BMP density would reflect newer development using green infrastructure.

Soil erodibility of the watershed was included in the analysis to represent the potential supply of fine sediment to the stream. Soil databases were accessed from the web soil survey (Soil Survey Staff, 2018). Soil erodibility (adjusted for the effect of rock fragments) maps were built using the soil data viewer add-on in ArcMap. The soil erodibility used in this analysis was the K-factor from the second revised universal soil loss equation (RUSLE2). This map was joined with a map unit name map for further referencing and data checking. Any missing erodibility values were given the values of 0.35 for silt loam/loam textured soils, 0.05 for sandy loam textured and organic soils, 0.02 for any soil in a complex with urban land, and 0.01 for urban land or soils classified as udorthents/highway. These soil erodibility values were chosen based on best professional judgement and by studying other map units of the same soil types which had values provided. Urban soils were given low erodibility values because it was assumed they were mostly either covered by impervious surface or compacted and would be less susceptible to surface erosion. An area-weighted average of soil erodibility was determined for each watershed.

As excessive bank erosion is one of the biggest problems with streams in the Chesapeake Bay watershed, it was also important to consider soil erodibility of the stream banks in the contributing stream network in addition to the watershed soil erodibility. A watershed-scale streambank erodibility measure was determined by intersecting the stream network shape file with the soil erodibility map shapefile, and calculating a weighted average based on the length of each stream segment. Both stream banks were counted together as one, because the soil survey delineated the entire floodplain as a single soil type.

Two slope measurements were calculated: average watershed slope, and the slope of the longest continuous stream reach in the network. Average watershed slope provides information on the energy of flow entering the channel, while stream slope is indicative of flow energy in the channel. Higher slopes provide a greater potential for degradation. Average watershed slope was determined by developing a watershed slope raster using the ArcGIS slope tool on DEMs that had been extracted to each watershed shape and size. Average slope was then found by observing the mean cell value under the statistics section of the source tab in the layer properties box. Up and downstream elevations used in the calculation of channel slope were determined by sampling the DEM at the project outlet and at the location of the farthest upstream first order stream extent. Distance was measured between these two points along the stream network.

2.2.2.2 Project-Scale Variables

In addition to the characteristics of the watershed contributing to a stream, attributes of an individual stream restoration project can impact both flow energy and erosion resistance. Additionally, specific design features such as instream structures and amount of land disturbed can have an impact on project success. Projects were also classified according to their design approach and Rosgen stream type (Rosgen, 1994) if the stream type was identified in the design report. Design approach was inferred from visual observations of project character in design plans. Common stream restoration approaches include natural channel design (NCD), regenerative stormwater conveyance (RSC), and valley restoration.

Project age was included based on the consideration that the vegetation and channel boundary become better established and more resistant to erosion over time. Alternatively, as the time since construction increases, the likelihood of a project experiencing high flow events increases. Project age was assessed as the year in which construction was completed. This date was determined by studying monitoring reports or discussing the project with stakeholders.

Project length is an important parameter in assessing stream projects, because it is indicative of the scale of the project and extent of disturbance involved. The length of construction was determined by studying design plan sets to discern the length of stream along the baseline of construction that was impacted by earth work such as grading and structure placement.

As discussed above, channel slope is an important indicator of flow energy and significantly affects the stability of a stream restoration project. The average slope of the restored channel was also computed from design plans by measuring the difference in elevation between two like stream features (e.g., top of riffle to top of riffle), or between up/downstream grade control points and dividing by the stream length between them.

Because design bankfull width and depth affect the distribution of boundary shear stress within the main channel, as well as the discharge at which the floodplain is accessed, these design parameters were included in the analysis. Where possible, design bankfull width and depth of the stream at riffle locations were found on typical cross section details or in design reports. Whenever this information was not available, however, estimates were determined by measuring channel width and depth from all cross sections included in the design plans at riffle sections and taking an average.

The amount of energy applied to the channel boundary by the flowing water is ultimately a function of the stream discharge. Bankfull discharge was included because it not only provides an indicator of flow energy but also assists in determining whether the channel was sized correctly. However, information on the bankfull discharge used for the design (primarily for projects designed using a NCD approach) was not available for each project. To provide a standardized estimate of stream discharge for each project, bankfull discharge in ft^3/s (Q_{bf}) was calculated based on drainage area in square miles (DA) using the Maryland Piedmont (Cinotto, 2003) and Coastal Plain (Kristolic and Chaplin, 2007) regional curves, as shown in equations 2-2 and 2-3, respectively. The regional curve discharge output in ft^3/s was converted to m^3/s for the statistical analysis.

$$Q_{bf} = 53.1(DA)^{0.842} \qquad (2\text{-}2)$$

$$Q_{bf} = 19.6655(DA)^{0.742} \tag{2-3}$$

Flood prone width is defined as the width of the floodplain at an elevation of two times bankfull depth above the channel invert and is indicative of the ability of the stream to access the floodplain during high flows. This floodplain dimension was found by choosing a typical design cross section within the project reach on the DEMs and then using the 3D analyst tools in ArcMAP to extract a plot of the cross-section elevations. GIS was used to determine this parameter, rather than the design drawings because the extent of design drawings frequently did not cover the width of the floodplain.

Specific stream power, a metric that describes the ability of a stream to do work on its boundary (banks and bed), was calculated using equation 2-4.

$$\omega = \gamma QS/w \tag{2-4}$$

where: ω = specific stream power (lbf/ft./s);
γ = specific weight of water (62.43 lbf/ft.^{3});
Q = stream discharge (ft.^{3}/s);
S = stream slope; and,
w = stream bankfull width (ft.).

Sinuosity is the ratio of the slope of the stream valley to the channel slope (alternatively, the ratio of the total stream length to valley length) and is often used in stream classification. Stream sinuosity provides a quantitative measure of how much the channel meanders. While stream meanders naturally migrate outward and downstream, stream channels that are designed with too high a sinuosity may experience aggradation and channel avulsion, while streams designed with too low a sinuosity tend to incise and/or erode the outside of meander bends. Therefore, sinuosity is a critical design factor that was considered in this analysis. Straight line valley length was determined by measuring the distance between the inlet and outlet locations of each project using the measure tool in Google Earth. Total stream length was determined from project design plans.

As with the average watershed soil erodibility, the length-weighted average soil erodibility of the streambank soils, as quantified by the K-factor from the RUSLE2 equation (USDA-NRCS, Washington, D.C.). The erodibility of the banks was determined by identifying the soil erodibility at the project location on the soil erodibility maps developed in the watershed-scale analysis.

Sediment size is an important indicator of channel bed erosion resistance, so it was included in this analysis to determine if larger bed material, which is less susceptible to entrainment, was correlated with higher stream restoration success. As with design discharge, the riffle median sediment size (D_{50}) in each project was determined by studying design plans or through communication with designers. If salvaged bed material was used in the channel, the D_{50} from the particle size distribution from existing conditions surveys found in design reports was used.

The use of in-stream structures is a common technique utilized in stream restoration for bank stabilization, grade control, and habitat enhancement (Harman et al., 2001; Thompson and Stull, 2002). However, varying scales of success and failure in their use have been documented, leading to criticisms of their use due to lack of planning in their design and implementation (National Research Council, 1992; Roper et al., 1998). For this reason, the density of structures in each stream project was considered. Structure density was determined by counting the number of in-stream structures implemented per one thousand feet of stream project. A single structure was counted as any foreign material introduced to the channel for a single purpose. For example, a series of root wads utilized in conjunction for the protection of one meander bend were counted as one structure.

Even the best stream restoration design can be impacted by upstream or downstream disturbances. To examine the susceptibility of each project to resist knickpoint formation and/or migration, the distance from the downstream end of each project reach to the nearest downstream grade control measure (e.g., instream structure, culvert, bridge etc.), and the distance from the upstream project extent to the nearest upstream grade control were determined by measuring along the channel thalweg. If the nearest grade control was not included in the design plans, this distance was assessed using the measure tool in Google Maps.

2.2.3 Data Analysis

All project data were stored in a Microsoft Access (Microsoft, Redmond, WA) database in both SI and English units. The statistical analysis was conducted using SI units. To scale the project-scale variables to account for the size of each stream reach, ratios were developed. These ratios and included variables are described in Table 2.8.

Table 2.8 Ratios developed to scale project-scale variables.

Ratio	Numerator	Denominator
Discharge to area	Bankfull discharge (m^3/s)	Watershed area (m^2)
Width to depth	Bankfull width	Bankfull depth
Entrenchment ratio	Flood prone width	Bankfull width

Preliminary data analysis included individually plotting all variable combinations listed in Table 2.9 to visually evaluate relationships between measures of project success and the explanatory variables. Based on these visual observations, data transformations were developed to ensure homoscedasticity and linear relationships. Outliers were also identified. Additional plots were developed to assess the relationships between each assessment score.

Regression analysis was used to evaluate relationships between the three measures of project success and the explanatory variables. Stepwise selection methods and "all-possible" regressions (SAS 9.4, Proc Reg, Cary, NC) were run to identify several models for each restoration metric. Potential models were evaluated using adjusted r^2, predicted r^2, and Mallows Cp to compare regression equations. Standardized regression coefficients were used to assess the magnitude of explanatory variables in multivariate regression models. Null hypotheses for variable significance were tested at $\alpha<0.05$.

Table 2.9 Preliminary data comparisons.

Response variable	**Explanatory dataset**
Function score (field assessment)	Watershed-level
Design Score (field assessment)	Watershed-level
Monitoring Score	Watershed-level
Function score (field assessment)	Project-level
Design Score (field assessment)	Project-level
Monitoring Score	Project-level

Preliminary diagnostic analysis of these models to identify potential problems in the regressions included summarizing and comparing the variables and general trends shown in each model (i.e. positive or negative effect), such as multicollinearity. Additionally, to determine the relationship between each explanatory variable and project success individually, the rcorr function in the Hmisc package in R was used to assess correlation. Spearman correlation was used because not all relationships were linear. These correlations, in addition to the variance inflation factor, were used to further inform regression model creation by helping identify multicollinearity. Because D_{50} information was not available for all of the projects, the project-level regressions were run twice: once without D_{50} as an explanatory variable, and once without the projects lacking D_{50} information so D_{50} could be included in the analysis. In addition, as two projects received 0% scores in the design assessment, these were taken to be outliers and the design assessment regressions were run with and without them.

2.3 Results and Discussion

Information was obtained from the project partners for 57 stream restoration projects; however, not all projects had sufficient information to be included in the study. Of these projects, the number of projects utilized per county is shown in Table 2.10 and the availability of project files is summarized in Table 2.11. All project data are available in a Microsoft Access database, which is available upon request. Where projects included a significant tributary, the tributary and main stem were evaluated separately, since the tributary watershed and channel had different characteristics from the main stem.

Since a complete collection of project information was not available for every project, not all projects were able to be assessed using all three assessment methods. In total, 41 project reaches were assessed using monitoring reports, while field assessments were completed for 44 project reaches. Of these reaches, 29 were assessed both in the field and using monitoring reports. Figure 2.1 is a map showing the locations of all assessment locations.

Distributions of the scores developed in each assessment are shown in Figure 2.3. There was no significant relationship between the geomorphic function score and either the design score or the monitoring score. However, there was a significant positive correlation between the design score and the monitoring score ($\rho = 0.47$, $p = 0.011$), indicating the monitoring reports contain more information about the durability of the constructed project and less information regarding geomorphic function, such as floodplain access, habitat, and flow diversity.

Table 2.10 Project breakdown by county.

County	Number of projects
Anne Arundel	9
Baltimore	9
Calvert	1
Frederick	6
Harford	8
Howard	9
Montgomery	7
Prince Georges	1

At the watershed scale, watershed area varied from 0.005 to 53.6 mi^2 with an average of 3.52 mi^2 and a median of 0.54 mi^2. Landuse in 2016 also varied between watersheds, with percent high density development ranging from 0-33%, percent forested from 0-88% and percent agriculture from 0-70%. Landuse changes in the project watersheds were typified by increases in high and medium density development and decreases in low density development, forest, and agriculture. Percent change in land use for the period 2001-2016 ranged from no change to an increase in low density development in one watershed from 23% to 33%.

Of the projects assessed, reach length ranged from 100 ft. to 4502 ft., while channel slopes ranged from 0.02% to 7.5%. Average and median project length and slope were 1508 ft. and 1294 ft. and 1.4% and 0.93%, respectively.

Table 2.11 Information availability.

Material Provided	Number of Projects
Design Report	16
Design Plan	39
As-Built Plan	24
Monitoring Reports	41

2.3.1 Project Assessment

Function assessment scores determined from field visits ranged from 42% to 100%. Lower function scores were commonly due to low bed heterogeneity, high bank heights, and lack of, or invasive-dominated, riparian vegetation, while projects scoring higher in the function assessment displayed bed and bank features associated with geomorphic equilibrium. Visually, projects that tended to score higher for function had low bank heights and well-established, native vegetation. For example, projects 7 and 28 scored perfect scores in the function assessment and exhibited the aforementioned attributes of a functionally successful stream restoration project, as well as a range of flow depths and velocities. Photographs shown in Figure 2.4 and 2.5

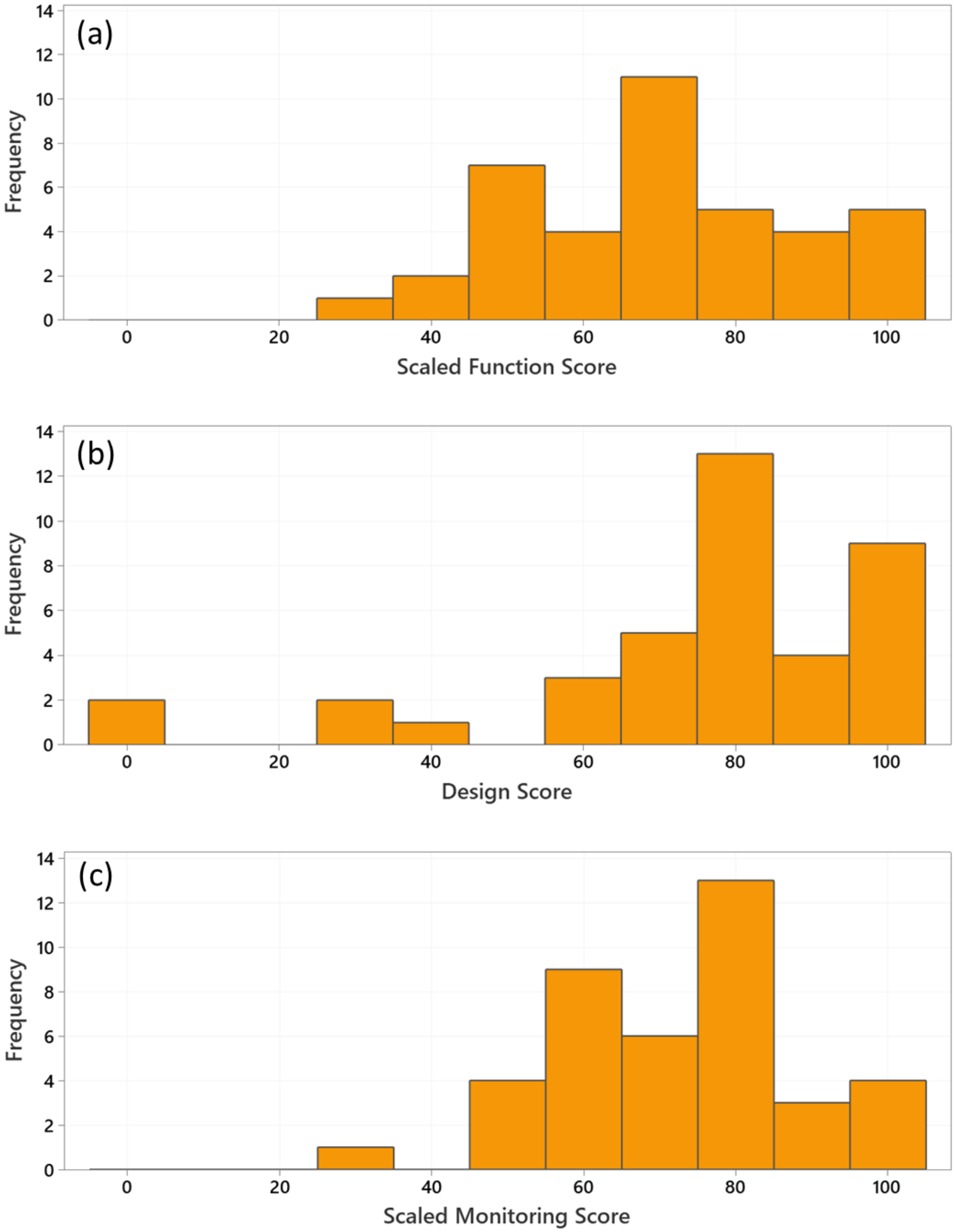


Figure 2.3 Score distributions from assessments; (a) function score from field assessment, (b) design score from field assessment, (c) monitoring assessment score.


03.13.2019

Figure 2.4 Project 7.


03.11.2019

Figure 2.5 Project 28.

highlight these characteristics. On average, the assessed projects scored highest in the riparian vegetation category and lowest in the cover diversity category. The categories exhibiting the greatest discrepancy between high-scoring (>75%) and low-scoring (<50%) projects were floodplain access and cover diversity.

Design assessment scores from the field ranged from 0% to 100%. Two of the oldest projects (constructed in 1995 and 1999) had the lowest design scores, which could reflect an improvement in design techniques with time and/or the increasing number of storms experienced by the oldest projects. Since the monitoring protocols were not necessarily targeted at assessing the function- and design-focused goals utilized in this study, it was difficult to accurately assess project success using monitoring reports without depending on photographs to fill in missing information. Also, since only half of the assessed projects had been assessed pre-construction, there was no consistent relative condition to which “success” was compared. Further, as only 12 of 33 projects had clearly stated goals, it was difficult to determine whether functional success was relevant to original project goals at all. Therefore, the monitoring report assessment tool was developed assuming function and design success were important. Project scores based on the monitoring assessments ranged from 33% to 100%. On average, projects scored highest in the bed aggradation/degradation category, and lowest in the structure category. The largest differences between high-scoring (>75%) and low-scoring (<50%) projects occurred in the bank stability, riparian vegetation, and structure categories.

Because the objectives on which this study focused tended toward geomorphic function and design success, certain elements were considered when reviewing the monitoring reports. These elements and the frequency of inclusion in the monitoring reports utilized in this study are shown in Table 2.12. If all of these elements were not included in the monitoring reports, assessment scores were estimated based on general descriptions given in the report, or based on monitoring photographs. Project assessment scores based on the monitoring reports ranged from a minimum of 33% to a maximum of 100%. The most significant problem noted in the monitoring reports was structure failure: approximately 30% of the projects had low structure scores. Poor bank stability affected approximately a quarter of the projects.

Table 2.12 Elements included in 44 assessed monitoring reports.

Monitoring Element Included	Number of Projects
Clearly stated project goals	18
Pre-construction monitoring	17
Baseline monitoring	25
Bank stability inspection	36
Planting inspection	27
Cross section survey	32
Longitudinal profile survey	23
Bed sediment survey	14
In-stream structure inspection	36
Photographic documentation	31

As discussed in the literature review, stream restoration has many goals, leading to much debate and difficulty in defining universally accepted success criteria. Some projects could be considered successful according to one definition of success, and unsuccessful according to another. For instance, in this study, a given project may have had very different levels of "success" depending on the evaluation tool. The assessment discrepancies between the design score and function scores for several projects are illustrated in Figure 2.6.

These differences in project assessment scores do not mean any project was strictly successful or unsuccessful, but instead likely reflect differences in project goals and constraints, whether they were explicitly stated or not. The greatest differences between scores occurred when the design score was high and the function score was low (e.g. projects 1, 4, 21, 33, 34, 42, and 47). These projects were typically constructed in urbanized areas and were confined by adjacent development. For example, project 47 scored 100% for the design, indicating the construction was resilient and stable. The function score, however, was only 50%, as it scored low for all function categories except bank stability and riparian vegetation. Attributes such as floodplain access and flow diversity were not apparent during the field assessment for these projects. As can be seen in Figure 2.7, project 47 consisted of mostly large rock, so sediment mobility was not intended. This project was located adjacent to a housing development, where space for construction was limited, and where out-of-bank flooding would have impacted homes. At some points along the stream, the project limits of disturbance aligned with adjacent property lines. Because of these spatial constraints, restoration of geomorphic function was difficult, and preference was clearly given to channel stability.

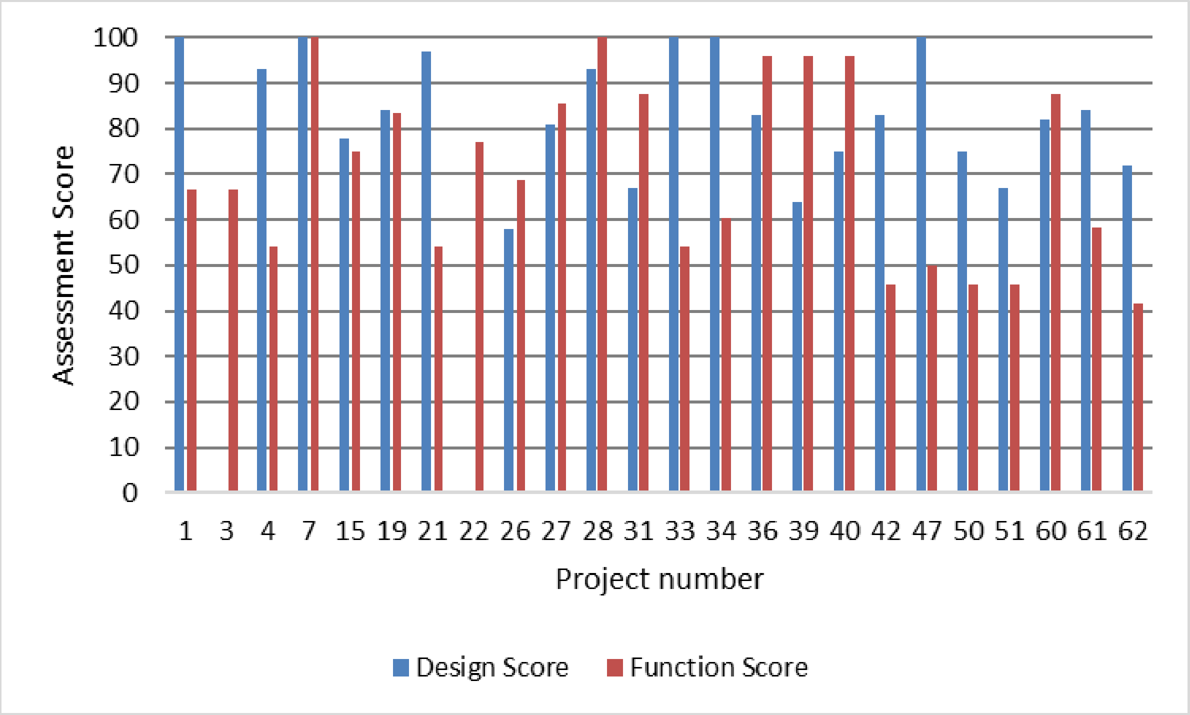


Figure 2.6 Comparison of design and function scores from field assessments for a subset of the projects.

In contrast, projects 3 and 22 scored zero in the design assessment but exhibited evidence of multiple geomorphic processes. These two projects were two of the oldest projects assessed in this study, having been constructed prior to 2000. In both projects, the majority of in-channel work consisted of bank stabilization through stone or wood placement. As none of the bank stabilization measures were observed during the field assessments, they had failed over the course of the project lifetimes. Since they were minimally invasive to the stream channel; however, their failure did not have significant effects on stream function. Both projects received high scores for bedforms, substrate, and cover. Photographs of these two projects are shown in Figures 2.8 and 2.9. Note that both projects appear to be transporting sediment and developing regionally appropriate bedforms and a diversity of velocities and depths, but no intact structural design components are apparent.

2.3.2 Watershed and Project Features Correlated with Project Success

Relationships between the three assessments of project success and both watershed and project characteristics were assessed statistically using correlation and multiple linear regression analysis. Spearman correlation between watershed-scale variables and assessment scores are generally weak, with the average watershed streambank soil erodibility ($\rho = -0.33$, $p = 0.038$; Table 2.13), the percent change in agriculture since project construction ($\rho = 0.40$, $p = 0.011$), and the percent of water and wetlands in 2016 ($\rho = 0.32$, $p = 0.047$) being significantly correlated with geomorphic function score. The design score is negatively

Figure 2.7 Project 47.

Figure 2.8   Project 3.

Figure 2.9 Project 22.

Table 2.13 Spearman correlation coefficients between watershed-scale variables and project assessment scores (values in bold denote statistically significant correlation coefficients, p<0.05).

Variable	**Function Score**	**Design Score**	**Monitoring Score**
2016 % high density development	0.18	-0.04	-0.02
2016 % medium density development	-0.01	0.04	-0.05
2016 % low density development	-0.24	-0.06	-0.21
2016 % forested	0.17	-0.02	0.14
2016 % agricultural	0.13	0.01	0.22
2016 % water	**0.32**	-0.12	0.09
%change high density since construction	-0.03	-0.04	-0.24
%change medium density since construction	-0.03	**-0.44**	**-0.41**
%change low density since construction	-0.17	-0.24	-0.13
%change forested since construction	0.08	**0.35**	-0.06
%change agricultural since construction	**0.40**	0.23	**0.36**
%change water since construction	-0.06	0.28	0.12
Length-weighted soil erodibility of stream channels in watershed network	**-0.33**	0.18	0.06
Slope of longest channel in stream network	-0.04	0.27	-0.04
Watershed area	0.27	**-0.41**	0.05
Stormwater practice density	-0.20	-0.17	-0.08
Area-averaged soil erodibility of the watershed	0.11	0.08	-0.22

correlated with watershed area (ρ = -0.41, p = 0.010) and percent change in medium density since construction (ρ = -0.44, p = 0.005). The percent change in forest land cover since project construction is also correlated with design success (ρ =0.35, p = 0.031) . Similarly, the project score based on the monitoring reports is negatively correlated with the percent change in medium density development (ρ = -0.41, p = 0.009) and positively related to agricultural land cover change (ρ =0.36, p = 0.024) since project construction. These correlations generally indicate that land cover and watershed area are important predictors of stream restoration project success, with lower project scores being associated with increased urbanization since project completion, likely due to increased stormwater runoff.

Several project characteristics are significantly correlated with the geomorphic function score (Table 2.14). Both W:D and sinuosity are positively correlated with stream function (ρ = 0.37, 0.44; p = 0.019, 0.005, respectively). Channels with low W:D are entrenched and unlikely to access the floodplain. Similarly, channels with low sinuosity were likely channelized and have narrower floodplains. In contrast, project function scores are inversely related to the bankfull discharge and the number of structures per 1000 ft. (ρ = -0.35, -0.38; p = 0.029, 0.019, respectively). Since both discharge and structure density are also correlated ρ = 0.53, p < 0.001), the relationship between these two project characteristics and the geomorphic function scores is difficult to assess via correlation alone.

Table 2.14 Spearman correlation coefficients between project-scale variables and project assessment scores (values in bold denote statistically significant correlation coefficients, $p<0.05$).

Variable	Function Score	Design Score	Monitoring Score
Year completed	-0.06	**0.47**	**0.35**
Project length/bankfull width	-0.24	0.22	-0.29
Project channel slope	-0.29	0.26	0.06
Width:depth	**0.37**	-0.14	0.13
Entrenchment ratio	-0.04	0.07	0.12
Bankfull discharge/watershed area	**-0.35**	0.23	-0.11
Specific stream power	-0.07	-0.23	0.00
Average streambank soil erodibility along project reach	-0.23	0.21	0.11
Sinuosity	**0.44**	-0.15	0.03
D_{50}/bankfull depth	-0.30	0.31	-0.11
Structure density (#/1000 ft.)	**-0.38**	0.15	0.07
Distance to upstream grade control from upstream end of project/bankfull width	0.18	0.10	-0.16
Distance to downstream grade control from downstream end of project/bankfull width	0.02	-0.24	0.03

2.3.3 Factors Influencing Geomorphic Function

Multiple linear regression was conducted to evaluate both watershed and project characteristics that are correlated to stream restoration project success. The significant regression equations are presented in Table 2.15. Because the explanatory variables were standardized by subtracting the mean and dividing by the standard deviation, the coefficients for each variable indicate the relative importance of that variable in the equation. The adjusted correlation coefficient (adj. r^2) indicates the amount of variance in the score explained by the equation, taking into account the number of predictors in the equation. The predicted correlation coefficient (pred. r^2) indicates how well the regression equation could predict project success scores and was used as a regression diagnostic to indicate model over-fitting.

All of the presented regression equations are highly significant and explain 21% to 69% of the variance in the project scores. Examination of the relationships in Table 2.15 show that increases in medium density development and decreases in agricultural land since project completion are significant predictors of both geomorphic function and design success. These watershed attributes appear in three of the six regression equations and have the highest coefficients in each equation, indicating their importance in predicting project geomorphic function and design success. Additionally, stormwater BMP density, the number of stormwater practices per unit area of medium and high density development, was negatively correlated with project design scores. Due to the transition in stormwater management from larger stormwater structures to a greater number of smaller, more distributed practices, a greater BMP density is indicative of more recent development that was likely not considered during project design. Although stormwater management reduces the impact of urbanization from more frequent storm events, there is less control for runoff from larger events, such as the 20-yr recurrence interval and larger storms.

Table 2.15 Regression equations between project assessment scores and watershed and project variables. All coefficients significant at $\alpha<0.05$ and coefficients represent the relative importance of the variable.

Project Score	Regression Equation*	Adj.^ r^2	Pred.# r^2	Regression p-value
Geomorphic Function	= 8.4 %ag_change – 5.7 Q/WS_Area^2 + 5.5 WD	0.38	0.30	<0.0001
Geomorphic Function	= 8.7 WD – 6.2 D50/BFD	0.24	0.17	0.005
Design	= -16.4 %med_change + 7.9 D50/BFD – 6.2 power	0.69	0.62	<0.0001
Design	= 12.5 Year + 8.8 D50/BFD – 7.6 BMPdens	0.50	0.37	<0.0001
Design	= -14.8 %med_change - 6.9 WS_Area	0.45	0.35	<0.0001
Monitoring Report	= –6.5 Proj_length/BFW + 5.9 Year	0.21	0.13	0.005

* %ag_change = percent change in agricultural land cover since construction, Q/WS_Area = bankfull discharge scaled by watershed area, WD = width:depth, D50 = median particle size of riffles, BFD = bankfull depth, %med_change = percent change in medium density development since project completion, power = specific stream power, Year = year of project completion, BMPdens = number of BMPs per square kilometer of high and medium density development, WS_Area = area of contributing watershed, Proj_length = length of project, and BFW = bankfull width.

^ Adjusted correlation coefficient

\# Predicted correlation coefficient

Urbanization affects more than just runoff volume and peak flow. A watershed containing higher percentages of rural land will have more space available for channel adjustment, energy dissipation, and riparian buffer development. Watershed land cover also has large effects on hydrological response. In their review of the "urban stream syndrome," Walsh et al. (2005) discuss "larger flow events with faster ascending and descending arms of the hydrograph" that are a result of the increased impervious area, and more efficient transport of runoff associated with urbanization. In other words, increased urbanization results in higher and flashier peak flows. Bledsoe (2002) described the effects of these hydrologic changes as a disruption in the balance between the capacity of a stream to move sediment and the amount of sediment delivered from the watershed, and summarized potential geomorphic responses including channel enlargement, bank instability, incision, and plant community alteration. In particular, he interpreted the work of Thorne (1990) to show that flashy flows can cause bank instability through pre-wetting, desiccation, and/or rapid drawdown. Additionally, urbanization has been shown to increase stream temperatures (Pluhowski,1970; Rice et al., 2011) which can increase stream bank erosion due to a difference between stream temperature and streambank soil temperature (Akinola et al., 2019).

The designed width-to-depth ratio (W:D) of the stream channel occurs in both regression equations predicting project geomorphic function, providing strong evidence that channels with a high W:D have better geomorphic function. The relationship between stream flow and flow area is described by the continuity equation:

$$Q = VA \tag{2-5}$$

where: Q = stream flow (ft.^{3}/s);

V = flow velocity (ft./s); and,
A = flow area (ft.^{2}).

Additionally, the relationship between flow area and velocity is governed by a force balance between gravity (flow-driving force) and stream channel friction (flow-resisting force). This relationship is commonly described using resistance equations, the most commonly used of which is Manning's equation (Manning, 1891):

$$V = \frac{R^{2/3} S^{1/2}}{n} \tag{2-6}$$

where: V = flow velocity (ft./s);
R = hydraulic radius (flow area divided by wetted perimeter, ft.);
S = energy slope (ft./ft.); and,
n = Manning's roughness coefficient.

The continuity equation shows that as discharge increases, either flow area or velocity must increase. Likewise, Manning's equation shows that as discharge increases, wetted perimeter must increase to balance the extra driving force with additional friction. In effect, flow area increases until flow reaches the floodplain, when wetted perimeter increases dramatically as the flow spreads across the relatively horizontal floodplain. This behavior is well-illustrated in Figure 2.10. As can be seen in the rating curve (stage-discharge relationship), larger increases in discharge result in smaller increases in stage when the flow reaches the floodplain.

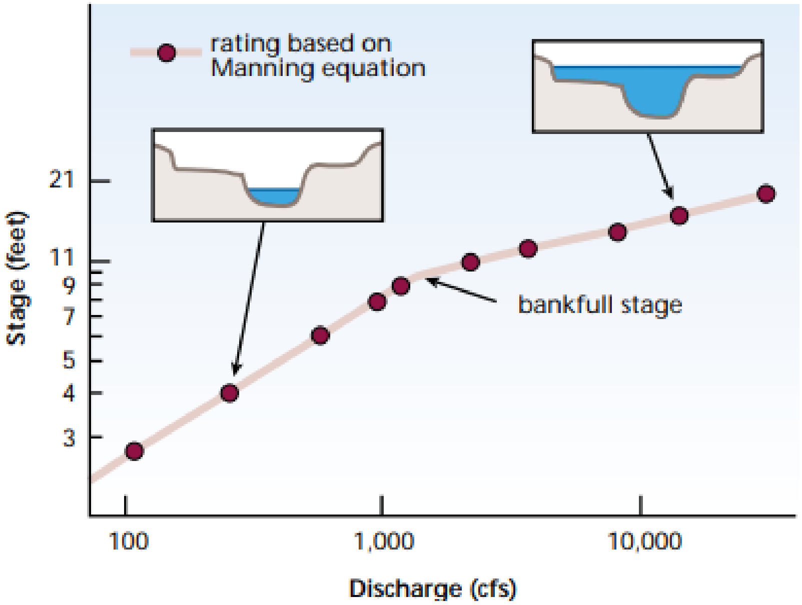


Figure 2.10 Determining bankfull stage from a rating curve (from FISRWG, 1998).

In shallower streams (i.e. those with higher width to depth ratios), flows can reach the floodplain at lower discharges and at more frequent intervals. Since floodplain connection is so important to stream function (e.g. Loose and Shader, 2016; Hupp et al., 2009), the positive correlation between W:D and function score provides a good basis for improvement of stream restoration design if geomorphic function is a primary goal. Inverse regression of width to depth ratio against function score showed that, according to this study, a W:D of 12 would result in a function score of 92%.

Both bankfull discharge per unit watershed area and the median riffle particle size, expressed as a fraction of bankfull depth, were negatively correlated with geomorphic function. Streams will relatively higher unit discharge will have higher energy and will be more likely to incise, reducing floodplain access. However, since not every design drawing or report indicated the bankfull discharge, this value was estimated for each project using Maryland non-urban regional curves rather than bankfull indicators and/or USGS gaging information. Additionally, not all of the project watersheds were rural, so there will be some error in this predictor. While the unit bankfull discharge is statistically significant, it only appears in a single regression relationship and the coefficient is relatively low, suggesting this explanatory variable is not as important as landuse or bed material particle size.

The median substrate particle size (D_{50}) was negatively correlated with geomorphic function, but positively correlated with the design success score. Upon further study of the function assessment and D_{50} data, it became apparent that projects with substrate D_{50} greater than 6 in. had significantly lower average scores in the bedforms and substrate categories of the function assessment ($p<0.05$). Because projects with larger bed sediment sizes tended to be armored and were intended to be immobile, it makes sense that these components of stream function would decrease with increasing D_{50}. In contrast, D_{50} was positively correlated with the durability of project designs and appeared in two of the three significant regression equations for design score. Projects with very conservative designs typically had material consisting of large rock, relative to the channel size (Figure 2.11), indicating these projects were designed as threshold channels (i.e. bed material sized to be immobile for most floods).

Other factors that are negatively related to project design scores include specific stream power and watershed area. The specific stream power represents the amount of work the stream flow can do on the channel bed and is a function of stream discharge, channel slope, and channel width; therefore, channels with high stream power are more likely to erode the channel and to move instream structures. Similarly, stream restoration projects with large watersheds, and thus larger discharges, are less resilient. Additionally, because the size of boulders used in stream restoration projects is limited by construction equipment, stream restoration projects in larger rivers must utilize structures constructed of a greater number of relatively smaller elements, which increases the risk of structure failure.

The regression analysis also indicates a positive relationship between construction year and design score, which suggests stream restoration design and construction techniques may be improving with time as a result of greater experience of restoration professionals, and/or the newer projects have experienced fewer large storms. Given that 2018 was Maryland's wettest year on record [annual total rainfall of over 80 in. compared to the 30-year average of 47 in. (PRISM Climate Group)], coupled with the shorter amount of time for vegetation establishment for the younger projects, support the conclusion that more experience within the stream restoration profession has resulted in more resilient projects. Year was also positively correlated with the project score based on the monitoring reports. This relationship could again be explained

Figure 2.11 Conservative design of project 19 used large rock relative the channel size.

by improved restoration designs and construction techniques with time, or by an increased ability to discern project success from newer and potentially more detailed monitoring reports. However, no relationship was apparent between the number of elements included in a monitoring report and monitoring score, so the assessment was not biased toward or against monitoring reports with more detail (Figure 2.12). As such, these results also suggest stream restoration design and construction are improving with time and experience.

Although there is no relationship between monitoring score and monitoring detail, there seems to be a strong positive relationship between construction year and the number of elements included in the monitoring reports, as the Spearman correlation between the two is 0.91. Figure 2.13 illustrates that monitoring reports are getting more detailed over time. Despite an increase in the amount of information included in monitoring reports, relationships between monitoring scores and watershed- and project-level variables in this study were weak. Few significant regression models or correlation coefficients related to the project scores based on the monitoring reports were developed, and most that were developed lacked consistency. Since conclusive relationships were developed with field-assessed function and design scores, this weakness shows that assessing stream restoration success using monitoring reports is difficult and may not provide sufficient insight into the benefits supplied by a restoration project. However, the definitions of success emphasized in this study may not perfectly align with those of the assessed projects. Since only half of the projects referenced a pre-construction assessment against which post-restoration conditions could be evaluated, and even fewer projects stated clear objectives, a definition of project-specific success was difficult to develop.

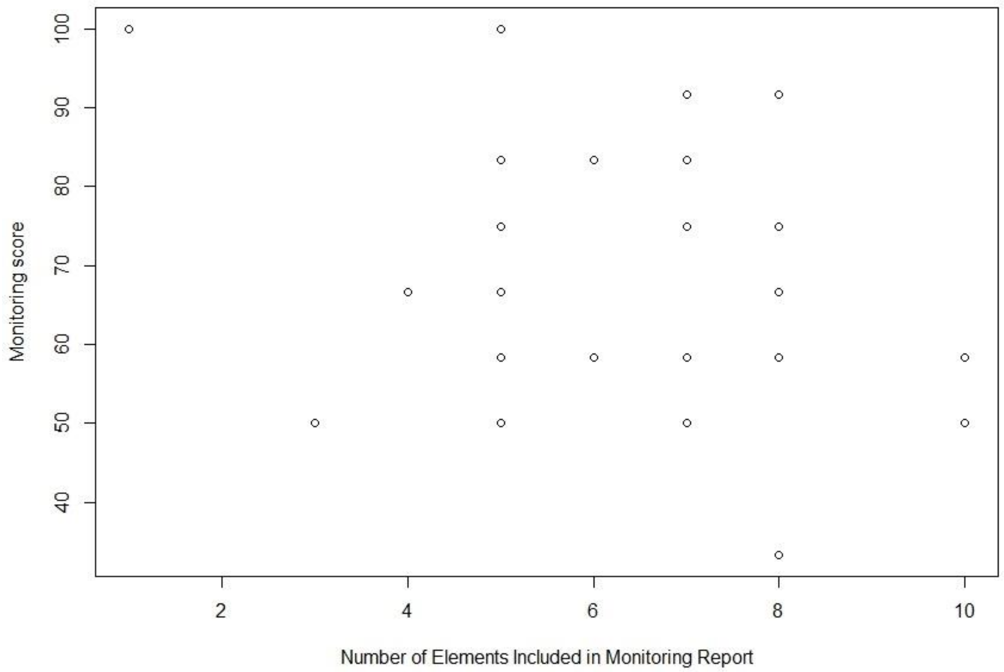


Figure 2.12 Relationship between monitoring report depth and monitoring score.

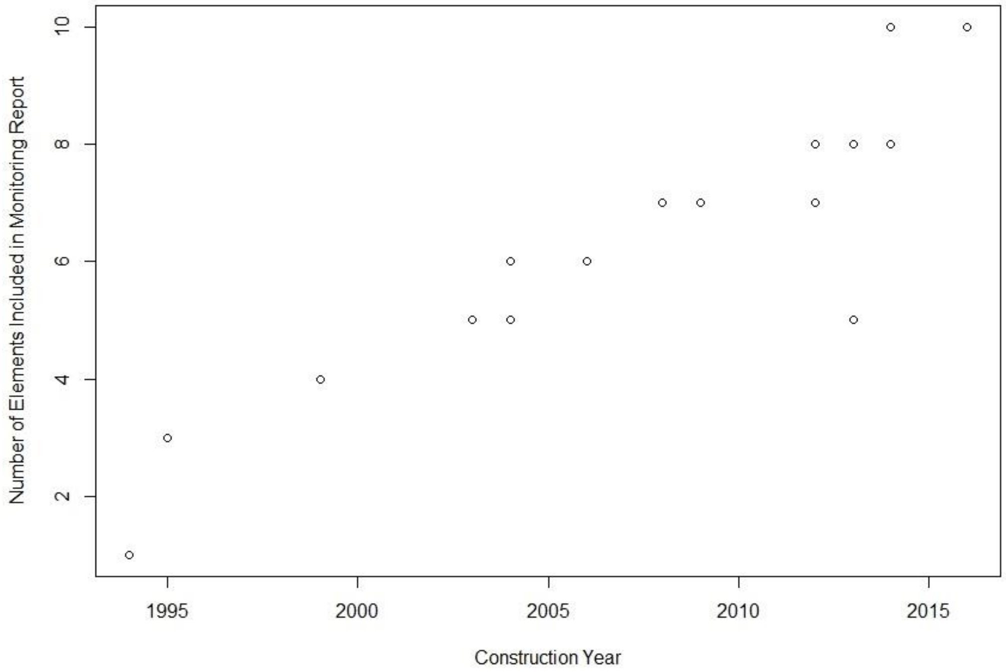


Figure 2.13 Increasing monitoring detail with time.

2.4 Stream Restoration Project Assessment Conclusions

Stream restoration has rapidly gained in popularity as a practice to meet TMDL requirements, but restoration science continues to lag behind the fast-growing practice. This study sought to bridge this gap by providing insight into the conditions under which stream restoration projects are successful. A selection of completed stream restoration projects in Maryland were assessed to evaluate project success.

In this study, restoration project success was defined with respect to geomorphic function and design resilience. For example, function success could align with compensatory mitigation goals of creating "functional lift," and design success could align with TMDL goals of erosion reduction and increased channel stability. Because these two goals may be contradictory (e.g. functional streams naturally migrate over time, but channel migration typically leads to design failure), it is unsurprising that the different assessment scores for an individual project are different. Thus, the answers to the research questions addressed by this study differ depending on project goals and the success criteria associated with those goals. For example, the use of larger bed material was negatively correlated with project geomorphic function but positively correlated to design success.

At the watershed scale, land cover was most strongly related to project success. Increased development within the contributing watershed following project construction was correlated with reduced design lifespan. In contrast, increasing agricultural landuse was positively related to the restoration of greater stream geomorphic function, likely due to more stable stream hydrology, fewer infrastructure constraints on designs, and more room for the re-creation of floodplains in rural watersheds. Stream restoration projects in larger watersheds and catchments with higher discharge and specific stream power were less successful, likely due to greater hydraulic forces on the channel and instream structures. At the project level, restorations with higher width to depth ratios scored higher on the functional assessment. Projects with greater bed particles sizes traded channel stability for geomorphic function as use of larger bed particle sizes resulted in increased project durability, but reduced channel mobility. Study results suggest stream restoration designs are improving over time, but the ability to determine project success from standard monitoring reports is limited.

3.0 Instream Structures

Instream structures have historically been utilized in stream restoration. Early attempts by humans to harness streams for water, food, or energy have involved the use of instream structures. In the United States, river-alteration occurred throughout the 1700s and 1800s to increase navigability and provide flood control (Puckett, 2007). Contemporary stream restoration in the United States began in the early 1900s and is differentiated from its predecessors because its goals were to improve fish habitat and water quality, rather than the suitability of a waterway for human use (Puckett, 2007). Since contemporary stream restoration emerged in the early 1900s, it has also utilized instream structures (Thompson, 2005). These structures focused primarily on fish and were implemented to decrease the distance between pools, increase the number of spawning locations, provide fish habitat and shelter, and in some cases detain fish in certain reaches (Thompson, 2005). Although degradation of instream ecosystems, habitat, and water quality are generally attributed to watershed-scale problems such as land use change or overfishing; in-stream structures have been an attractive solution to these issues because they can be implemented on a local scale (Thompson, 2005). However, little evidence exists that these structures improve fish populations (Thompson, 2006; Griffith & McManus, 2020).

The modern stream restoration industry has been growing exponentially since the early 2000's and is valued at over $1 billion dollars per year (Bernhardt et al., 2005). Although specific practices have evolved since the early 1900s, modern stream restoration is still performed to rehabilitate streams that have been negatively affected by anthropogenic influences (Puckett, 2007). The goals of such rehabilitation can include improved water quality, riparian buffer quality, aquatic organism habitat, and/or reduced sediment loading from the channel boundary (Endreny & Soulman, 2011). The Clean Water Act (CWA) is a major driver of stream restoration, especially in the mid-Atlantic United States. Section 404 of the CWA mandates net-zero cumulative stream losses (Clean Water Act, 2002). As a result, stream restoration is often performed to offset disturbances to streams caused by road construction or other development. Under section 303 of the CWA, states must establish water quality standards and identify impaired waters (Clean Water Act, 2002). Thus, stream restoration is also performed to reduce pollution loads to impaired downstream waterways to meet total maximum daily load (TMDL) reduction goals (Clean Water Act, 2002; Noe et al., 2020). Another major driver of stream restoration, especially on the west coast of the United States, is restoring stream habitat for endangered anadromous fish species such as sockeye salmon (Cramer, 2012).

Stream restoration generally refers to a combination of reach-scale practices that can include livestock exclusion, instream structures, hard stabilization measures, bio-engineering techniques, riparian replanting, floodplain reconnection, and dam/ dike removal (National Research Council, 1992). However, stream restoration can also include watershed-scale practices such as reforestation, runoff attenuation, and erosion control to address the watershed-scale processes responsible for stream degradation (National Research Council, 1992; Thompson, 2005). The focus of this project is instream structures.

A widely reported issue for instream structures long-term is failure (Mooney et al., 2007; Niezgoda & Johnson, 2006; Puckett, 2007; Thompson, 2005). One possible explanation of structure failure is a lack of robust design guidance; for most instream structures, there is little consensus about how they should be designed or whether they achieve their design goals (Roni et al., 2002; Thompson, 2005). Practitioner surveys confirm the need to improve structure design and construction guidelines, with 80% of practitioners reporting that existing guidelines are inadequate (Radspinner et al., 2010).

The shortcomings in instream structure design guidance stem from issues related to their development and the conclusions drawn about them after they are implemented. The majority of design and construction techniques for instream structures have been developed through a process of trial and error with little understanding of stream function and without an underlying methodical approach (Puckett, 2007; Thompson, 2005). Although use of hydrodynamic models have been recommended for structure design, their use is limited because 3D flow and sediment transport models are complex and computationally intensive (Sotiropoulos & Diplas, 2014). Most design guidance uses a “cook book” approach that rarely accounts for site conditions (Radspinner et al., 2010; Sotiropoulos & Diplas, 2014). Thus, restoration design is informally referred to as “the art of restoration” because practitioners are required to make personal judgements in light of limited design guidance (Thompson, 2005).

Another issue that could contribute to poor instream structure performance is post-construction monitoring, which is performed for only a handful of projects (Thompson, 2005). This issue was highlighted by Bernhardt et al. (2005) who reported that only 6% of the stream restoration projects in the Chesapeake Bay watershed included post-construction monitoring. Without post-construction assessments of instream structures, there is a low likelihood that successes and failures will be identified and used to improve design guidance.

Instream structures are influenced by a wide variety of factors. Locally, there are factors related to their construction: the geometry of each component of the structure, what materials were used, the size of these materials, and the proximity to other structures. On a larger scale, structures are affected by factors related to the reach and watershed where they are located. Given the lack of research-based design guidance, the goal of this project was to evaluate existing instream structures with the aim of informing structure design. To achieve the project goal, instream structures were evaluated in the field and the structures scores were correlated with watershed and project characteristics, as well as design specifications.

3.1 Instream Structures Literature Review

3.1.1 Bank Protection

Bank protection (BP) structures are a family of instream structures that directly reinforce or block streambanks from erosive flows. The BP structures evaluated in this study were constructed out of rocks or logs and were either walls or toe protection. BP walls are generally taller than stone toe protection. As suggested by the name, toe protection aims to protect the lower part of the streambank, where shear stress and scour tend to be higher. BP structures not assessed as part of this study include root wads and branch packs.

3.1.1.1 Purpose

Regardless of structure height, all BP structures aim to protect the streambank toe which is where most bank failures originate (Baird et al., 2015). BP is considered a hard stabilization practice because it physically reinforces the stream channel as opposed to soft stabilization practices that provide stabilization by redirecting or decreasing flow velocities adjacent to the channel banks (Doll et al., 2003). BP is an alternative to soft stabilization practices; however, they are typically less desirable than soft stabilization because they alter the streambanks more, decreasing their value as habitat (Doll et al., 2003). Where bank protection is a priority, BP can be utilized in conjunction with flow-deflecting structures for additional protection (Baird et al., 2015). On a project scale, BP is used to prevent meander migration, maintain channel sinuosity, or protect infrastructure (Niezgoda & Johnson, 2006). For example, BP structures are often installed in the proximity of bridges or confluences where flow impingement poses a threat to bank stability (King County WA, 1993).

3.1.1.2 History and Earliest Instance

The predecessors to contemporary BP structures largely date back to the 1930's in the form of bank-habitat structures that aimed to compensate for lack of undercut banks, root structures, and large woody debris (Thompson, 2005). These early BP structures included but were not limited to bank lunkers, channel constrictors, and riprap revetments (Thompson, 2005). Like contemporary structures, these structures did not alter the hydrology or morphology of stream channels but simply aimed to stabilize the banks against erosion (Thompson, 2005). Unfortunately, these early structures experienced considerable problems including the collapse of structures attempting to simulate bank overhangs, decay of wood structures constructed above the low water level, and poor vegetation growth where riprap revetments had been installed (Thompson, 2005).

3.1.1.3 Current Design

The two major BP types assessed in this study that had well documented designs were imbricated rock walls and stone toe. Imbricated rock walls consist of large rectangular stones, stacked at near-vertical angles, that extend up the entire streambank (Figure 3.1). These rock walls are advantageous for protecting banks where there will be flows directed against the bank or where soil piping is a risk (MDE, 2000). The stones used to construct imbricated rock walls are large and typically weigh upwards of 500 lb. with diameters between 8 in. and 3 ft. (King County WA, 1993; NRCS, 2007e). These stones are typically sized so that the longest axis is least one third of the designed wall height (MDE, 2000). When constructing imbricated rock walls, stones should be staggered so that a given rock is centered on the joint between the two rocks below it (MDE, 2000). The wall itself should slope away from the channel at a slope between 1H:3V and 1H:6V (MDE, 2000). The base of imbricated rock walls should extend into the stream bed below the depth of scour and have a trench directly adjacent to the stream-side of the footers that is filled with riprap sized to resist bankfull flows for extra stability (MDE, 2000). Finally, to avoid soil piping, the bank behind imbricated rock walls is graded back at a 2H:1V and the remaining space behind the wall is filled with gravel (MDE, 2000). This gravel fill is then capped with a layer of soil that is deep enough to permit the growth of vegetation (MDE, 2000). Figure 3.2 depicts a cross-section view illustration of an imbricated rock wall from MDE (2000). Vegetated rock walls are an alternative type of imbricated rock wall where the wall is constructed directly against a soil face and vegetation, typically livestakes, is planted in the gaps in the stone to provide stabilization (Figure 3.3; NRCS, 2007e). The cost of imbricated BP is $90 per linear foot (King County WA, 1993; MDE, 2000).

Figure 3.1 Two examples of imbricated rock walls from restoration project 1 (a) and 4 (b), respectively.

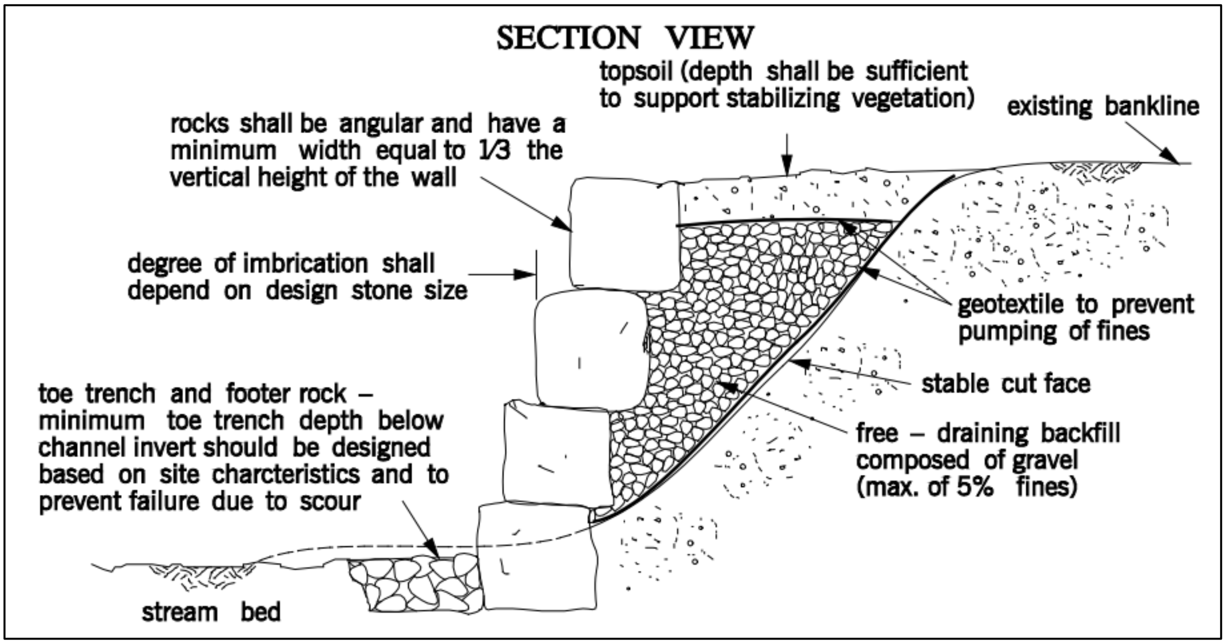


Figure 3.2 Design detail for an imbricated rock wall (MDE, 2000).

Stone toe is as a restoration practice that involves placing riprap along the toe of the streambank to provide stabilization and prevent undercutting (Massachusetts DEP, n.d.; MDE, 2000; Baird et al., 2015; Iowa DNR, 2018b; Bigham, 2020). Two examples of stone toe are pictured in Figure 3.4. It should be noted that "stone toe" is sometimes used to refer to any rock placed to directly reinforce the streambank toe; this type of structure can include short imbricated BP. Stone toe as a restoration practice typically uses riprap, which is

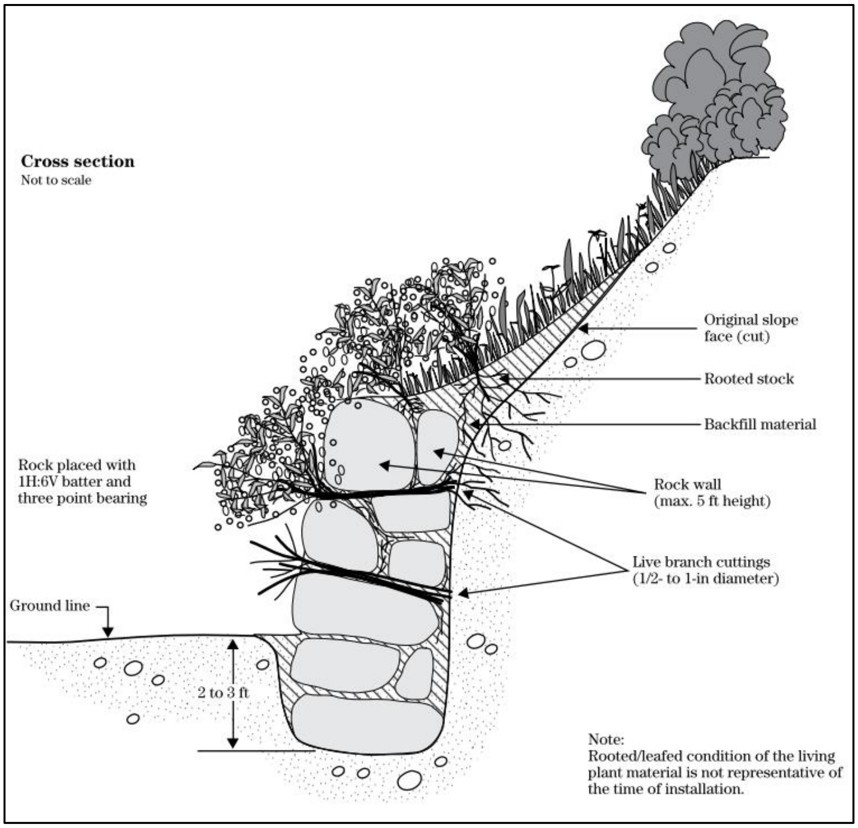


Figure 3.3 Illustration of vegetated rock wall (NRCS, 2007f).

advantageous because riprap is self-adjusting in response to disturbances (MDE, 2000; Baird et al., 2015). The riprap used to construct stone toe is generally sized to some design flow between 2 and 100 years, and is placed with a thickness that exceeds the largest rocks in the mix, typically 1.5- 3 times the D_{50} (NRCS, 2007e ; Baird et al., 2015). Oversizing stones is discouraged when designing stone toe because it can lead to excess cost and construction difficulties (King County WA, 1993). Stone toe is constructed from the base of the streambank to the level of vegetation growth on the bank, ideally to protect only the part of the streambank that cannot be vegetated (NRCS, 2007e; Baird et al., 2015). Given that stone toe is constructed using dumped rock, design guidance recommends placing it at a maximum slope between 1.5H:1V and 2H:1V (NRCS, 2007e; Baird et al., 2015). The cost of stone toe is estimated to be between $17 and $67 per linear foot (Massachusetts DEP, n.d.; MDE, 2000).

Extensions of the stone toe into the bank behind the structure (Figure 3.5), known as tiebacks, are recommended to increase stability, especially at the structure margins (King County WA, 1993; Baird et al., 2015). A terminal tieback at the end of the structure provides additional protection by preventing flow expansion and subsequent erosion (McCullah & Gray, 2005; Baird et al., 2015). Located at the ends of the structure, terminal tiebacks are typically angled 30° to 45° into the bank while intermediate tiebacks are located in the middle of the structure and are angled perpendicular to the bank (NRCS, 2007e; Baird et al., 2015). Tiebacks should be spaced every 1- 2 channel widths, extend into the bank as far as meander migration is expected, and be constructed using 20% more rock per linear foot than the stone toe itself to maximize stability (Baird et al., 2015). Flow-deflecting structures can also be utilized on the downstream end of stone toe to provide the same function as terminal tiebacks (Baird et al., 2015). Furthermore, stone toe should be keyed into the streambed a minimum of 2 ft. or 1.5 times the thickness of the stone toe to ensure stability.

Figure 3.4 Examples of stone toe from restoration project 22 (a) and 33 (b).

BP structures are typically constructed on the outside of meander bends where secondary flows make banks susceptible to erosion. Reinforcement along banks is most needed along the downstream end of a bend, as erosion potential remains high after the bend itself (King County WA, 1993). It is therefore recommended that BP extend one channel width upstream of where the line tangent to the upstream inside bank would meet the outside bank and extend 1.5 channel widths downstream of where the bend ends (Figure 3.6; Baird et al., 2015).

3.1.2 Full Span Vanes

Full span, or channel-spanning, vanes (FSVs) encompass a wide variety of structures that extend across the entire width of the stream channel, intentionally alter channel hydraulics, and provide grade control. some are designed to provide BP by redirecting flow away from the banks (Mooney et al., 2007; Hickman, 2019). FSVs are constructed using dumped (Figure 3.7) or stacked rocks, logs, or a combination of the two (Hickman, 2019). Cross vanes are the most ubiquitous member of this diverse structure family, which also includes vanes, vortex rock weirs, sills, modified j-hooks, grade control structures, step structures, a- and u- vanes, w-weirs, and crib structures (Hickman, 2019). Sills are the most simple type of FSV, as they are flat and constructed perpendicular to streamflow. Cross vanes consist of two single arm vanes that slope upwards towards the banks from the channel bed, connected in the center of the channel by a flat sill oriented perpendicular to streamflow (Puckett, 2007; Radspinner et al., 2010). Cross vanes concentrate flows which creates a downstream scour pool while aggradation occurs upstream, creating a riffle (Mooney et al., 2007). Modified j-hooks, which are also referred to as asymmetrical u-vanes, consist of a single arm vane on one bank that is connected to a sill that spans the rest of the channel (Mooney et al., 2007; NRCS, 2007a).

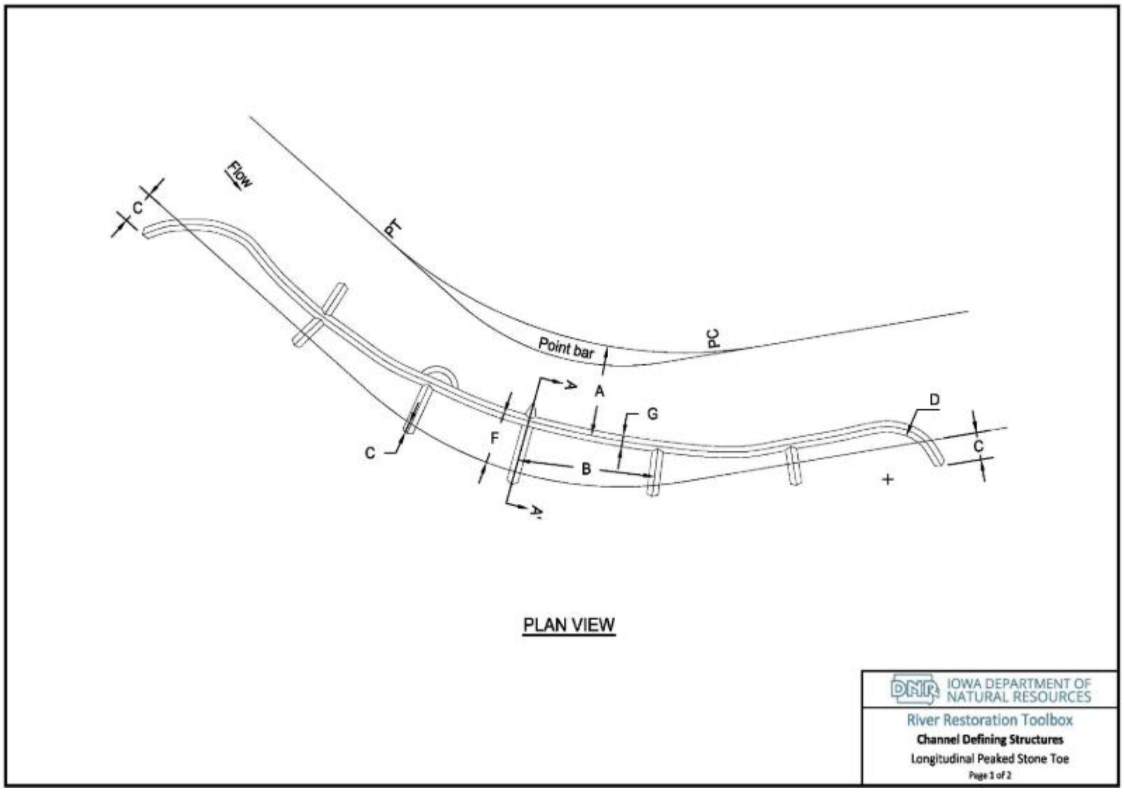


Figure 3.5 Stone toe protection with terminal and intermediate tiebacks (Iowa DNR, 2018b).

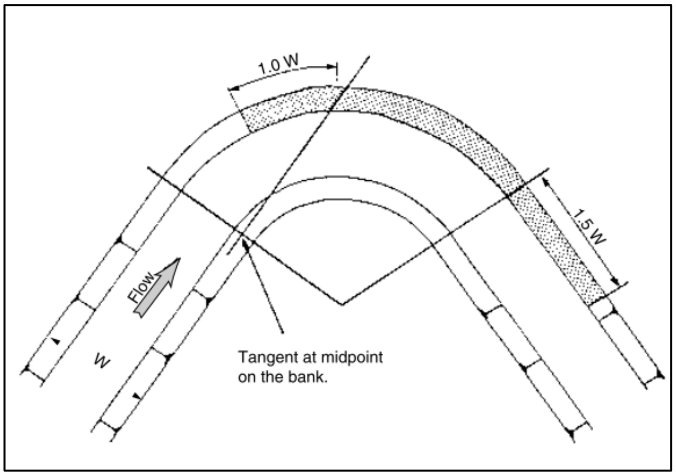


Figure 3.6 Recommended minimum extent of bank protection (King County, WA, 1993).

Figure 3.7 A cross vane constructed using dumped stone from restoration project 35.

3.1.2.1 History and Earliest Instance

Humans have been constructing the predecessors to modern channel-spanning vanes for centuries, possibly millennia. As documented by Puckett (2007), some of the earliest channel-spanning structures were constructed by native Americans to provide easier fish capture by redirecting fish or preventing upstream or downstream migration (Gilmore, 1953; Lutins, 1992). Channel-spanning structures were also utilized in China as early as 256 BC to provide irrigation and flood control (Li & Xu, 2006). Moreover, channel-spanning weirs were constructed in the 11th century in Wales to direct flows through the Old Dee Bridge to downstream power mills (Cragg, 1997). The earliest use of FSVs in stream restoration originates from the 1930s, during a boom in stream restoration overseen by the Civilian Conservation Corps and the US Forest Service (Thompson, 2005). These early channel-spanning weirs were constructed to increase instream habitat and restore streams (Mooney et al., 2007). Many of the design guidelines developed during this era of stream restoration were utilized well into the 1980s and 1990s, often providing more detailed design guidance compared to then contemporary resources (Thompson, 2005). The vortex rock weir was developed in the 1980s to provide grade control and increase flow diversity (Puckett, 2007).

Based on 1996 design guidance from Dave Rosgen, cross vanes are used in stream restoration design to provide energy dissipation where sinuosity is constrained and to create scour pool habitat for aquatic organisms (Puckett, 2007). Presently, cross vanes are one of the most widespread instream structures utilized in stream restoration; upwards of 80% of practitioners reported having experience with these structures (Radspinner et al., 2010). Cost estimates for cross vanes range from $1,212 to $8,000 (MDE, 2000; Puckett, 2007).

3.1.2.2 Purpose

FSVs are designed to function over a range of flows, provide grade control, and dissipate energy over their drop (MDE, 2000; Rosgen, 2001; Doll et al., 2003; Gordon & Collins, 2016). FSVs create a step in the channel bed reducing upstream and downstream channel slopes, and the footers prevent the migration of knick-points (Copeland et al., 2000). Channel-spanning structures usually cause upstream deposition where the channel bed is held in place and a downstream scour pool due to the drop over the structure (MDE, 2000;

Rosgen; 2001; Doll et al., 2003; Radspinner et al., 2010). Moreover, the drop over these structures provides flow diversity and habitat in the form of a downstream scour pool (MDE, 2000; Rosgen, 2001; Doll et al., 2003). Channel-spanning vanes can also be utilized to increase water surface elevation for irrigation diversions, stabilize incising channels, and raise water levels to promote floodplain and secondary channel access (Mooney et al., 2007).

Certain FSVs, such as cross vanes, also provide BP by redirecting flows away from the banks and concentrating them in the center of the channel (MDE, 2000). Cross vanes also prevent natural channel migration and are often used as an alternative to traditional “hard stabilization” practices, such as BP, that are more invasive and associated with decreased stream function (Rosgen, 2001; Sotiropoulos & Diplas, 2014). As a result, FSVs can be used to protect bridge piers by directing flows through them (Sotiropoulos & Diplas, 2014). Although FSVs are designed to function and remain intact during high flow events, they have a high risk of failure due to their location within the main channel. Therefore, Hickman (2019) recommended these structures only be utilized where infrastructure protection and grade control are required.

3.1.2.3 Current Design

As stated in the previous section, it is recommended that FSVs only be utilized where infrastructure protection and grade control are required (Hickman, 2019). Although this section will outline rules-of-thumb for constructing channel-spanning vanes, design calculations and modeling are always recommended for these structures due to high risk for unintended bed or bank erosion, impaired aquatic organism passage, and overall structure failure (Cramer, 2012; Gordon & Collins, 2016).

FSVs are typically constructed out of stone, wood, or a combination thereof and the materials that naturally occur in a stream should be strongly considered when deciding structure material (Figures 3.8 and 3.9; MDE, 2000; Hickman, 2019). Logs are the least expensive construction material for FSVs; however, their design life can be limited due to natural decay if they are in a location where they experience cycles of wetting and drying (Hickman, 2019). Logs are best utilized where baseflow is consistent and continual submergence is ensured (Hickman, 2019). Wood FSVs are also more prone to undermining than their stone counterparts (VDSWC, 2004; NRCS, 2007a). The diameter of logs used to construct FSVs should be at least 8 inches, but bundles can be used as long as logs are bolted together or bound with sturdy cables or rebar (MDE, 2000; Rosgen, 2001; VDSWC, 2004).

Stone is a more expensive construction material for FSVs, but it tends to be more durable, easier to construct, and easier to key into the banks (Hickman, 2019). Stone is recommended where a long design life is required, for example, in infrastructure protection projects or where grade control is a goal of the structure (MDE, 2000; VDSWC, 2004). Boulders should be sized to resist design discharges with a 1.1- 1.5 factor of safety and be heavy enough to prevent vandalism (NRCS, 2007c; Gordon & Collins, 2016). Stones should be resistant to breakdown, have flat faces that allow them to fit together (Doll et al., 2003). The boulders used to construct FSVs should be stacked on the joint between the two rocks below them and footers should be slightly bigger than the stones above them to maximize stability (MDE, 2000). Regardless of construction material, FSVs should be constructed utilizing geotextile fabric on the upstream side of prevent soil piping through the structure (Doll et al., 2003).

A common failure mode for FSVs is undermining, which is caused by scouring below footers on the downstream side of the vane, which results in structure failure (Figure 3.10; Puckett, 2007). As a result,

Figure 3.8 Two examples of log full span vanes from restoration projects 28 (a) and 36 (b).

Figure 3.9 Two examples of rock full span vanes from restoration projects 24 (a) and 28 (a).

properly designed footers are among the most important features of FSVs. Typically, FSVs are constructed with 1-2 layers of footers that are “shingled” in the downstream direction so they extend beyond the vane rocks into the pool (MDE, 2000). Depth of scour is the main criterion used to determine the appropriate footer depth. For vanes with sloped arms, such as cross vanes, this maximum scour depth occurs adjacent to the banks where the drop height is the greatest and should be used to inform structure the footer depth (Hickman, 2019). Where preventing the migration of a knick-point is a design objective, or where the channel consists of easily transported sediment, footers should be 1.5- 3 times deeper than the calculated depth of scour or should extend to a resistant layer such as bedrock (Hickman, 2019). Doll et al. (2003) noted that rocks used to constructed cross vanes generally weigh between 1-2 tons; the consensus throughout most design literature is that rocks should be sized according to shear stress based on a design flow (MDE, 2000; Rosgen, 2001; VDSWC, 2004; NRCS, 2007c; Iowa DNR, 2018a). As identified by Mooney et al. (2007), FSVs have higher rates of success when constructed on bedrock than alluvial material. However, this guidance conflicts with guidelines put forward by MDE (2000) which advises against constructing FSVs on bedrock. Other options for increasing the longevity of FSVs include the use of concrete, eco-bricks, and grout, but these materials may conflict with stream restoration design principles which prioritize using materials native to the stream channel (Mooney et al., 2007).

Figure 3.10 Examples of a knick-point and resulting structure failure from restoration project 8. A full span vane that failed due to the migration of a knick-point, such that the structure is now above the current baseflow water surface elevation and structure materials were displaced into the downstream pool (a) and the downstream reach that was affected by this knick-point (b).

While footer depth is the primary defense against failure due to knick-point migration or excessive scour pool growth, the height of a structure and the resulting elevation drop play a considerable role in determining the depth of scour caused by a structure, as well as its suitability for aquatic organism passage. Generally, a larger drop over a structure increases shear stress and thus the likelihood of the displacement of structure materials (Doll et al., 2003). Where excessive scour is the primary concern, the maximum drop over a cross vane should not exceed 2 ft. (MDE, 2000). Where aquatic organism passage is a concern, MT DNRC (2020) recommends drops should not exceed 1.5 ft. while VDSWC (2004) recommends drops should not exceed 0.5 ft. Differences in the recommended drop height reflect the swimming abilities of different species of fish native to Montana and Virginia. Although high flow conditions are important to consider for structural stability and scour, FSVs should also maintain sufficient depth during low flow conditions to allow fish passage (MDE, 2000).

Another common failure mechanism for FSVs occurs when water erodes around the structure at the banks, known as flanking (Figure 3.11; Puckett, 2007). To protect against flanking, FSVs should be constructed into the banks a sufficient length that flows cannot bypass the structure. Most design guidance simply recommends that FSVs be keyed into the banks (Rosgen, 2001; Doll et al., 2003; Puckett, 2007; Gordon & Collins, 2016). E. Hickman (2019) recommends a key-in distance between a quarter and half of the bankfull width of the channel. The orientation of these keys is mostly provided in pictures in the design guidance, leading to two types of structure keys: extended-arm keys and cut-off sills. Extended-arm keys are extensions of each FSV arm into the bank (Figure 3.12). Cut-off sills, which are mostly associated with Natural Channel Design structure guidance, extend perpendicularly into the bank (see Rosgen, 2001; Doll et al., 2003; NRCS 2007a; Figure 3.12). Although it is advised to key FSVs into the bank at bankfull elevation where possible, keyins below bankfull depth are permissible where a key-in at bankfull depth would result in arm slopes outside of the recommended range (Rosgen, 2001; Doll et al., 2003).

Figure 3.11 Two full span vanes that failed due to flanking. a) shows a rock cross vane from restoration project 31; b) shows a log cross vane from restoration project 28, which is missing the entire right arm.

Arm slope is a design parameter only applicable to certain FSVs. Sills do not have sloped arms, while most vane-type structures do. Where arm slope is applicable, such as for cross vanes, they should slope upwards from the center of the channel to the channel banks to encourage flow redirection away from the channel banks (Doll et al., 2003). Recommended arm slope ranges vary; for example, Maryland Department of the Environment (2000) recommends 3- 7%, Rosgen (2001) recommends 2- 7%, and Doll et al. (2003) recommends 2- 20%. Flume studies by (Puckett, 2007) indicate that increased arm slope could decrease bank stability.

For cross vanes, it is recommended that each arm and the sill occupy 1/3 of the bankfull channel width (MDE, 2000; NRCS, 2007b; Sotiropoulos & Diplas, 2014), and that each arm be angled 20° to 30° horizontally with respect to the upstream bank (MDE, 2000; Doll et al., 2003). It should be noted that increased bank angles are associated with increased bank protection as well as increased risk of structure failure, while smaller bank angles may not be suitable for small streams due to flow deflection into the opposite bank (Sotiropoulos & Diplas, 2014). See Figure 3.13 for illustrations of FSVs, specifically cross vanes, and Table 3.1 for a summary of design recommendations for the construction of FSVs.

Cross vane placement is generally recommended in streams where riffle-pool sequences naturally occur: Rosgen A3-A4, B3-B4, C3-C4, F3-F4, and G3-G4 (MDE, 2000). Additionally, Murphy & Valenzuela (2018) recommend placing vanes in channels with width to depth ratios greater than 12. The Maryland Department of the Environment (2000) recommends the use of cross vanes in streams that are actively incising, have moderate to high gradients, and have coarse bed material. Cross vanes are not appropriate in channels with exposed bedrock, or where there is no reason to prevent channel migration (MDE, 2000).

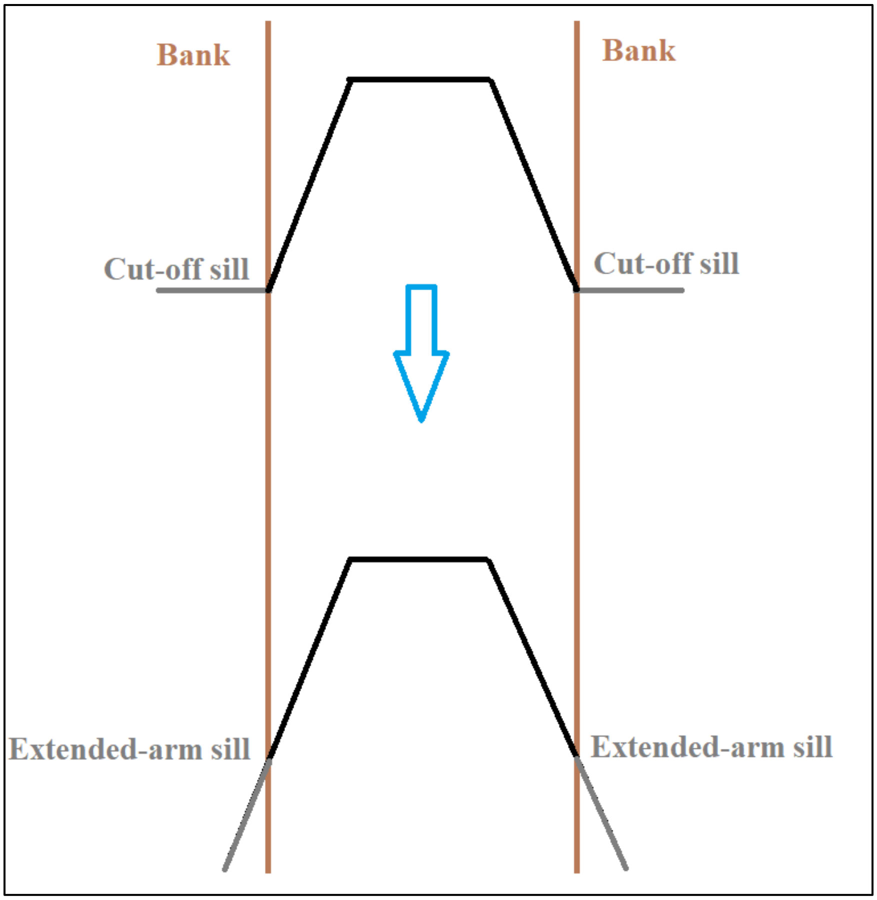


Figure 3.12 Full span vanes with cut-off sills (top) and extended-arm sills (bottom).

Where space is a constraint, cross vanes can be constructed without a sill, but this carries a risk of higher failure rates stemming from a greater likelihood of flow redirection from one arm against the opposite arm (Hickman, 2019). A-vanes are another alternative cross vane constructed with an extra sill to distribute energy and decrease the step height of a given step (NRCS, 2007a, Sotiropoulos & Diplas, 2014; Hickman, 2019).

FSVs should not be constructed at the apex of meanders because of increased risks of flanking as the meander bend naturally migrates (Mooney et al., 2007). Doll et al. (2003) recommend placing FSVs in runs. FSVs constructed in sequence have higher success rates than those constructed alone due to increased energy dissipation over a series of structures (Biedenharn & Hubbard, 2001; Mooney et al., 2007; NRCS, 2007d). However, when constructed in sequence, the top of the vane sills should align with the channel slope to prevent backwatering or excessive energy dissipation (Mooney et al., 2007). When constructing FSVs to redirect flows for infrastructure protection, they should be constructed 1.5-3.0 bankfull, as the scour pool will extend approximately twice the length of the shortest vane arm (Mooney et al., 2007). Additionally, the deepest part of the scour pool created by a cross vane will occur at the end of the shortest arm (Mooney et al., 2007).

FSVs are most effective in slightly different conditions than partial span vanes (PSVs). FSVs are noted to perform more effectively in high gradient straight reaches, whereas PSVs perform are more effective in more sinuous reaches especially when installed in meander bends (MDE, 2000; Puckett, 2007).

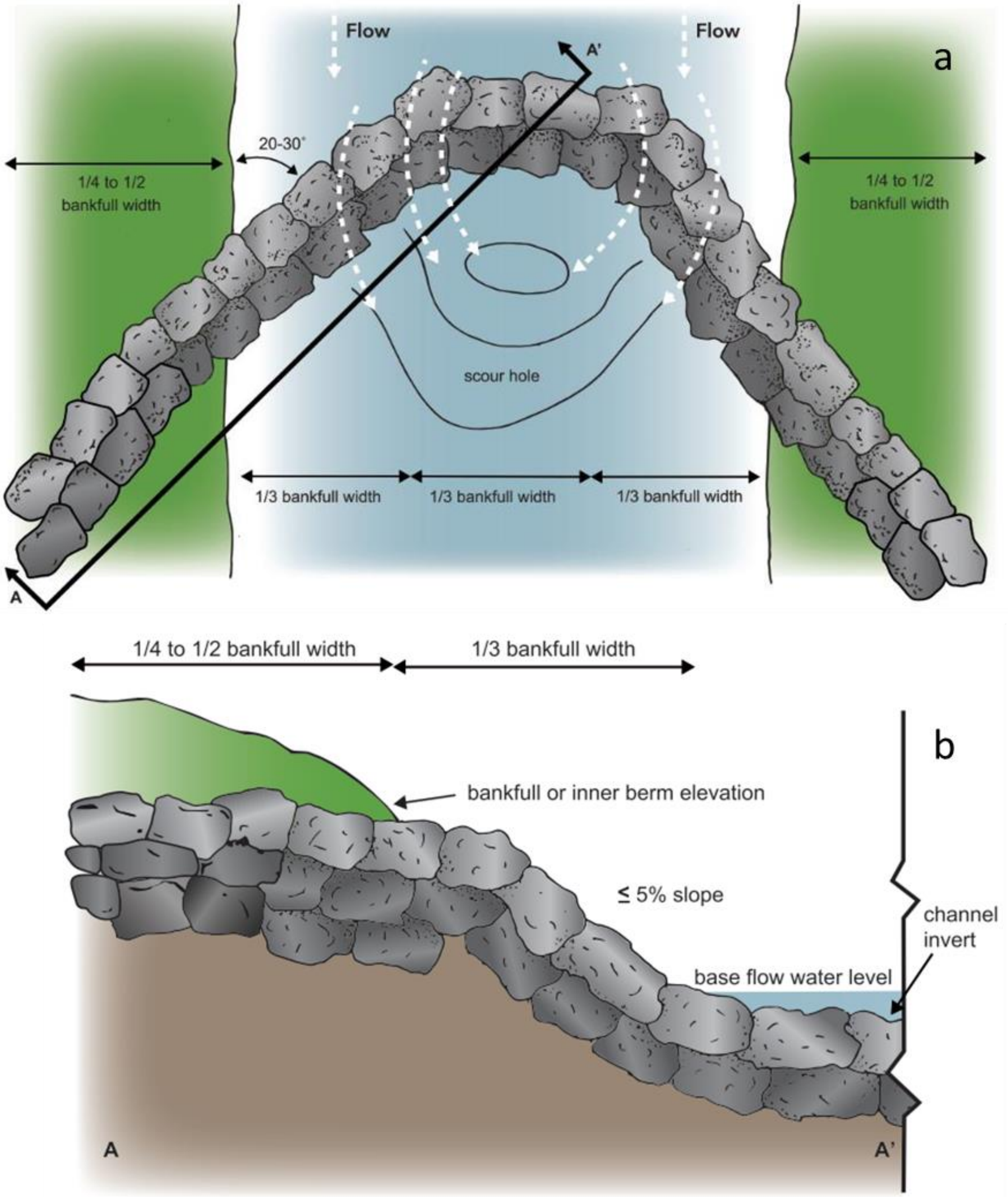


Figure 3.13 Cross vane plan view (a) and profile (b) (Hickman & Thompson, 2010a).

Table 3.1 Summary of design dimensions for full span vanes, specifically with regards to parameters analyzed in this study.

Structure Parameter	**Value**	**Source**
Key distance	Minimum ½ BFW 2 ft. minimum	Iowa DNR (2018a) VDSWC (2004)
Key angle	90°	VDSWC (2004)
Arm bank angle	20°- 30°	MDE (2000), Rosgen (2001), Doll et al. (2003), VDSWC (2004), Sotiropoulos & Diplas (2014), Iowa DNR (2018a)
Arm normal distance	1/3 bankfull width	MDE (2000), Rosgen (2001), VDSWC (2004), NRCS (2007a), Sotiropoulos & Diplas (2014)
Arm slope	2- 20% 2-15% 2-7% in smaller systems 2- 7 % 3- 7 %	Doll et al. (2003) VDSWC (2004) Rosgen (2001), NRCS (2007a), Iowa DNR (2018a) MDE (2000)
Sill length	1/3 bankfull width	MDE (2000), Johnson et al. (2001), VDSWC (2004), Iowa DNR (2018a)
Footer depth	1-2 tiers of boulders	MDE, (2000), Doll et al. (2003)
Boulder width	Minimum b-axis, 1.5 ft. Generally, 1-2 tons in gravel-cobble bed streams	VDSWC (2004) Doll et al. (2003)

3.1.3 Partial Span Vanes

Partial span vanes (PSVs) are instream structures that affect stream flow, but do not span the entire width of the channel. PSVs slope downwards from the channel banks to channel bottom and are often angled in the upstream direction, although there are instances of structures situated perpendicular to flow or angled in the downstream direction (Radspinner et al., 2010). Because PSVs redirect flows, they are often used to provide bank protection and create aquatic organism habitat in the resulting downstream scour pool (MDE, 2000). PSVs can be constructed out of stone, logs, or a combination thereof (Hickman, 2019). This project evaluated single arm vanes and j-hook vanes. Single arm vanes are a flow redirection structure also referred to as single-wing vanes and straight vanes (MDE, 2000). Developed in the 1990s by Dave Rosgen, j-hook vanes are a variant of single arm vanes that have a j-shape formed by a sill that extends farther into the channel and creates a larger scour pool (Rosgen, 2001). These structures constitute the most common PSVs utilized in the mid-Atlantic United States, but it should be noted that other single arm vanes exist including bendway-weirs, barbs, groins.

3.1.3.1 Purpose

PSVs redirect flows away from channel banks and create a downstream scour pool (MDE, 2000). Flow redirection results in lower near-bank velocities downstream, which induces deposition and makes conditions more suitable for the establishment of vegetation (Radspinner et al., 2010). PSVs can be an appropriate alternative to traditional hard bank stabilization practices given that they are less expensive, have fewer negative impacts on riparian ecosystems, and affect riparian drainage and hydrology to a lesser extent (Baird et al., 2015). PSVs may also provide ecological value by creating flow diversity and a downstream scour pool that can serve as habitat for aquatic organisms (Rosgen, 2001; McCullah & Gray, 2005). Furthermore, practitioner surveys conducted by Radspinner et al. (2010) indicate that PSVs are a common and widespread element in contemporary stream restoration with between approximately 70 to 80% of practitioners having experience with them.

3.1.3.2 History and Earliest Instance

The predecessors to contemporary PSVs were described by Thompson (2005) and referred to as deflectors. Deflector structures were widely utilized throughout the 1930s in the Civilian Conversation Corps era of stream restoration, primarily to create flow diversity for aquatic organisms (Thompson, 2005). These deflectors included a wide variety of bank-attached and mid-channel structures such as triangle deflectors, peninsular-wing deflectors, v-deflectors, y-deflectors, a-deflectors, and I-deflectors (Thompson, 2005). Many of these structures fell out of favor in the 1960s due to high failure rates and little evidence of improved aquatic organism habitat (Thompson, 2005).

3.1.3.3 Current Design

Current design guidelines for single arm vanes and j-hook vanes share considerable similarities which, unless otherwise specified, will be discussed generally as the current guidelines for PSVs. PSVs can be constructed out of rock, logs, or a combination of these materials (Figures 3.14; Hickman, 2019). Log is less expensive than rock and is recommended for projects where in-channel wood is the primary contributor to diversity in channel morphology (Doll et al., 2003). Brown (2000) recommends using logs in channels that do not contain large rock. It is noteworthy that, because wood decays, structures constructed out of wood are likely to have shorter design lives, especially if they are subject to wet-dry cycles, which increase decomposition rates compared to being continuously submerged (Hickman, 2019). The diameter of logs used to construct PSVs should be at least 8 in., but bundles can be used as long as logs are bolted together or bound with sturdy cables or rebar (MDE, 2000; Rosgen, 2001; VDSWC, 2004).

Stone construction materials are recommended for projects where PSVs must be durable, such as where infrastructure protection is a goal (MDE, 2000; VDSWC, 2004). Stone is also recommended for projects where large rock naturally occurs (Hickman, 2019). While stone PSVs are easier to construct than their log counterparts, they are more expensive (Hickman, 2019). The rocks used to construct PSVs should be sized with a 1.1-1.5 factor of safety such that they maintain stability during design flows (NRCS, 2007c; Gordon & Collins, 2016). MDE, (2000) recommends using rocks with a median diameter of 2.5 ft. and minimum weight of 200 lb. Doll et al. (2003) notes that rock sizes will vary based on design flows, but that stones used in gravel and cobble-bed channels will generally be between 1- 2 tons. The stones used to construct PSVs should be rectangular with a long axis at least 3.5 times the shortest axis to ensure stability (McCullah & Gray, 2005).

Additionally, the stones used to construct PSVs should be resistant to dissolution or natural decay, and have the same geology as native material if possible (Doll et al., 2003).

Figure 3.14 Two examples of rock partial span vanes. A single arm vane from restoration project 7 (a) and two single arm vanes from restoration project 31 (b).

PSVs should be situated in the planform such that they are angled 20° to 30° to the upstream bank (Figure 3.15; MDE, 2000; Doll et al., 2003). When choosing bank angles, there is a tradeoff between smaller and larger angles. Larger bank angles will result in a greater lengths of downstream bank protection, but create a higher risk of scour and structure failure (Doll et al., 2003; Sotiropoulos & Diplas, 2014). Although smaller bank angles are associated with increased structure stability, in small streams small bank angles can cause flow deflection into the opposite bank (Sotiropoulos & Diplas, 2014).

The arm of PSVs should slope downwards from the streambank into the streambed, where the tip should be buried (MDE, 2000). Recommended arm slope ranges vary; for example, MDE (2000) recommends 3- 7%, Rosgen (2001) recommends 2- 7%, and Doll et al. (2003) recommends 2- 20%. Although previous literature (Rosgen, 2001) recommended the vane arm key into the bank at bankfull elevation, more recent design guidelines recommend lower key-in elevations such that maximum arm slopes are not exceeded (Doll et al., 2003).

General design guidance recommends that PSVs be keyed into banks ¼ to ½ of the bankfull channel width (Figure 3.15; Hickman, 2019). MDE (2000) recommends tying log single arm vanes five to six feet into the bank, rock PSVs two to three rocks into the bank, and rock j-hook vanes one to two rocks into the bank. It is also recommended that the arm of PSVs generally only occupy 1/3 of the bankfull width (MDE, 2000; VDSWC, 2004; Sotiropoulos & Diplas, 2014). However, for channels less than 20 ft. wide, the PSV arms may occupy up to 50% of the channel width (Doll et al., 2003). The depth of footers for PSVs should be determined based on the deepest depth of scour, which will occur closest to the bank where the total drop in water surface elevation will be greatest over the structure (Hickman, 2019). It is recommended that multiple layers of footers be used such that they extend to a depth 1.5 to 3 times the depth of scour (Hickman, 2019).

To enhance stability, footers should be placed such that they protrude in the downstream direction and are centered over the joint between the two underlying stones (MDE, 2000). See Figures 3.15 and 3.16 for illustrations of single arm vanes, a simple type of PSV.

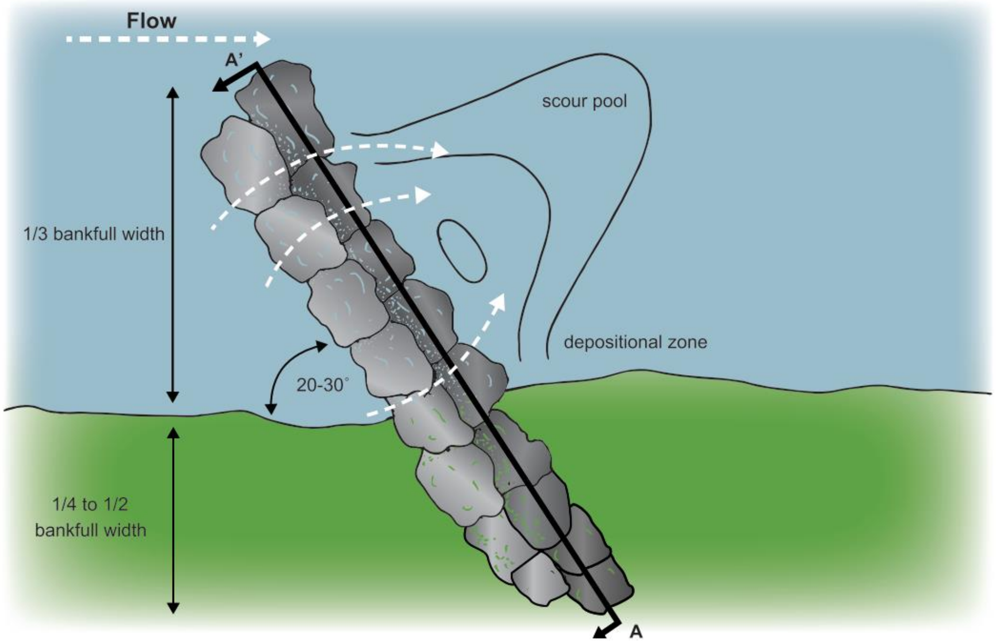


Figure 3.15 Plan view of a single arm vane (Hickman & Thompson, 2010).

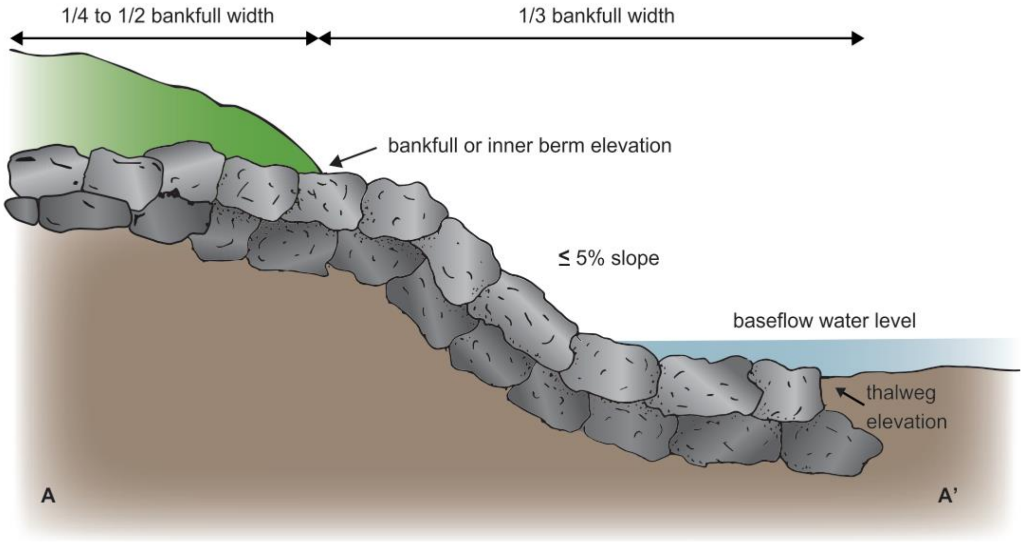


Figure 3.16 Profile view of a single arm vane, section A-A' in Figure 3.15 (Hickman & Thompson, 2010).

J-hook vanes are similar to single arm vanes, but include a sill that is usually slightly curved (Figure 3.17; Rosgen, 2001). Previous design recommendations recommended spacing the top row of stones by half the diameter of the rocks, to induce additional scour (MDE, 2000; Rosgen, 2001); however, this recommendation is no longer used in practice. Contemporary j-hooks have largely been replaced by modified j-hooks, a FSV, discussed in section 2.2.3. It is recommended that the upper-most sill rocks extend at most 10% of the bankfull depth above the channel bottom and that the underlying footers be at least three times this protrusion height deep below the streambed (MDE, 2000; Rosgen, 2001). Furthermore, an entire j-hook vane should occupy no more than 60% of the bankfull width (MDE, 2000). See Table 3.2 for a summary of design recommendations for PSVs, with respect to the variables considered in this study.

Figure 3.17 Two examples of rock j-hooks, including the sill portion of a j-hook from restoration project 28 (a) and a large j-hook from restoration project 35 where the sill is submerged (b).

It is recommended that PSVs be spaced by 5 to 7 channel widths when they are being placed for meander development or by 1 channel width when they are being used to create aquatic organism habitat (MDE, 2000). When protecting infrastructure, it is recommended that PSVs be placed 1.5 to 2 bankfull widths upstream of the infrastructure (Sotiropoulos & Diplas, 2014). PSVs, usually single arm vanes, can be placed in series along the outside of meander bends to provide meander protection and increase the durability of each structure (MDE, 2000; NRCS, 2007a). Sotiropoulos & Diplas (2014) recommend a vector-based spacing method when placing PSVs in meander bends, which is depicted in Figure 3.18. Using this method, the first PSV is placed at the apex of the meander bend and angled 20° to 30° to the tangent line of the apex of the meander. The second PSV is placed such that it is aligned with the tip of the previous vane, with respect to a 5° offset from the tangent line of the meander apex. If a third PSV is constructed, it is placed such that it is aligned with the tip of the second vane, with respect to a 20° offset from the tangent line of the meander apex (Figure 3.18).

Table 3.2 Summary of design recommendations for partial span vanes.

Structure Parameter	Value	Source
Key distance	1/3 bankfull width	Iowa DNR (2018c)
	15 ft.	MD NRC (2001)
	2- 3 rocks into bank (single arm vane) 1-2 rocks into bank (j-hook) 5 ft. (log structures)	MDE (2000)
Key angle	90°	VDSWC (2004)
Arm bank angle	20°- 30°	Brown (2000), MDE (2000), MD NRC (2001), Rosgen (2001), Doll et al. (2003), VDSWC (2004), Iowa DNR (2018c)
Arm normal distance	Maximum 1/2 bankfull width	Doll et al. (2003)
	1/3 bankfull width	VDSWC (2004), NRCS (2007a),Sotiropoulos & Diplas (2007a), Iowa DNR (2018c)
	1/4- 1/3 bankfull width	Brown (2000), Rosgen (2001)
	Maximum 1/4 bankfull width	MDE (2000), MD NRC (2001)
Arm slope	2- 20%	Doll et al. (2003)
	2-15%, 2-7% in larger systems	VDSWC (2004)
	2- 7%	Rosgen (2001), NRCS (2007a), Iowa DNR (2018c)
	3- 7%	MDE (2000)
J-hook sill length	1/3 bankfull width	Rosgen (2001), VDSWC (2004), Iowa DNR (2018c)
	4/15 bankfull width	MDE (2000)
Footer depth	3x sill protrusion height (gravel/ cobble bed)	Rosgen (2001)
	6x sill protrusion height (sand bed)	Doll et al. (2003)
	1-2 tiers of rocks	MDE (2000)
Boulder size	2.5 ft. minimum diameter 200 lb. minimum	MDE (2000)
	Generally 1-2 tons in gravel-cobble bed streams	Doll et al. (2003)
	2-4 ft. typical diameter	MD NRC (2001)
	Minimum b-axis of 1.5 ft.	VDSWC (2004)

PSVs have a high risk of failure because they are constructed in the active channel, as a result, they are best used purposely to protect infrastructure or provide erosion control (Hickman, 2019). Common failure mechanisms for PSVs include undermining, flanking, and displacement of rocks (Radspinner et al., 2010). To ensure stability of these structures, PSVs should not be constructed in channels with exposed bedrock, slopes greater than 3%, high sediment or debris loads, or where channel migration is desired (MDE, 2000; Doll et al., 2003; Hickman & Thompson, 2010).

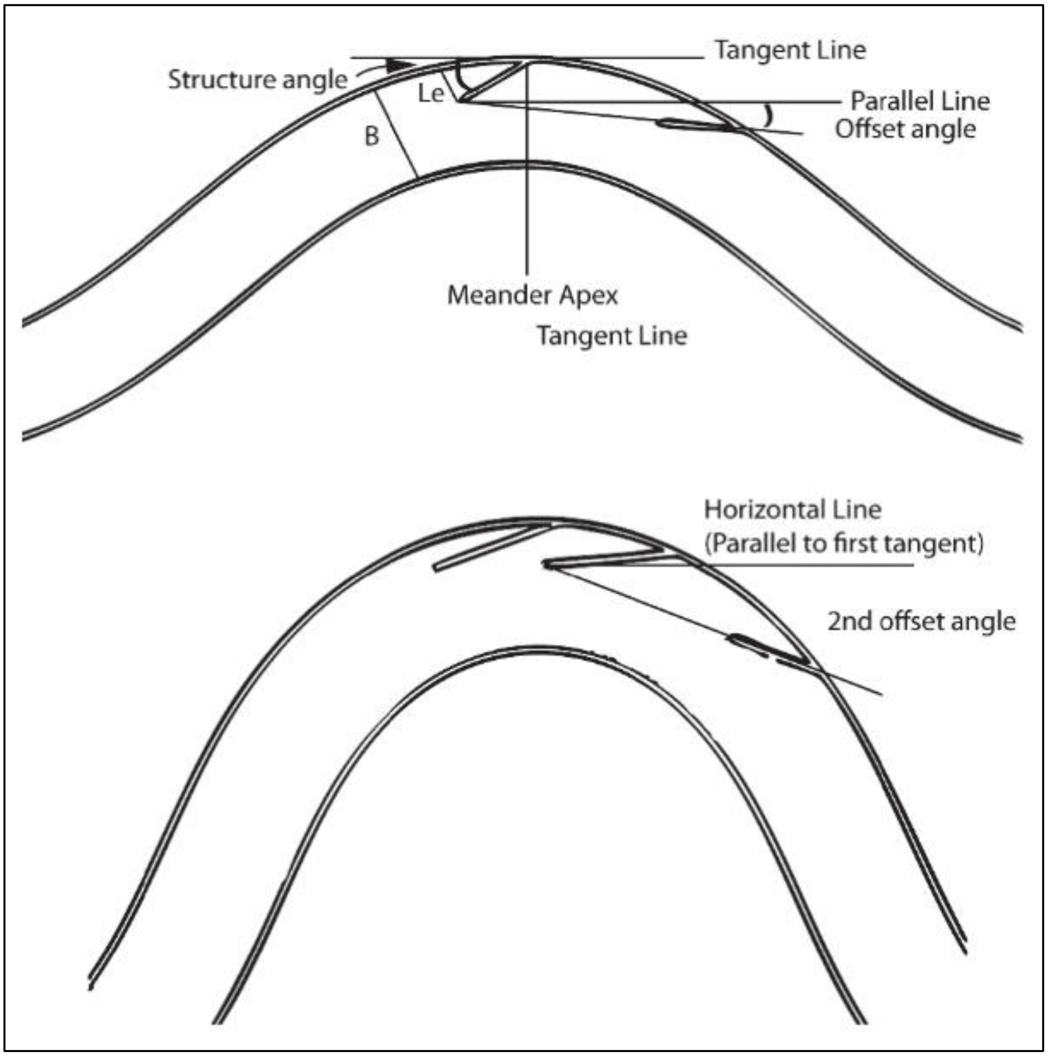


Figure 3.18 Illustration of vector-based spacing method from Sotiropoulos & Diplas (2014).

3.1.4 Constructed Riffles

Constructed riffles (RFs) are instream structures constructed on or at the channel bed out of substrate. Sometimes RFs are constructed with larger rock on the upstream and/or downstream end of the structure to provide stabilization. RFs are often designed based on natural riffles, which are a stream bedform that occur in conjunction with pools (Doll et al., 2003). Riffles typically occur in streams with slopes of 0.001-0.02 and occur periodically, alternating with pools, every 5 to 7 channel widths (Figure 3.19; Montgomery & Buffington, 1997; Walker, 2002).

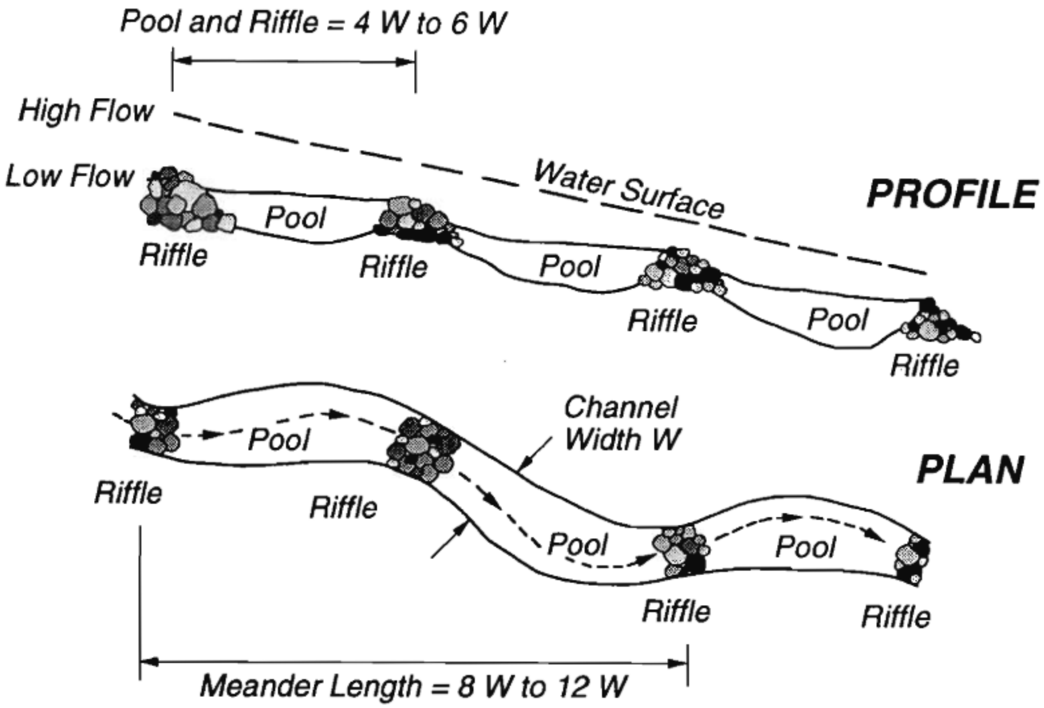


Figure 3.19 Profile and plan-view of riffle-pool morphology (Newbury et al., 1997).

Natural riffles are characterized by coarser bed substrate, shallower flows, and steeper water surface slopes than pools (Doll et al., 2003). Riffles account for a considerable amount of the hydraulic diversity where they occur by creating standing waves, hydraulic jumps, and backwater regions (Radspinner et al., 2010). Moreover, turbulence associated with riffles causes oxygenation of the water that flows over them (Figure 3.20; Radspinner et al., 2010). The sediment transport behavior at riffles differs at low and high flows. It is theorized that low flows winnow fine material from the surface of riffles, depositing it in pools, while high flows scour pools, leading to the deposition of sediment on the surface of riffles, a phenomena referred to as velocity reversal (Walker, 2002; Hassan et al., 2021). Riffles have considerable habitat value: riffles are the most productive habitat for benthic macroinvertebrates and are utilized by some species of fish for spawning (Walker, 2002; Doll et al., 2003).

3.1.4.1 Purpose

Because natural riffles can take between 10 and 100-years to reestablish, RFs are frequently used to rapidly restore bed conditions where natural riffles have been disturbed or are nonexistent (Walker, 2002). The purpose of RFs is to provide habitat, usually for fish spawning but also for macroinvertebrates, and to provide bed stabilization or protect structures that are located under the channel bed (Walker, 2002). RFs

Figure 3.20 A riffle located along the Rapidan River in Virginia.

have a significant effect on channel hydraulics and can be responsible for between 50 to 100% of the energy dissipation through a reach by creating form and grain roughness (Walker, 2002). At high flows, RFs do not become washed out and still provide significant flow resistance (Walker, 2002). Due to their roughness, RFs can also be used to increase water elevations and encourage overbank flows during high discharges (Walker, 2002). RFs can also be installed to regulate sediment transport and provide grade control (Iowa DNR, 2018a). As a result, constructed riffles can be used to significantly increase the stability of constructed channels, as compared to uniformly graded channels (Newbury & Gaboury, 1993).

3.1.4.2 History and Earliest Instance

RFs were first utilized to restore the spawning locations for anadromous fish where habitat had been lost (Watershed Restoration Program, 1997). One of the earliest instances of RFs was constructed in Scotland during the mid-1950s, as described by Newbury (1995), wherein practitioners dumped gravel into a newly-diverted stream channel every 5-7 channel widths resulting in a riffle-pool channel after a few flood seasons. In the United States, RFs were first utilized by practitioners on the west coast (Watershed Restoration Program, 1997). However, practitioner surveys indicate that RFs are a common instream structure with widespread use throughout the entire United States (Radspinner et al., 2010).

3.1.4.3 Current Design

Given that RFs are typically constructed to recreate well-developed, natural riffles, they can be designed based on existing riffles in the reach of interest or a reference reach (Newbury & Gaboury, 1993). Ideally, RFs should replicate reference reach flow, substrate, cover, and channel conditions to maximize the habitat value they provide (Watershed Restoration Program, 1997). Given that RFs affect channel hydraulics and bed elevation, their effect on upstream and downstream pools should be considered (Newbury & Gaboury, 1993). Moreover, sequences of RFs should be constructed so that their crests follow the channel slope (Newbury & Gaboury, 1993).

RFs are typically constructed out of some bed substrate analog such as bed material from the reach of interest, bed material from an outside reach, or quarried rock. For channels with floodplains, this substrate should be sized to resist movement at bankfull discharge (Watershed Restoration Program, 1997). A good rule of thumb when constructing riffles is to use a range of rock sizes that would naturally occur in riffles, and size the D_{50} to be stable during some maximum permissible flow depth (Walker, 2002). Newbury et al. (1997) recommended riprapping channel banks adjacent to RFs to enhance stability. This element of design guidance should be considered carefully, especially when habitat improvement is an objective, because riprapped banks are associated with reduced stream function and habitat value (Baird et al., 2015). Figure 3.21 shows RFs that utilized bank armoring, while Figure 3.22 shows constructed riffles that did not utilize bank armoring.

Figure 3.21 Two examples of constructed riffles that included armor on the adjacent banks. Constructed riffle from restoration project 10 that is experiencing bank erosion on the adjacent banks, despite large rocks that were placed to provide armoring (a). Constructed riffle from restoration project 18 that utilized the same substrate to construct the riffle and the bank armor (b).

The average recommended riffle spacing is 5-7 channel widths in streams below 2% slope and 2- 4 channel widths in steeper channels, 2- 4% slopes, or where channel obstructions are common (Walker, 2002). When determining RF placement, the location of weakly developed riffles or existing pools should be strongly considered (Watershed Restoration Program, 1997; Walker et al., 2004).

RFs should span the entire channel width over their length (Walker, 2002). The length of RFs can be estimated from natural riffles (Walker, 2002). However, general guidelines of their length are between 1 and 3 channel widths (Walker, 2002) or 1 to 4 channel widths (Iowa DNR, 2018a). RFs have a triangular cross section along the thalweg, with a crest and slopes on either side (Figure 3.23; Walker, 2002). The crest of RFs may be constructed out of larger rocks to increase structure stability (Walker, 2002). The elevation of this

Figure 3.22 Two examples of RFs that did not utilize armor on the adjacent banks. Constructed riffle from restoration project 9 (a). Constructed riffle from restoration project 28 that is constructed directly upstream of a cross vane that is providing stabilization (b).

crest will affect channel hydraulics most, therefore it should not be so high that it results in undesired losses in channel capacity or causes excessive backwatering upstream (Watershed Restoration Program, 1997). Generally, RFs should still permit the conveyance of bankfull flows through the channel with the assumption that flow is critical at some point over the riffle (Froude number = 1; Newbury et al., 1997). Equation 3-1 allows calculation of the maximum crest height that will contain a discharge of interest, given channel geometry (Walker 2002):

$$\Delta_{max} = Y_b + \left(\frac{q^2}{2gY_b}\right) - \frac{3}{2}\left(\frac{q^2}{g}\right)^{\frac{1}{3}} \tag{3-1}$$

where Δ_{max} is maximum crest height (m); Y_b is maximum upstream water depth or bank height (m); $q = Q/W$ and is the design unit discharge (m^2/s); W is channel width (m); and g is gravitational acceleration (m/s^2; Figure 3.23). When solving Equation 1, conditions should correspond to subcritical flow in the channel (Walker, 2002). Pasternack & Brown (2013) considered RF amplitude, the distance between the riffle crest and bottom of the pool, and found that an amplitude less than 2.5 ft. (0.75 m) or amplitude/D_{50} of approximately 10-12 maximized habitat creation and enhancement for salmon. The crest, as well as the entire RF surface, should be v-shaped to ensure flows remain centrally concentrated (Walker, 2002). The "dip" between the highest point of the crest and lowest point, the apex depth, should generally be between 1 and 2 ft. (0.3 and 0.6 m; Walker, 2002). Alternatively, the recommended slope from the bank to the apex depth of a RF is between 3:1 and 2:1 (Iowa DNR, 2018a).

Although the slope of RFs should be based on what would be appropriate in a given stream, an average slope of the downstream riffle face is 4%. The downstream slope of RFs should generally be below 10%, but slopes as high as 17% have been observed in the field (Walker, 2002). Furthermore, the upstream face of the RF should have a steeper slope (between 25% and 100%) than the downstream face to encourage sediment deposition on the crest and downstream face (Walker, 2002).

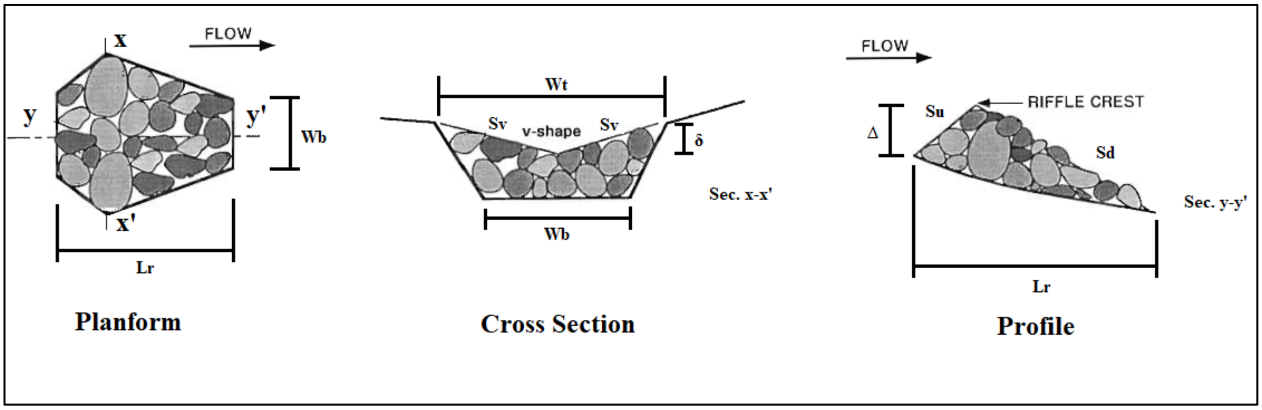


Figure 3.23 Illustrations of constructed riffles with dimensions adapted from designs in Newbury et al. (1997) where L_r is riffle length, W_b is bottom width, Δ is crest height, S_u upstream face slope, S_d is downstream face slope, $\boldsymbol{\delta}$ is apex depth, W_t is top width, and S_v is side slope.

3.1.5 Regenerative Stream Conveyance

Regenerative stream conveyance (RSC) is an instream best management practice (BMP) that consists of alternating riffle-weirs and pools underlain by infiltration media (Flores et al., 2012). RSCs are also referred to as regenerative stormwater conveyances, coastal plain outfalls, and sand seepage wetlands (MD DNR, 2018). Development of this management practice was the result of new stormwater regulations in the state of Maryland that stressed environmental site design (Flores et al., 2009). These new regulations led to more widespread adoption of BMPs that encouraged stormwater infiltration, including rain gardens, bioretention cells, and grassed waterways (Flores et al., 2009). As a result, RSCs are most widely implemented in the mid-Atlantic United States (Duan et al., 2019).

RSCs were originally developed in Maryland as a way to remediate highly incised outfall channels that had previously been addressed using trapezoidal concrete channels or riprap (Flores et al., 2009). RSCs constructed to address degraded outfalls are referred to as dry channel RSCs and are better described as a stormwater retrofit than a stream restoration practice, since they are installed in ephemeral channels downstream of stormwater outfalls (Berg et al., 2013). Use of RSCs was expanded to perennial or intermittent streams to increase floodplain access for flow events below the 1.5-yr recurrence interval and to create stream and wetland complexes, referred to as wet channel RSCs (Berg et al., 2013). Given the project focus on structures used in the restoration of predominantly perennial streams, dry channel RSCs were not evaluated. All further reference to RSCs refers only to wet channel RSCs.

3.1.5.1 Purpose

RSCs are designed to keep water on site for as long as possible by slowing it down and spreading it across the floodplain, which is accomplished by the riffle-weirs and berms on the floodplain (MD DNR, 2018).

RSC riffle-weirs are constructed at elevations that detain water on the floodplain and utilize berms perpendicular to streamflow, constructed to span the floodplain adjacent to each riffle-weir (Figure 3.24; MD DNR, 2018). Furthermore, vegetation and the roughness of the weirs slow the water as flow moves through the system (MD DNR, 2018). Increasing floodplain access has positive hydrologic functions including increased groundwater recharge, support of riparian vegetation, and increased biogeochemical processes (MD DNR, 2018). RSCs further encourage biogeochemical processes, which occur in the pools or the infiltration media that underlies the entire system (MD DNR, 2018). RSCs also increase energy dissipation and sedimentation (Flores et al., 2012).

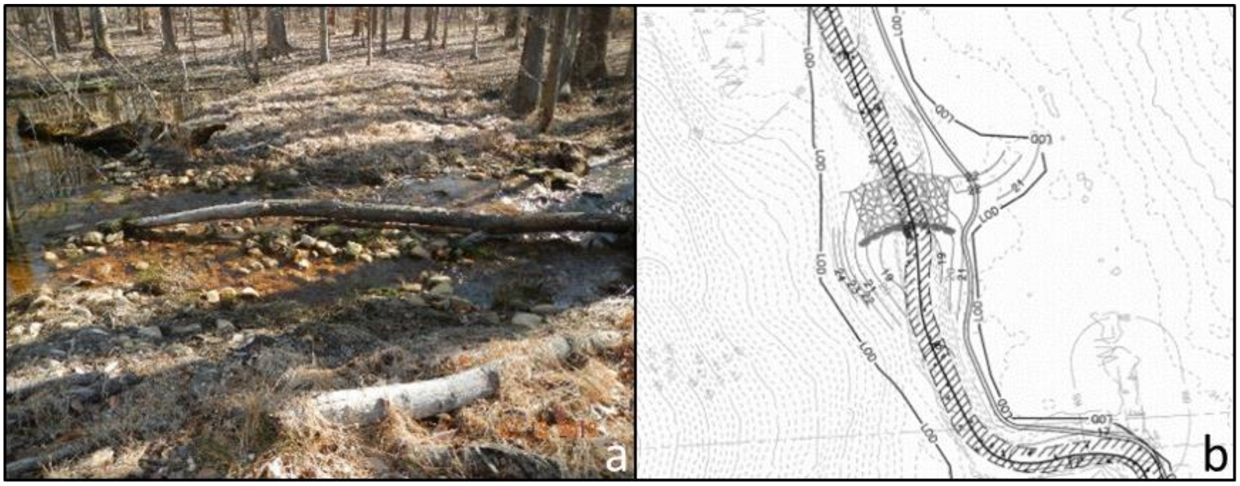


Figure 3.24 Regenerative stream conveyance weir and floodplain berm (a) with the corresponding design plan from restoration project 23 (b). In the photograph, water is flowing from left to right and can be seen on the floodplain detained behind the berm.

3.1.5.2 Current Design

RSCs are typically constructed for watershed areas between 10- 30 ac., but are rarely used in watersheds exceeding 50 ac., due to limitations related to cost and material sizing (WV DEP, 2012). These structures can be constructed in three contexts. In high gradient channels, where slopes exceed 2%, RSCs can mimic the energy dissipation function of natural step pool or cascade bedforms (Figure 3.26; Flores et al., 2012). High gradient RSCs are often employed to remediate highly incised streams that have formed deep gullies (Flores et al., 2012). In lower gradient channels, where slopes are less than 2%, RSCs are installed to accommodate baseflow discharges and convey and disperse high discharges by spreading them over the floodplain (Flores et al., 2012). Finally, RSCs can be constructed as isolated riffle-weirs that encourage sedimentation in the main channel and slowly restore floodplain connectivity by raising the channel bed (Flores et al., 2012). Although they can be adapted for steeper slopes, RSCs are not recommended where slopes exceed 10% (Flores et al., 2012). Where channel slopes exceed 5%, it is recommended that cascades be installed, followed by three riffle-weir pool sequences (Flores et al., 2012; WV DEP, 2012).

The riffle-weirs consist of an upstream slope, riffle, and a downstream slope (Figure 3.25; Flores et al., 2012). Cobbles are placed on the riffle portion of the weir and sometimes on the upstream slope which is referred to as a cobble apron (Flores et al., 2012; MD DNR, 2018).

Figure 3.25 A high gradient regenerative stream conveyance (RSC) structure at restoration project 6 (a) and a low gradient RSC sequence at restoration project 6 (b).

The downstream slope of the riffle-weir consists of large rocks that form a weir/ crest and footer rocks (Figures 3.26 and 3.27; Flores et al., 2012; MD DNR, 2018). The cobbles used to construct the apron and riffle of an RSC weir should be at least 6 in. in diameter but sized to resist the anticipated hydraulic forces (Flores et al, 2012). Riprap between 9.6 in. and 13.2 in. can be used in place of cobble (WV DEP, 2012). The thickness of the layer of particles used to construct the apron and riffle should be twice the D_{50} of those particles (Flores et al., 2012). The apron on the upstream slope of the riffle-weir should be a minimum of 4 ft. long (Flores et al., 2012), while riffle should be a maximum of 8 ft. and a minimum of 20 ft. in width (Flores et al., 2012; WV DEP, 2012). Finally, following placement of riffle rocks, gravel and sand should be washed into the riffle-weir to fill any voids (MD DNR, 2018).

The weir/ crest should be constructed out of boulders that are at least 3-4 times heavier than the riffle material, and at least 2 ft. in diameter (Flores et al., 2012). Sandstone is recommended for RSCs constructed in the coastal plain, while granite or silica stones can be used in other regions (Flores et al., 2012). Limestone and other cemented stones are not recommended for use due to risk of degradation over time (Flores et al., 2012). The weir crest should be curved upwards towards the bank at approximately 20°, tying into the bank at or one foot below the floodplain elevation and extending into the bank a distance of at least 2 ft. (Flores et al., 2012; MD DNR, 2018). Unlike other instream structures where footers are placed directly below other large stones and function as a foundation, the footers of an RSC crest should be angled along the downstream slope of the riffle-weir such that they hold up the crest boulders and are generally exposed to flow (Flores et al., 2012). Multiple layers of footers should be used below the crest rocks and should tie into the pool at least two feet below its lowest point (Flores et al., 2012). Furthermore, footers should maintain the parabolic shape of the crest (MD DNR, 2018). Acceptable footer materials can be roughly 26.4 in. in diameter or smaller where shear stresses are lower (WV DEP, 2012).

RSC pools should be at least twice as long as the upstream weir (Flores et al., 2012). Although pool width should be maximized, pools should be at least the width of the upstream weir and can be irregularly shaped with depths between 1.5 ft. and 3 ft. (Flores et al., 2012; WV DEP, 2012; MD DNR, 2018).

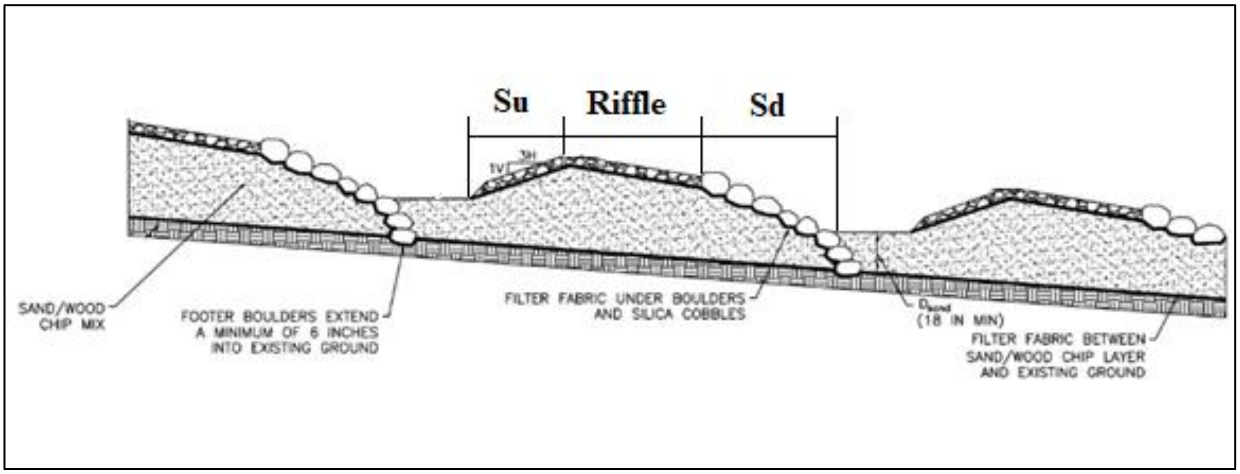


Figure 3.26 Longitudinal view of regenerative storm conveyance sequence with an upstream slope/cobble apron (Su), a cobble riffle (Riffle), and a downstream boulder weir and footers (Sd; Greenville County, SC, 2018).

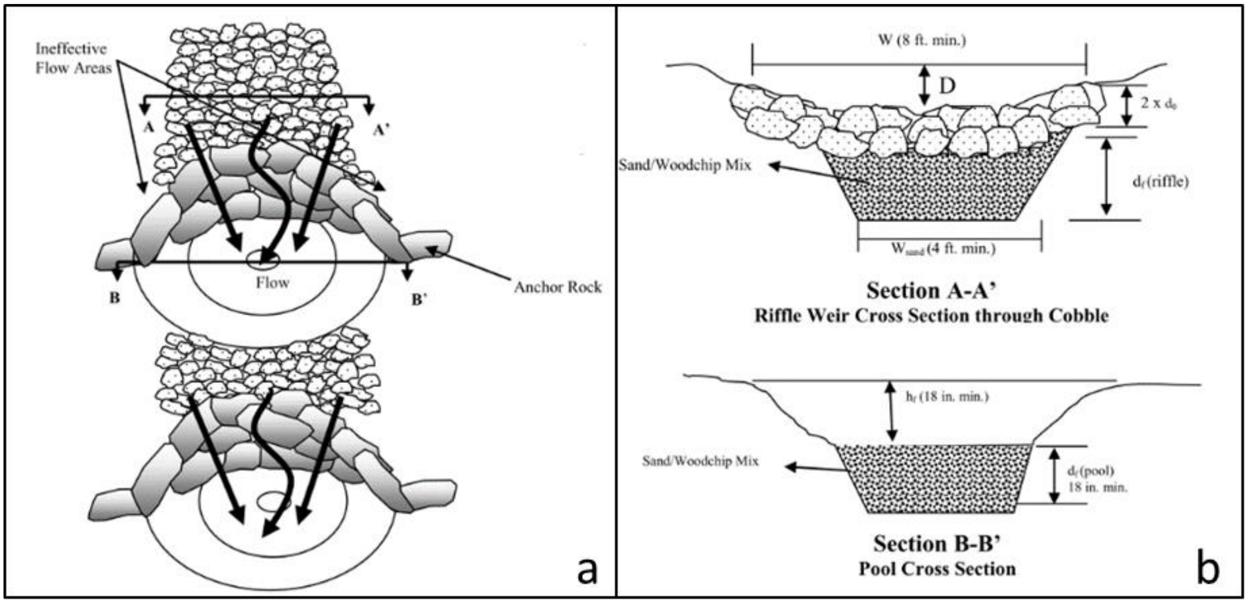


Figure 3.27 Regenerative stream conveyance plan view (a) and cross sections (b; Flores et al., 2012).

Furthermore, pool side slopes should be at most 3H:1V if unarmored or lined with concrete sand, and the longitudinal slope through the pool should not exceed 1% (Flores et al., 2012; WV DEP, 2012; MD DNR, 2018).

The entire RSC system should be underlain by infiltration media consisting of organic matter and sand (MD DNR, 2018). Given that RSCs are often constructed to raise the bed of incised channels, this infiltration media is employed as fill in the existing channel during construction (MD DNR, 2018). When filled with infiltration media, the channel itself can be utilized as the haul road for the project wherein construction occurs from downstream to upstream causing minimal disturbance to the floodplain (MD DNR, 2018). This infiltration media also benefits water quality by encouraging hyporheic and biogeochemical processes (MD DNR, 2018). The ratio of organic matter to sand in the infiltration media should be 1:4 by volume, and it should be spread with a minimum width of 4 ft. and minimum depth of 1.5 ft. (Flores et al., 2012). The sand used in this mix should be between 0.02 and 0.04 in. in diameter and be silica-based; rock dust should not be used (WV DEP, 2012). Wood chips are recommended as the source of organic matter for the infiltration media because they leach less dissolved organic carbon, phosphorus, and nitrogen compared to more easily decomposed organic matter (e.g., leaf litter; Duan et al., 2019). Slow-decomposing organic matter in the infiltration media is also beneficial because it gives the riparian system more time to adjust to the RSC and contribute carbon to the system (Duan et al., 2019). Finally the sand and organic matter should be added in layers, rather than a mix, to encourage heterogeneity of the hyporheic zone (MD DNR, 2018). When installing RSCs, notice should be taken of the natural soil properties. Where stratified lenses of gravel or sand are observed, they should be mimicked as the channel is filled (Flores et al., 2012).

Berms are the final component that RSCs can include, typically in wider valleys. Berms should extend outwards from where the riffle-weirs tie into the banks and continue along the floodplain perpendicular to streamflow until they reach natural topographic elevations (Figure 3.27; MD DNR, 2018). To minimize the risk of failure, the berms should be flat and broad with a top width of at least 3 ft. (MD DNR, 2018). These berms should not be constructed out of silty material, should be covered in woodchips, and should be vegetated to minimize the risk of failure (MD DNR, 2018).

Finally, certain general practices are recommended when designing RSCs. Disturbance of existing riparian vegetation should be minimized (MD DNR, 2018). To ensure proper drainage, it is recommended that pools drain to their design depth within 72 hours of storm events (WV DEP, 2012). Finally, it is recommended that RSCs be stable and capable of conveying 100-yr discharges without risk of failure (WV DEP, 2012).

3.1.6 Step Pools

A geomorphic feature of natural streams, step pools (SPs) typically occur where channel slope exceeds 3% and bed material consists of boulders and gravel (Johnson et al., 2002). When used in stream restoration, SP structures consist of alternating sills and pools where the step sills are composed of boulders or logs and pools have finer materials such as sand, gravel, or cobbles (MDE, 2000). Typically, SPs are constructed in sequences but can be constructed in isolation to dissipate energy and provide grade control. Figure 3.28 depicts two examples of SPs.

3.1.6.1 Purpose

SPs can be constructed to restore natural bed conditions, but are frequently used to rehabilitate incised channels that have been affected by urbanization or land use change (Chin et al., 2009). Like natural SPs, constructed SPs provide grade control, energy dissipation, and channel stabilization (MDE, 2000; Doll et al., 2003; VDSWC, 2004; Iowa DNR, 2018). SPs are also effective for creating instream habitat, particularly in ephemeral and intermediate streams because the pools hold water when the channel would otherwise be dry (MDE, 2000; Iowa DNR, 2018a). Constructed SPs are effective for remediating incised streams because they convey water over steep slopes, eliminate large drops, and allow aquatic organism passage (Chin et al., 2009).

Figure 2-28 Two examples of step pools from restoration project 4 (a) and 28 (b).

3.1.6.2 Current Design

SP channels should be constructed where they are geomorphically appropriate, typically streams where slopes are between 3 and 6.5% (MDE, 2000; Iowa DNR, 2018a). Where slopes exceed 6.5%, streams are more likely to trend towards cascade bedforms, which still have large in-channel obstructions but lack defined sills (MDE, 2000). Generally, it is recommended that SP sequences have a pool spacing between 1 and 4 channel widths (MDE, 2000; VDSWC, 2004) or 0.5 and 4 channel widths (Iowa DNR, 2018a). Moreover, Iowa DNR (2018a) recommends that roughly 70% of total SP length correspond to pools and roughly 30% correspond to sills.

Ratio of mean steepness is another parameter used to design SPs, which is the ratio between SP slope and channel slope (MDE, 2000). Ratio of mean steepness is found using by Equation 3-2 (MDE, 2000):

$$Ratio\ of\ Mean\ Steepness = \frac{\left(\frac{H}{L}\right)_{avg}}{S} \tag{3-2}$$

where H is step distance (ft.), L is the length between those steps (ft.), and S is the channel slope (ft./ft.). Generally, a ratio of mean steepness between 1 and 2 is recommended for SP channels (MDE, 2000; VDSWC, 2004). Given that steps/sills are subject to considerable hydraulic forces, sill height and particle size should positively correlate with one another (Chin et al., 2009). Sill stones should be sized with respect to the hydraulic forces to which they will be subjected; a rule-of-thumb is the b-axis of stones should be 1- 1.5 times the step height (Chin et al., 2009). Moreover, SP sills should be constructed with 1 to 2 layers of footers to mitigate the risk of undermining (MDE, 2000). It is also recommended that SP sill key into the bank 2 ft. (VDSWC, 2004; Iowa DNR, 2018a). In flume studies, it was noted that 90% of SP failures were the result of failure of the front-most keystone that supported the rest of the sill stones (Zhang et al., 2018). During construction, care should be taken the ensure the stability of this front-most footer rock (Figures 3.29-30).

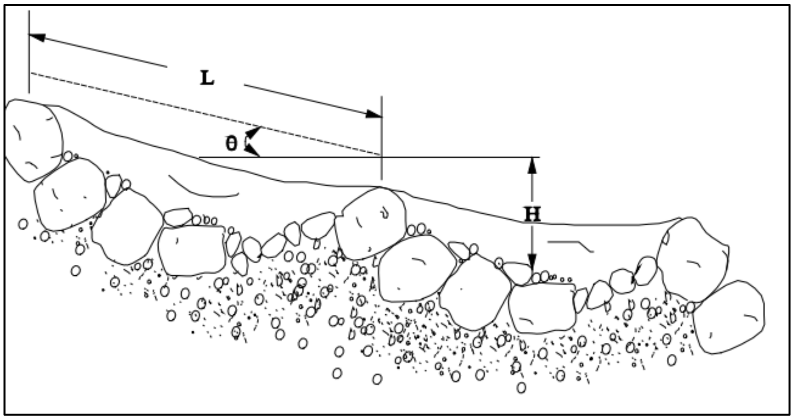


Figure 3.29 Profile view of a step pool where L is the length between steps, Θ is the channel slope, and H is the step distance (MDE, 2000).

3.2 Instream Structures Methods

Structures within 39 projects in the Maryland Piedmont and Coastal Plain were evaluated (Figure 3.31). These projects were chosen to have diverse characteristics including age, location, watershed size, and design approach. Projects with significant tributaries were subdivided such that the tributaries were treated as separate projects from the mainstems.

Field assessments took place during the Spring of 2019 and Winter of 2020. Structure type was recorded, then each structure was evaluated in three areas of potential success: structural stability, impact on sediment transport, and function (Table 3.3). The “structural stability” category consisted of two subcategories, “percent remaining” and “material movement,” which corresponded to two subcategory scores: *ScorePCTRemain* and *ScoreMatMove*. The “sediment transport” category consisted of two subcategories, “unintended aggradation” and “unintended erosion or scour,” which corresponded to two subcategory scores: *ScoreErosion* and *ScoreAggrad* (Table 3.3). The “function” category did not consist of any subcategories, and structures were rated based on a single score: *ScoreFunction* (Table 3.3). The importance of each of these three categories on structure success was deemed equally important, so they were given equal weight and used to develop a final, overall score (*ScoreOverall*) ranging from 0-18 to quantify the performance of each structure. *ScoreOverall* was used as the main response variable in statistical analyses, but analyses were also performed using scores in each of the five subcategories (Table 3.3).

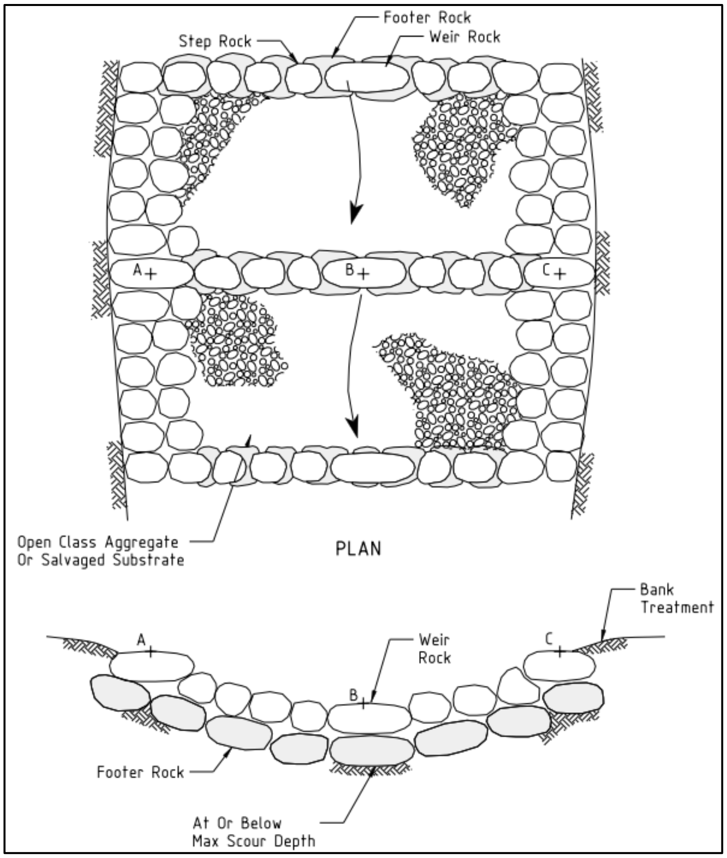


Figure 3.30 Plan view (top) and cross section (bottom) of a step pool (VDSWC, 2004).

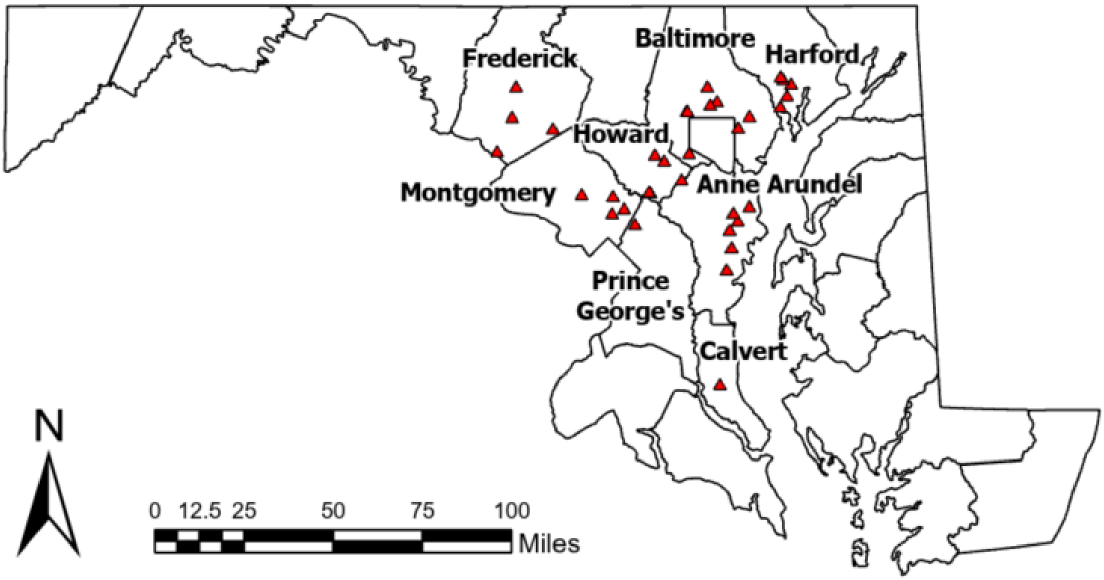


Figure 3.31 Selected project locations in Maryland.

Table 3.3 Structure assessment methodology.

Category	**Subcategory**	**Scoring System**	
		Score	**Criteria**
Structural stability	Percent remaining (*ScorePCTRemain*)	3	75- 100% remaining
		2	50- 75% remaining
		1	25- 50% remaining
		0	0 – 25% remaining
	Material movement (*ScoreMatMove*)	3	Significant
		2	Moderate
		1	Slight
		0	None
Sediment transport	Unintended erosion or scour (*ScoreErosion*)	3	Significant
		2	Moderate
		1	Slight
		0	None
	Unintended aggradation (*ScoreAggrad*)	3	Significant
		2	Moderate
		1	Slight
		0	None
Function	Function (*ScoreFunction*)	6	Yes
		3	Partially
		0	No

Structures had a range of predictor variables subdivided into structure-, project-, and watershed-scale variables (Appendix B, Table B.1). Structure-scale predictors encompassed data about each structure related to the construction, geometry, and relationship to other structures. Structure-scale data about each structure were gathered from engineering design plans. Project-scale and watershed-scale data were gathered as part of a previous project from engineering design plans and using ArcMAP (ESRI, Redlands, WA). Project-scale data included properties of the restoration project reach related to flow energy, erosion resistance, and design approach. Watershed-scale data considered properties of the project watershed that could influence flow energy or erosion resistance of the channel boundaries. While structure-scale predictors varied for each structure, project- and watershed-scale predictors were the same for all structures within a given restoration reach.

Preliminary data analyses were performed to determine the average subcategory scores for log and rock structures in each structure family. Single- and multi-variate linear regression analyses were used to determine the relationships between structure-scale predictors and *ScoreOverall*. Linear mixed-effects models were used to determine the relationship between project- and watershed-scale predictors and *ScoreOverall*, with *Project* as a random effect (Harrison et al., 2018).

3.2.1 Structure Assessment

To assess structure success, three main questions were considered:

1. Is the structure intact?
2. Is the structure causing unintended erosion or sedimentation?
3. Is the structure functioning effectively in the context of the overall project?

The "structural stability" structure assessment category evaluated whether structures were intact and consisted of two subcategories bu which structures could be scored: "percent remaining" and "material movement" (Table 3-1). Both "structural stability" subcategory scores, *ScorePCTRemain* and *ScoreMatMove,* could be between 0 and 3 (Table 3.3). *ScorePCTRemain* was used to quantify the amount of the structure that was remaining in the channel. The highest value of *ScorePCTRemain* was a 3 which corresponded to 75-100% of the structure remaining in the channel, while a 2 corresponded to 50-75%, a 1 corresponded to 25- 50%, and 0 was the lowest score, which corresponded to 0-25% of the structure remaining in the channel (Table 3.3). *ScoreMatMove* was used to quantify the removal or shifting of materials from the structure that had or could lead to structure failure or impaired function. *ScoreMatMove* ranged from 0 to 3 and corresponded to the degree of material movement: significant (0), moderate (1), slight (2), or none (3; Table 3.3).

The "sediment transport" structure assessment category assessed whether structures were causing unintended aggradation or erosion and consisted of two subcategories were structures could receive a score between 0 and 3: "unintended erosion or scour" and "unintended aggradation" (Table 3.3). The "unintended erosion or scour" subcategory score, *ScoreErosion*, was used to quantify the degree to which a structure had caused or been compromised by unintended erosion of the channel boundaries. The "unintended aggradation" subcategory score, *ScoreAggrad*, was used to quantify the degree to which a structure had caused or been compromised by the unintended deposition of sediment. The sediment assessment of a structure related to the specific function of each structure family. For example, a cross vane, which is expected to have the sill flush with the upstream channel bed and a downstream scour pool, would lose points if these features had not been developed or maintained. *ScoreErosion* and *ScoreAggrad* could be between 0 and 3 and corresponded to the degree to which unintended aggradation or erosion had occurred: significant (0), moderate (1), slight (2), or none (3; Table 3.3).

Finally, the "function" assessment category evaluated whether structures were functioning in the overall context of the project and included no subcategory. The function subcategory score, *ScoreFunction*, could be 0, 3, or 6 and corresponded to the qualitative ratings of "no," "partially," or "yes," respectively, depending on whether a structure was serving its intended purposes. *ScoreFunction* was determined using knowledge about structure purpose within the context of a project. For example, cross vanes are designed to provide grade control so a cross vane would be given a "no" if it was not providing grade control.

Given this scoring system, structures were assessed based on "structural stability", "sediment transport", and "function" and could receive a score between 0 and 6 in each of these categories. The overall structure, *ScoreOverall*, ranged from 0 to 18 and was developed by taking the sum of all subcategory scores (*ScorePCTRemain*, *ScoreMatMove*, *ScoreErosion*, *ScoreAggrad*, and *ScoreFunction*).

3.2.2 Explanatory Variables

Explanatory variables for this project were subdivided into watershed-, project-, and structure-scale predictors (Appendix B, Table B.1). Watershed- and project-scale predictors were the same for all structures from a given reach. Watershed-scale variables described properties of a watershed that related to flow energy and erosion resistance. Project-scale variables described properties of a design reach related to flow energy, erosion resistance, and design approach and were determined from engineering design plans and as-builts using ArcMap. Structure-scale explanatory variables were unique to each structure and varied depending on the structure family. Structure-scale predictors were obtained from engineering as-built drawings or design plans for each project and described how structures were constructed, their geometry, and their position in the channel with respect to other structures and channel morphology.

3.2.2.1 Watershed-scale Variables

Watershed-scale explanatory variables are summarized in Appendix B, Table B.2. Where appropriate, these variables were scaled to channel size as listed in Table B.3.

Best management practice (BMP) density was included as an explanatory variable because stormwater BMPs attenuate the release of runoff to natural systems. Increased BMP density was predicted to have a positive effect on structure performance by reducing stormwater volume and peak flows. Furthermore, stormwater requirements in the state of Maryland have been increasing since 1985 and rapidly expanded the use of environmental site design in the late 1990s, which employs a large number of smaller practices (Flores et al., 2009; Withers, 2019). BMP density was developed by dividing the total number of BMPs in a watershed by the area of high and medium density development (*BMPDens*). It was predicted that higher *BMPDens* would correspond to newer developments where smaller, more distributed practices were employed, as compared to older development which may not have had stormwater management or used fewer, larger BMPs. Thus, we predicted that structures located within watersheds with higher *BMPDens* would have increased performance because of greater runoff attenuation.

Watershed soil erodibility was determined using the soil erodibility K-factor from the second revised universal soil loss equation (RUSLE2) and area-averaging the erodibility of all soils within a watershed (*AreaK*). We predicted that greater *AreaK* would correspond to increased fine sediment supply to a stream, which was predicted to increase the risk of structure aggradation.

Drainage network stream bank soil erodibility was also determined using the K-factor from RUSLE2, but was calculated by averaging only the streambank erodibility of all tributaries draining to a project reach (*DrainageK*). Like *AreaK*, we predicted that greater *DrainageK* would correspond to greater sediment supply to a system due to increased likelihood of system-wise bank erosion, increasing aggradation risk. Furthermore, we predicted that increased *DrainageK* could also be correlated to increased local bank erodibility, increasing the susceptibility of structures to local erosion and scour.

Longest channel slope (*LongChSlp*) was the average slope from a project outlet to the farthest upstream first-order channel. We predicted that larger values of *LongChSlp* would correspond to increased channel flow energy, resulting decreased structure performance.

Land use was determined from the National Landcover Database from 2016 (NLCD 2016) using aggregations outlined by the Maryland 2008 land use category descriptions (Table 2.7; MDP, 2010). Land use was expressed as a faction of total watershed area used for the following categories: high density development (*FracHighDen*), medium density development (*FracMedDen*), low density development (*FracLowDen*), agriculture (*FracAg*), forest (*FracForest*), and open water/wetlands (*FracWater*). Specific information about these categories and their relationship to NLCD 2016 land use categories can be found in Table B.4. Land use within a watershed was included as an explanatory variable because of the impact of land use on watershed hydrology and stream sediment supply. We predicted that greater *FracHighDen* would correspond to lower structure scores, due to increased stormwater runoff and peak discharges. We also predicted that increased *FracForest* would correspond to greater structure performance due to decreased peak flow rates.

Percent change in land use since project completion was also calculated and used as a predictor variable corresponding to each of the aforementioned land use categories: high density development (*HighDenCh*), medium density development (*MedDenCh*), low density development (*LowDenCh*), agriculture (*AgCh*), forest (*ForestCh*), and open water/ wetlands (*WaterCh*). For land use change, two additional categories were developed using the other categories: urban (*UrbanCh*) and rural (*RuralCh*). *UrbanCh* corresponded to urban land use change, or the change in both high and medium density development in a watershed; this predictor aimed to give a more complete view of development in a watershed. *RuralCh* corresponded to rural land use change, or the change in forested, agricultural, and open water/wetlands and similarly aimed to give a complete view of changes in areas within a watershed where water would be slowed or infiltrated. It was predicted that structure performance would decrease as *UrbanCh* increased and *RuralCh* decreased.

3.2.2.2 Project-scale Variables

Project-scale explanatory variables are summarized in Table B.5. Similar to the watershed-scale variables, project variables were scaled to the channel size (Table B.3).

Two project-scale variables were categorical: design approach and Rosgen channel type (NRCS, 2007g). Design approach (*DesignApproach*) was the design approach of a project which was determined based on visual observations of project and included the following categories: natural channel design (NCD), regenerative stream conveyance (RSC), wetland restoration, and valley restoration. Rosgen channel type (*RosgenType*) was the Rosgen channel type of a project reach and was recorded for each stream if this information was documented in the design plans or report (NRCS, 2007g).

Year completed is the year a project was completed (*YearComp*), and gives insight into multiple factors that could influence the success of instream structures. Older projects would have more opportunity to establish vegetation and re-equilibrate following construction, both of which could influence the degree to which erosion was visible along the channel boundaries during the assessment. On the other hand, older projects would have a greater likelihood of having experienced high flow events that could negatively impact structure performance.

Project length is the length of stream restored as part of a stream restoration project (*ProjLen*) and describes both the extent of disturbance and restoration of a project. As a result, higher *ProjLen* could have a negative impact on structures due to the greater length of disturbance or a positive impact on structures by increasing the degree to which a structure was "insulated" within the restored system. *ProjLen* was expressed as a number of bankfull widths.

Project slope was calculated as the average slope between the two common stream features at the upstream and downstream end of the project (*MainChDSlp*), such as riffles or grade control structures. *MainChDSlp* was included as a project-scale variable because slope is one of the primary factors driving flow energy through a project reach. It was predicted that higher values of *MainChDSlp* would result in greater flow energies, causing decreased structure performance.

Flood prone width was the width of the floodplain at an elevation that was two times the bankfull depth above the deepest point in the channel (*Flood*). *Flood* indicated the floodplain width during high discharges. Systems with narrower floodplains (referred to as more confined) will have greater flow depths during high discharges, resulting in greater shear stresses along the channel boundaries per unit discharge. Smaller values of *Flood* were predicted to decrease structure performance. *Flood* was scaled using bankfull width to yield entrenchment ratio (floodprone width/bankfull width; Table B.5).

Design discharge is commonly used in stream restoration to represent the range of natural flow conditions that produce the stream morphology in a given reach. There are multiple methods that can be used to determine design discharge. Design discharge was only listed for some of the projects in this study, so bankfull discharge values were estimated using regional curves for the Maryland Piedmont (Cinotto, 2003) and Coastal Plain (Krstolic & Chaplin, 2007). These methods calculated bankfull discharge (*BFDisch*) using drainage area. It was predicted that higher values of *BFDisch* would correlate to increased likelihood of structure failure.

Sinuosity quantified the degree to which a stream meandered and can be calculated by dividing stream length by valley length or stream slope by valley slope (*Sinuosity*). *Sinuosity* was calculated by dividing total stream length, as determined from design plans, by valley length as determined in Google Earth (Google LLC, Mountain View, CA) as the straight-line distance, following the channel, between the upstream and downstream project extents. Many of these restoration projects altered channel sinuosity. *Sinuosity* was included as a predictor variable because a design sinuosity differing from natural equilibrium could have negative impacts on structures. Structures in channels with too high *Sinuosity* could risk excessive aggradation or be abandoned altogether because of channel avulsion. Structures in channels with too low a *Sinuosity* could risk flanking or scouring as the channel adjusts to increase sinuosity.

The project-scale soil erodibility of the project banks (*ProjectK*) is a similar explanatory variable to *DrainageK*. Both use the soil erodibility K-factor from RUSLE2, but *ProjectK* encompasses only the streambanks of the project reach, rather than the project reach and tributaries. High *ProjectK* values could increase the likelihood of scour or bank erosion that could compromise structure stability, thus reducing structure score.

The median particle size of riffles (riffle D_{50}; *RFD50*) was included as an explanatory variable to quantify bed stability. *RFD50* was determined using design plans or through communication with designers. *RFD50* was scaled to bankfull width to scale it to stream size. It was predicted that larger values of *RFD50* would result in greater channel stability and possibly result in increased structure performance.

Structure density was included as an explanatory variable to encompass the effect of nearby structures on the performance of individual structures on a project-wide scale. Structures were classified as any foreign materials added to the channel as part of the stream restoration design and included in-stream structures not studied as part of this project, such as root-wads. Structures density (*StrucDen*) was measured as the number of structures per 1000 ft. of stream. Literature indicates that some structures have a protective effect when in close proximity to one another, so it was anticipated that higher values of *StrucDen* would generally result in better structure performance (MDE, 2000; McCullah & Gray, 2005).

Distance from the upstream and downstream-most ends of the project to the nearest grade control structure was also considered (*USGC* and *DSGC* respectively). Projects with downstream grade control are more likely to be protected against channel incision due to the migration of downstream knickpoints. Similarly, upstream grade control could reduce channel incision due to bed scour from high flows. *USGC* and *DSGC* were both scaled to bankfull width to quantify their proximity with respect to project stream size.

Finally, the project itself was included as a project-scale explanatory variable to determine the significance of the individual project (e.g. design and construction techniques, project oversight, etc.) relative to structure design characteristics.

3.2.2.3 Structure-scale Variables

Stream restoration structures were grouped into six structure families, including bank protection (BP), full span vanes (FSV), partial span vanes (PSV), constructed riffles (RF), regenerative stream conveyance (RSC), and step pools (SP). BP structures are walls that aim to protect streambanks from direct flows and stabilize the channel margins. FSVs and PSVs are weir-type structures constructed in the stream channel to redirect streamflow, create downstream pools, and provide grade control (FSVs only). As the names imply, FSVs span the entire stream channel whereas PSVs only span a portion of the channel. RFs are constructed on the stream channel bed with the intent of creating a stable riffle bedform that provides habitat and channel stabilization. RSCs are valley-scale structures that consist of alternating weirs and pools that detain water, encourage overbank flows, and enhance the hydrologic connectivity of a stream with adjacent groundwater and riparian areas. Finally, SPs are constructed in steep reaches and consist of alternating steps and pools that provide energy dissipation and grade control. Structure-scale variables differed between each of the six structure families and were related to structure geometry, construction technique, or features of a given structure type. Information on structure-scale predictors is provided in Appendix B.

To account for the size of the stream where a structure was constructed, all length variables were scaled with respect to a length parameter such as bankfull width, bankfull depth, or step distance. Lengths measured in planform were scaled using bankfull width. Lengths measured vertically were adjusted using either bankfull depth or step distance. Bankfull depth was used for BPs, FSVs, PSVs, and RFs. Given that SPs are often constructed to convey streamflow through unstable, high gradient reaches, average step distance was used rather than bankfull depth because it represents the average distance over which each "unit" of the structure is dissipating energy. For RSCs, vertical length-scale variables were scaled to the distance between each weir crest and the downstream weir crest, also referred to as step distance. The RSCs assessed as part of this project occurred in sequence sometimes, but often occurred as individual units that minimally interacted with each other, so the RSC weirs were considered individual structures while a step pool sequence was viewed as a single structure. Where possible, the step distance was determined based on the distance between the top of two weirs but was evaluated with respect to another structure or stable bedform (riffle) when not possible. The ratios developed to scale the structure-scale predictors are provided in Tables B.13 – B19.

Structure-scale variables for each structure were determined from engineering as-built and design drawings. For some projects the data consisted of as-built drawings and design plans, just as-builts, or just design plans. As a result, the following hierarchy was used determine which source of information would be used in preference to others: as-built structure tables or details; as-built drawing measurement using AutoCAD; design plan structure tables or details; design plan drawing measurement using AutoCAD; and, photographic analysis from field investigations. Analysis using AutoCAD was performed by uploading engineering design plan sheets into AutoCAD, scaling the image to the drawing scale, and using the measure tool to determine lengths and angles.

Common Structure Variables

Certain structure-scale variables were common between most or all structure families. These variables quantified general construction practices such as footer depth, material type and sizing, location with respect to stream planform, and location with respect to other structures. Lists of structure-scale variables common to all structures, their units, data sources, and acquisition method are provided in Tables B.6 and B.13.

Material type was a categorical variable shared between all structures (*Type*), except constructed RFs and RSCs, and could be either rock, log, or composite. Where all aspects of a structure interacting with flow were stone, that structure was designated as “rock.” Where all aspects of a structure interacting with flow were wood, excluding in-bank stabilization stones, that structure was designated as “log.” Finally, composite structures were those where the construction included stone and wood and both materials were exposed to the flow.

The size of stone construction materials was quantified by boulder width (*BouldWid*), or the average intermediate (middle or b) axis length of construction stones. The intermediate axis of stone size was only determined based on construction material specifications (i.e. structure tables or design specifications). The size of wood construction material was quantified by log diameter (*LogDia*), also determined from structure tables or design specifications. The values for material size were estimates since most were given as minimum or maximum sizes rather than exact sizes, since the materials were natural and not manufactured. *BouldWid* and *LogDia* were both scaled with respect to bankfull depth.

Footer depth was the distance from the channel bottom to the lowest average depth of footers (*FootDep*) and was scaled by bankfull depth (BPs, FSVs, PSVs) or step distance (SPs, RSCs) depending on the structure. *FootDep* was not a variable for RFs. *FootDep* was determined based on specified depths or by multiplying the number of layers of footers by the size of the construction material.

Distance upstream (US) or downstream (DS) to other structures that deflected flows (*USFlo*, *DSFlo* for FSVs, PSVs, RSCs, and SPs) and structures that were flush with the channel boundary (*USFlu*, *DSFlu* for BPs or RFs) was also determined. These groups of structures were differentiated in the analysis because structures affecting flow are more likely to redirect and concentrate flows, which may affect the hydraulic stress on structures in their proximity. *USFlu*, *DSFlu*, *USFlo*, and *DSFlo* were all scaled by bankfull width.

Planform location was used to quantify the location of structures in the stream planform. *Planform* was a categorical variable that was determined qualitatively and given a value of 0, 1, or 2 corresponding to curvature of the channel planform where a structure was located: straight (0), slight bend (1), and bend (2).

The objective of including this variable was to represent the likelihood of secondary flows in the channel (i.e. helical flow present in meander bend) which could affect structure success.

Finally, channel dimensions at each structure was quantified using width to depth ratio (*BFWBFD*). *BFWBFD* was determined by dividing bankfull width by bankfull depth. Bankfull width and depth were determined using the highest resolution information provided in the design plans, where values of each of these were provided at each structure. Where structure-level information was not present, project-scale bankfull widths and depths were used as determined from design plans.

Bank Protection

The unique structure-specific variables collected for BP were type (*Type*), wall height (*WallHeight*), wall length (*WallLength*), and whether or not the construction material was stacked or unstacked (*StackUnstack*). *Type* and *StackUnstack* only applied to log and rock BP, respectively. *Type* for log BP included two categories: log toe and log meander protection. Log toe consists of logs stacked parallel to the streambank, typically secured by a combination of wood posts (or piles) and rebar to secure the logs to each other (Figures 3.32 and 3.33). Log meander protection consists of log toe, crib logs that extend into the streambank, and root wads, all of which are secured by cables and wood piles (Figures 3.34 and 3.35).

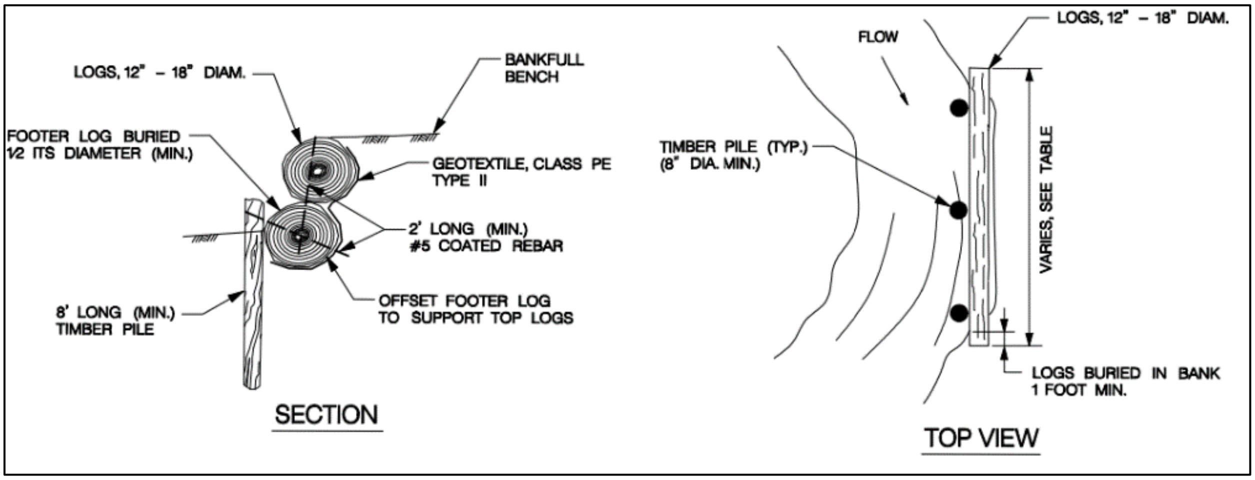
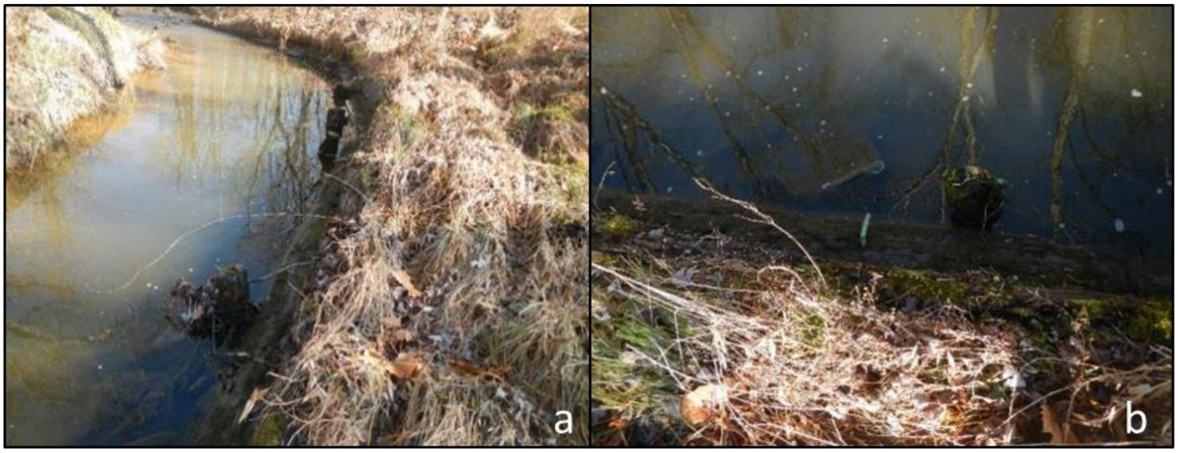


Figure 3.32 Design detail drawings for log toe from restoration project 28.

StackUnstack was used to describe the practice used to construct rock BP: stacked or unstacked. Generally, stacked BP was constructed using the design approach referred to as imbricated BP (Figures 3.36 and 3.37) while unstacked BP was constructed using the stone toe design approach, where rocks are placed loosely along the toe of the streambank (Figure 3.38). *StackUnstack* was determined exclusively using site photographs because actual construction techniques sometimes differed from the design details.



Figures 3.33 Log toe structure on the right streambank (a) and log toe with exposed rebar and visible wood piles (b). Both images are from restoration project 36.

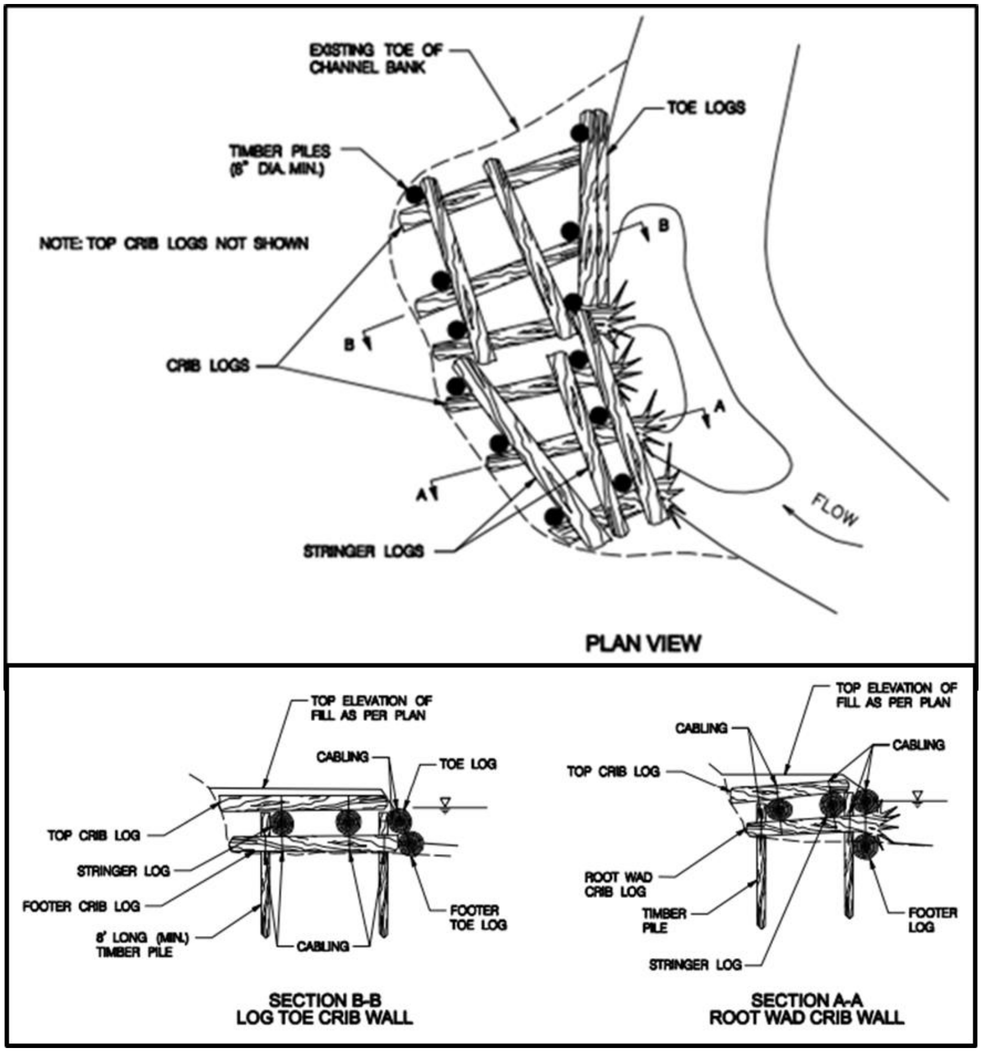


Figure 3.34 Design details for log meander protection from restoration project 28.

Figure 3.35 Pictures of log meander protection from restoration project 28.

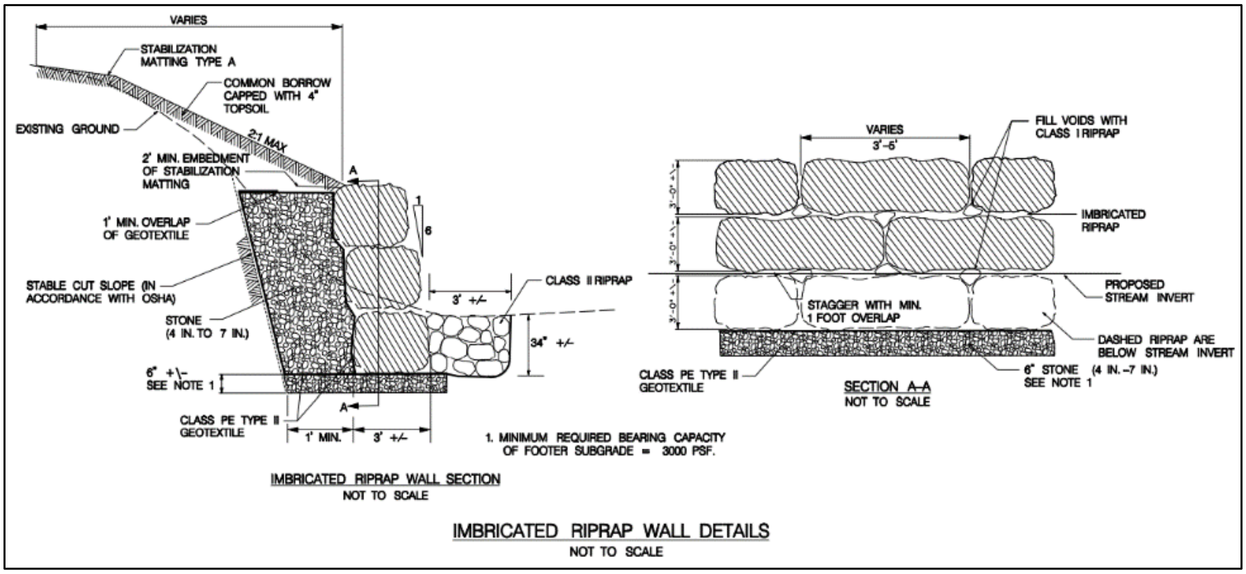


Figure 3.36 Detail for imbricated rock wall from restoration project 36.

Wall height was the average distance from the streambed to the top of a BP structure (*WallHeight*). Wall length was the total length of a BP structure with respect to the stream centerline (*WallLength*). *WallHeight* was represented as a fraction of bankfull depth and *WallLength* was expressed as a number of bankfull widths. BP-specific structure-scale predictors are provided in Table B.7 and the ratios developed to scale BP-specific structure-scale predictors are shown in Table B.14.

Full Span Vanes

The unique structure-specific variables for FSVs related to properties of the keys, arms, and sill. *Type* was a categorical variable used to classify the type of FSVs. *Type* had nine possible categories based on a

Figure 3.37 Stacked imbricated bank protection from restoration project 2.

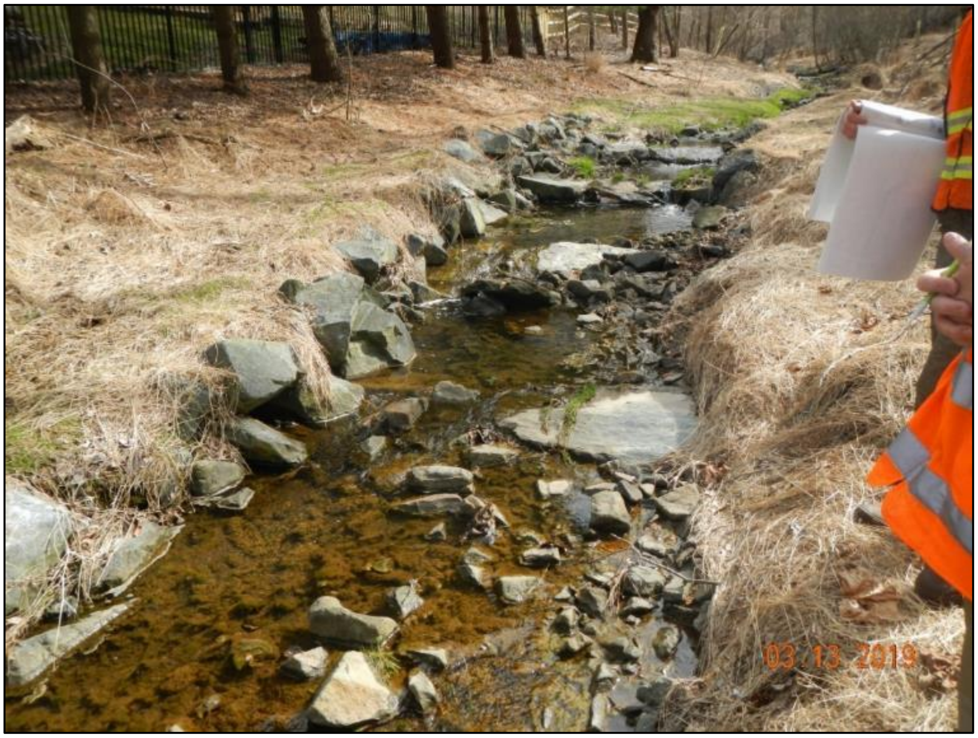


Figure 3.38 Unstacked bank protection from restoration project 3.

combination of three construction material types and three structure types. FSVs were either sills, cross vanes, or modified j-hooks. Sills were defined as structures that generally extended straight across the channel with arms that did not slope upwards to the bank (i.e. sills were flush with the streambed). Cross vanes were defined as any "alphabet-weir," such as A, U, or V weirs, consisting of at least two arms that sloped upwards towards the channel banks. Modified j-hooks consisted of a single arm and a long sill that extended across the channel into the opposite bank. FSVs could be constructed out of either rock, logs, or a combination of the two (composite). Thus, *Type* consisted of nine unique types of FSVs based on design approach and construction material.

Variables for the bank key (the portion of a FSV constructed into the bank) were key bank angle (*KeyAng*) and key normal distance into the bank (*KeyDist*). Variables for the arms were arm bank angle (*BankAng*), arm length (*ArmLen*), arm normal distance in the channel (*ArmNorm*), arm slope (*ArmSlp*), and vertical distance occupied by structure arms in the channel (*ArmVert*). Variables for the sill were sill length (*SillLen*) and sill protrusion height (*ProtHeight*). Figures 3.39 and 3.40 depict a FSV with each of these dimensions labeled for reference.

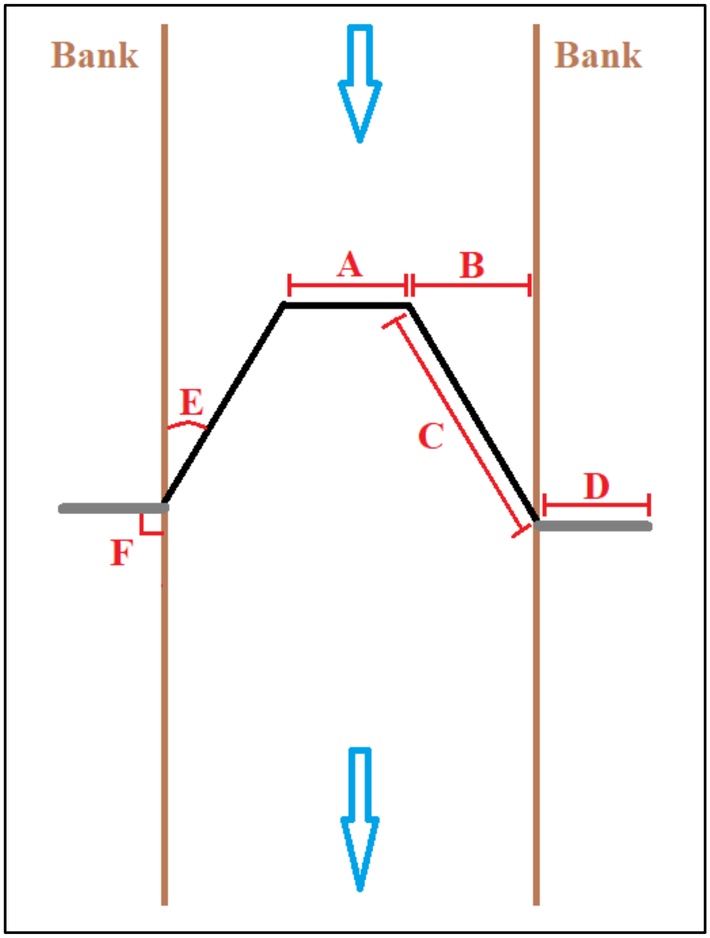


Figure 3.39 Plan view of cross vane where A = SillLen, B = ArmNorm, C = ArmLen, D = KeyDist, E = BankAng, and F = KeyAng.

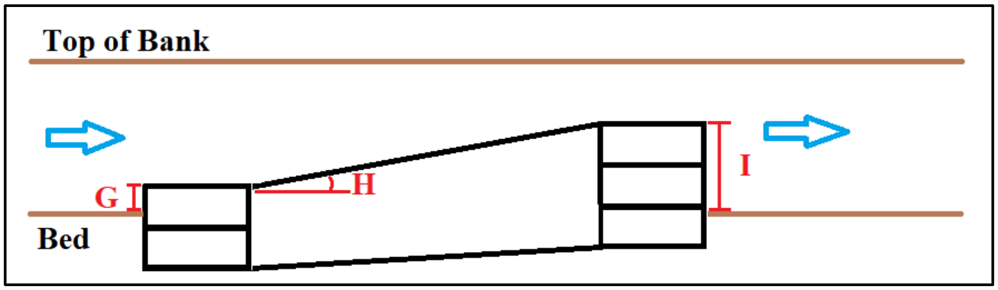


Figure 3.40 Profile view of cross vane where G = ProtHeight, H = ArmSlp, and I = ArmVert.

BankAng was measured with respect to the upstream bank. *KeyAng* was measured the same as *BankAng*, such that when a key was a straight extension of the FSV arm (see Figure 3.39) the angle of the key and arm were the same. Where the arm or key was oriented perpendicular to streamflow, the angle was 90°. Where the arm or key was oriented parallel to streamflow, the angle was 0°. *ArmSlp* was measured as the slope along the top-most face of a vane arm from the sill to where the structure keyed into the bank. *ArmSlp* was measured in percent (rise/run * 100). *BankAng*, *KeyAng*, and *ArmSlp* were not scaled because they are dimensionless.

ArmLen was the length of the arm when viewed in planform (i.e. excluding the additional distance that would be added if slope was accounted for). Likewise, *SillLen* was the length of a FSV sill. Completely straight sill structures were counted as only having a sill, which occupied the entire channel. Sills with slightly angled arms, or a slight bend in the middle, were considered to have arms but no sill. *ArmNorm* was measured as the distance perpendicular to flow that a FSV arm occupied in the channel. Similarly, *KeyDist* was measured as the distance perpendicular to flow that a key occupied in the bank. *ArmLen*, *SillLen*, *ArmNorm*, and *KeyDist* were all scaled to bankfull width.

ProtHeight was measured as the distance from the top of the sill to the upstream channel bed. *ProtHeight* was frequently zero because FSVs are often designed so that their sills are flush with the upstream bed (Hickman & Thompson, 2010a). *ArmVert* was measured as the total vertical distance a FSV, including the sill and arms, occupied in the channel. Both *ProtHeight* and *ArmVert* occupied by structure were scaled to bankfull depth.

FSVs are typically constructed with two arms and a key that extends into the bank from each arm. For each structure, data were collected for each arm and key leading to “right” and “left” observations. Distinguishing between right and left is arbitrary and means very little when trying to meaningfully interpret results and develop design guidance. Using the distinction of “inside of meander” or “outside of meander” arms was considered as a way to categorize arms based on similar hydraulic conditions, but this alternate labeling approach was limited by structures located in straight reaches and differing bend geometries. Right and left data were combined using knowledge of restoration design to determine singular representative values. *ArmSlp* and *ArmVert* were similar for most structures, so they were averaged for analysis. *BankAng* and *KeyAng* were averaged when similar (within 5°). However, when *BankAng* or *KeyAng* were different, the most extreme value was used where “extreme” was defined as outside the recommended range of 20° to 30° (MDE, 2000; Rosgen, 2001; Doll et al., 2003; VDSWC, 2004; Sotiropoulos & Displas, 2014; Iowa DNR, 2018a).

ArmLen and *ArmNorm* were chosen to correspond to the arm with the largest arm normal distance in the channel. The most extreme bank or key angle and the arm with the largest normal distance in the channel were chosen to represent the structure because it was predicted that these values would correspond to aspects of structure design more likely to result in structure failure. Finally, because modified j-hooks have an arm and an extended sill, values from the single arm were chosen to represent the structure. FSV-specific structure-scale explanatory variables and ratios developed to scale FSV-specific explanatory variables are provided in Tables B.8 and B.15, respectively.

Partial Span Vanes

PSVs share most of their structure-scale explanatory variables with FSVs. *Type* was the only explanatory variable for partial PSVs that differed from FSVs. Six types of PSVs were identified based on a combination of three construction material types (rock, log, or composite) and two structure types. The two structure types were single arm vanes and j-hooks. Single arm vanes are a single, straight arm that extends from one channel bank into the channel bed. J-hook vanes consist of an arm connected to a sill that does not connect to the bank.

Like FSVs, the other structure structure-scale variables for PSVs related to properties of the key, arm, and sill. Variables for the key were key bank angle (*KeyAng*) and key normal distance (*KeyDist*). Variables for the arm were arm bank angle (*BankAng*), arm length (*ArmLen*), arm normal distance in channel (*ArmNorm*), arm slope (*ArmSlp*), and vertical distance occupied in channel (*ArmVert*). Finally, variables for the sill were sill length (*SillLen*) and protrusion height (*ProtHeight*). These variables were the same as the variables for FSVs. See Table B.9 for PSV-specific structure-scale explanatory variables and Table B.16 for ratios developed to scale PSV-specific structure-scale explanatory variables.

Constructed Riffles

The unique structure-specific variables for RFs describe their dimensions and how they were constructed and include length/width (*RFLenWid*), substrate depth (*RFSubDep*), substrate D_{50} (*RFD50*), and downstream (*RFDSGC*) and upstream grade control (*RFUSGC*). *RFLenWid* was the ratio between length and width of a RF, where length was parallel to streamflow and width was perpendicular to streamflow. *RFSubDep* described the maximum depth of material used to construct a RF and was scaled to bankfull depth. *RFD50* was the median particle size of the material used to construct a RF and was scaled to bankfull depth. Finally, some RFs were constructed with grade control, a rock or log sill, at the upstream and/or downstream end of the structure. The variables *RFUSGC* or *RFDSGC* were binary and indicated the presence, or lack of, one or both. Tables B.10 and B.17 provide additional detail on the variables used to describe constructed riffles.

Regenerative Stream Conveyance

The unique structure-specific variables for RSCs describe the two major components of each individual RSC “unit”: the weir and the pool. Variables related to the weir were length/width (*WeirLenWid*), width/bankfull width (*WeirWidBFW*), width/valley bottom width (*WeirWidValley*), weir crest slope (*WeirSlp*), cobble D_{50} (*WeirD50*), and cobble thickness (*WeirCobDep*). Variables related to the pool were length/width (*PoolLenWid*), depth (*PoolDep*), and the presence or absence of a stone perimeter (*Perimeter*). The thickness of the underlying infiltration media was also quantified (*InfMedThick*). Unlike other instream structures, the vertical scaling variable used for RSCs was step height because it represented the potential energy acting on a given weir.

WeirLenWid was the ratio between the length and width of the weir, where length and width are parallel and perpendicular to streamflow, respectively. RSCs were typically constructed in the context of a stream channel and floodplain; therefore, weir width was scaled to both bankfull width (*WeirWidBFW*) and valley bottom width (*WeirWidValley*). The latter indicated what fraction of the valley width the weir occupied. Valley bottom width was determined in AutoCAD at each weir location using topographic maps of the site, based on inflection points between floodplains/terraces and hillslopes. *WeirSlp* was the slope along the top of the riffle-weir, parallel to streamflow, and was expressed as a percent. *WeirD50* was the median particle diameter of the surface material used to construct RSC weirs and was scaled to step distance. *WeirCobDep* was the thickness of the uppermost weir substrate and was also scaled by step distance. RSC weirs also had footer variables such as footer depth (*FootDep*) and boulder diameter (*BouldWid*). These footers were present on the downstream face of some RSC weirs. *FootDep* was determined based on the distance below the bottom of the pool that footers extended and was scaled by the step distance.

Similar to *WeirLenWid*, *PoolLenWid* was the ratio between length and width of the pool where length was parallel to streamflow and width was perpendicular to it. *PoolDep* was the distance between the pool water surface (elevation of the crest of the downstream weir) and the lowest point of the pool. *PoolDep* was scaled to step distance. *Perimeter* was a binary variable that described whether or not RSC pools were surrounded by reinforcing stones. Most projects included an underlying sand/woodchip mixture, the thickness of which was quantified as the variable *InfMedThick* and scaled to step distance. See Table B.11 for RSC-specific structure-scale explanatory variables and Table B.18 for ratios developed to scale RSC-specific structure-scale explanatory variables.

Step Pools

SPs consist of alternating sills and pools. The unique structure-specific variables used to describe SPs quantified the properties of an entire SP sequence or average properties of the individual pool-sill units that comprise the system. These variables were number (*Number*), average step slope (*HLavg*), ratio of mean steepness (*HLavgS*), sill width (*SillWid*), pool depth (*PoolDep*), pool length/width (*PoolLenWid*), total length (*TotalLen*), substrate depth (*PoolSubDep*), pool substrate D_{50} (*PoolSubD50*), and perimeter (*Perimeter*; Tables B.12 and B.19). *Number* referred to the number of step pools in a system of SPs, and was determined by counting the number of pools present in a system. The average slope of each step was represented by the variable *HLavg*. *HLavg* could also be represented by the equation "(H/L)avg" where H was the change in elevation between two sills and L was the horizontal distance between those two sills. The ratio of mean steepness of each SP system was represented by the variable *HLavgS* and was the ratio between average SP slope and channel slope. *HLavgS* could also be represented by the equation "(H/L)avg/S" where S was the slope of the stream where a SP system was constructed. *SillWid* was the average width of the sills constructed in a SP sequence and was scaled to bankfull width. *PoolDep* was the average depth of all pools in a system, where depth is the height of water that would be impounded in the pool by the downstream-most sill. *PoolDep* was scaled to the average step distance of the system. *PoolLenWid* was the average ratio of the length and width of all pools, where length was parallel to streamflow and width is perpendicular to it. *TotalLen* was measured as the distance between the upstream-most and downstream-most sills of the SP system, and was expressed as a number of bankfull widths. *PoolSubDep* was the depth of the substrate placed at the bottom of each pool and was scaled to average step distance. Likewise, *PoolSubD50* was the median diameter of the substrate placed on the bottom of the pools and was scaled to average step distance. Finally, similar to the RSCs, *Perimeter* was a categorical binary variable used to quantify whether the pools were constructed with or without a rock perimeter.

3.2.3 Data Analysis

RStudio version 4.0.3 was used to perform all statistical analyses (Version 4.0.3; R Core Team, 2020). The “car”, “lme4”, “qpcR”, “QuantPsych”, “rsq” libraries were used for certain statical functions and the “ggplot2” library was used for plotting. Given that many datapoints overlapped in scatterplots of the data, the plots shown in this chapter were generated using “jitter” which slightly offsets points from one another so the total number of data points is clear. The main statistical analyses were conducted using *ScoreOverall* (between 0 and 18) as the response variable. Statistical analyses were also conducted using the five structure assessment subcategory scores: *ScorePCTRemain*, *ScoreMatMove*, *ScoreErosion*, *ScoreAggrad*, *ScoreFunction.*

First, data were scaled as appropriate and compiled into final datasets that contained structure-, project-, and watershed-scale predictors. Initially, relationships between *ScoreOverall* and the explanatory variables were assessed visually using scatter plots and quantitatively using simple linear regression. The studentized residuals of these simple regressions were plotted as scatterplots, histograms, and Q-Q plots to investigate outliers and assess normality.

Based on the initial data analysis, data transformations were performed on all variables as appropriate to ensure homoscedasticity and normally distributed residuals. Predictor variables were transformed by either applying a base 10 logarithm or square root. Predictor variables were also checked for underlying polynomial relationships. The highest order polynomial relationships found/investigated were quadratic. When predictors were identified as having a quadratic relationship, that predictor was squared to create a new predictor that could be added to the linear models to encompass quadratic behavior. A square root transformation was investigated for *ScoreOverall*. The best transformation of each predictor variable was plotted against the untransformed and square-root-transformed *ScoreOverall*. Based on these plots, it was determined that leaving *ScoreOverall* untransformed would maximize the homoscedasticity and normality of the distribution of residuals.

Once transformed, each of the final datasets were further divided. Where applicable, structure families were sorted into log structures and rock structures. Since the number of composite structures was too low to be analyzed separately, composite structures were included in both categories. The level of design information provided about each structure varied from project to project, so not all explanatory variables could be quantified for each structure. As a result, each dataset was further subdivided to either maximize the number of structures in each dataset or maximize the number of explanatory variables in each dataset. The “maximum structures” datasets were developed by excluding response variables with large amounts of missing data. However, some structures were still excluded from the “maximum structures” datasets, typically if a structure was missing large amounts of data that would cause one or multiple predictor variables to be excluded due to missing data. The “maximum predictor” datasets were developed by excluding all structures in a dataset that had missing data to allow for assessment of all the predictor variables. For example, the result of these two subdivisions resulted in four final datasets for FSVs: rock maximum structures, rock maximum predictors, log maximum structures, and log maximum predictors. Maximum predictor datasets were subsets of maximum structure datasets, so statistical relationships of a given variable that only occurred in the maximum predictor datasets but not in the maximum structure datasets were excluded.

Analysis of the final datasets was performed separately for structure-scale and project- and watershed-scale predictors. For structure-scale predictors, regression analysis was used to determine significant relationships between *ScoreOverall* and the explanatory variables using $\alpha < 0.05$ as the criteria to reject the null hypothesis that a variable was not significant. Both single linear regressions and forward stepwise selection were used to develop a set of significant single- and multi-variate models. To gain additional insight into these relationships, significant predictor variables were analyzed against score in each of the five structure assessment subcategories using linear regression.

Significant models were then evaluated by broadly interpreting the model (i.e. did an explanatory variable have a positive or negative effect); summarizing important model parameters such as adjusted r2, predicted r^2 or predicted residual error sum of squares (PRESS), p-value, slope and intercept estimates, error, and sample size; and, visually assessing model fit, outliers, and data points with high leverage. Multicollinearity of multi-variate linear models was assessed with the variable inflation factor at a threshold of <5 to ensure parameters were not causing variable inflation. Multicollinearity in all models was considered by developing correlation matrices to determine which parameters were highly correlated and possibly redundant. Using knowledge about each structure and this suite of diagnostic tools, final relationships between structure-scale predictors and *ScoreOverall* were determined. Furthermore, significant relationships that had small r^2 values (typically < 0.10) were excluded from the final results because they indicated the variable explained little of the variance in the structure scores.

Relationships between project- and watershed-scale predictors and *ScoreOverall* were assessed using linear mixed-effects models. To account for the grouping effect of project on project- and watershed-predictors, which resulted in identical or very similar predictor values for all structures from a given project, each model was developed with a single project- or watershed-scale predictor as a fixed effect and *Project* as a random effect. Linear mixed-effects models were only utilized to analyze datasets containing at least five levels of the random effect (five projects) that contained a minimum of three observations each (allowing one degree of freedom for each sub-model; Harrison et al., 2018). An all-possible models approach was used with $\alpha < 0.05$ to determine when fixed effects (project-/watershed-scale predictors) were significant. Each statistically significant model was examined using the same set of diagnostics as the structure-scale models to determine the final results. Moreover, predictors that produced significant relationships were analyzed against score in each of the five structure assessment subcategories to gain insight into the nature of these relationships.

The structure assessment subcategory scores were analyzed for all of the structures and each structure family. The average subcategory score was summarized as a fraction of the highest possible score. Subcategory scores for structures with rock and wood construction were analyzed using Mann-Whitney nonparametric 2-sample tests to determine if average subcategory scores differed significantly between each construction material.

3.3 Instream Structures Results

In total, 536 structures located within 38 projects in Maryland, across seven counties were assessed. The final dataset included 510 structures: 147 bank protection (BP) structures, 105 full span vanes (FSVs), 68 partial span vanes (PSVs), 102 constructed riffles (RFs), 57 RSC weirs (RSCs), and 31 step pools (SPs). Many of the excluded structures were vortex rock weirs, which were not included in the final datasets because they had high rates of failure and subsequently are no longer used in practice. A small number of RSC weirs were excluded from the final datasets because their design plans indicated that the step distance to the downstream weir was negative, which presented issues when performing transformations and created outliers for all design variables that were scaled to step distance. The following sections will describe the significant relationships found within the data. See Tables B.20 to B.34 for descriptive statistics for each structure family.

3.3.1 All Structures

The average score in each structure assessment subcategory was determined for all log and rock structures, respectively (Table 3.4). Log structures received the highest scores in *ScorePCTRemain* and lowest in *ScoreFunction* (Table 3.4). The trend of log structures scoring high in *ScorePCTRemain* was observed in other datasets, such as log FSVs and PSVs. Unintended aggradation was not commonly associated with rock structures; the most common problem observed for rock structures overall was material movement (Table 3.4).

Mann-Whitney nonparametric 2-sample tests were conducted to compare scores between all log and rock structures for each structure assessment subcategory. These tests indicated that rock structures scored significantly lower for *ScorePCTRemain* and *ScoreMatMove,* likely because individual rocks are easier to mobilize because they are only secured by their submerged weight and adjacent stones, making them easier to move than entire logs. Although the Mann-Whitney nonparametric 2-sample tests took sample size into account, it should be noted that the sample sizes between all log (n = 36) and rock (n = 492) structures were very different.

Table 3.4 Average subcategory score, as a fraction of the maximum score for all log (n = 36) and rock (n = 492) structures.

	Average Fraction of Highest Possible Score	
Subcategory Score	**All Log Structures**	**All Rock Structures**
*ScorePCTRemain**	0.96	0.86
*ScoreMatMove**	0.87	0.75
ScoreErosion	0.88	0.83
ScoreAggrad	0.85	0.88
ScoreFunction	0.83	0.82

* Assessment subcategory scores are significantly different (α < 0.05) between log and rock structures using Mann-Whitney nonparametric 2-sample test.

Two significant models were developed for all structures using *ScoreOverall*: one for log structures and one for rock structures (Table 3.5). No significant models were developed using structure-scale predictors. There was a negative relationship between *ScoreOverall* and *DrainageK* for log structures (n = 26, adj. r^2 = 0.273, p-value = 0.0077; Figure 3.41), indicating that log structures are more susceptible to failure in watersheds with highly erodible riparian soils. *DrainageK* ranged from 0.35 to 0.43, with higher values indicating greater susceptibility to erosion. Results of a linear mixed-effects model indicated the random effect, *Project*, did not explain any variability in the scores for log structures (Table 3.5)

For the rock structures, there was a negative relationship between *ScoreOverall* and *MedDenCh* (n = 282, adj. r^2 = 0.207, p-value = 0.0024; Figure 3.42). *MedDenCh* ranged from 1.4% to 5.6%. To explore the role of individual projects, a linear mixed-effects model was developed with *Project* as the random effect. This model showed *Project* explained 12.6% of the variability in the data while the fixed effect, *MedDenCh*, explained 8.0% of the variability (Table 3.5). The combination of these two models indicates that, while land cover change following construction was significant, the specific project in which a rock structure was constructed played a larger role in determining the success of rock structures overall.

Table 3.5 Significant linear mixed-effects models for all log (n = 36) and rock (n = 282) structures.

Structure Family	**Fixed Effect Regression Equation** (*ScoreOverall* = …)	**Model r^2**	**Fixed Effect r^2**	**Random Effect r^2**	**Fixed Effect p-value**
All log structures	= - 45.88 *DrainageK*	0.121	0.121	0.0	0.0379
All rock structures, excluding RFs	= -1.17 *MedDenCh*	0.207	0.080	0.126	0.0024

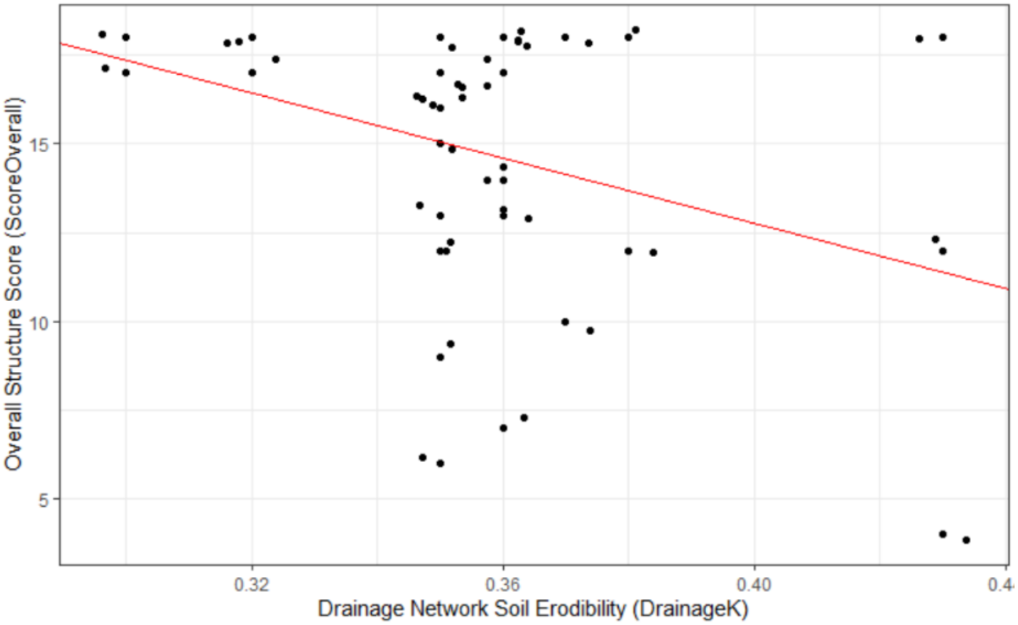


Figure 3.41 Overall structure score versus the length-weighted USLE soil erodibility (K) of the stream drainage network.

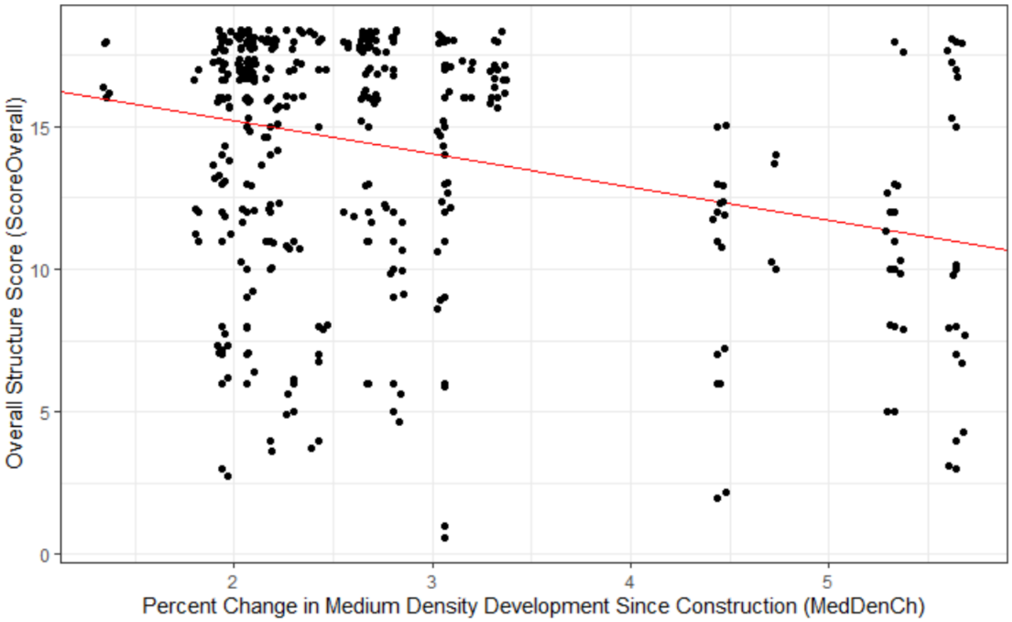


Figure 3.42 Overall structure score versus the percent change in medium density development following project construction.

3.3.2 Bank Protection

Average structure assessment subcategory scores for log and rock BP are listed in Table 3.6. *ScoreMatMove* was the lowest-scoring subcategory for log BP while there were no observed issues related to unintended aggradation. Similarly, rock BP received the highest scores for *ScoreAggrad* and the lowest scores in *ScoreMatMove*.

Mann-Whitney nonparametric 2-sample tests were conducted to investigate the difference between assessment subcategory scores between log and rock BP. These tests indicated that log and rock BP did not have significantly different scores in any subcategory (Table 3.6). Thus, structure material was not an important factor with respect to score in each subcategory. Although the Mann-Whitney nonparametric 2-sample tests take sample size into account, it should be noted that the sample sizes of log (n = 13) and rock (n = 113) BP were very different.

Five significant models were developed for rock BP using *ScoreOverall*: two corresponding to structure-scale predictors (Table 3.7) and three corresponding to project-/watershed-scale predictors (Table 3.8). No significant models were developed for log BP, likely due to the small sample size (n = 13). Project- and watershed-scale predictors were not analyzed for log BP because there were too few projects and structures to develop linear mixed-effects models.

Table 3.6 Average subcategory score, as a fraction of the maximum score for log (n = 13) and rock (n = 138) bank protection (BP).

	Average Fraction of Highest Possible Score	
Subcategory Score	**Log BP**	**Rock BP**
ScorePCTRemain	0.96	0.90
ScoreMatMove	0.79	0.77
ScoreErosion	0.92	0.85
ScoreAggrad	1.00	0.97
ScoreFunction	0.94	0.88

Table 3.7 Significant linear regression equations for rock bank protection (BP; n = 127).

Structure Family	**Linear Regression Equation** (*ScoreOverall* = …)	**Adjusted r^2**	**Predicted r^2**	**Regression p-value**
Rock BP	= 15.76 for stacked = 13.84 for unstacked	0.040	0.013	0.0133
Rock BP	= 4.16 *WallHeight*	0.132	0.106	< 0.0001

Table 3.8 Linear mixed-effects models for rock bank protection (BP; n = 116).

Structure Family	**Fixed Effect Regression Equation** (*ScoreOverall* = …)	**Model r^2**	**Fixed Effect r^2**	**Random Effect r^2**	**Fixed Effect p-value**
Rock BP	= -3.30 *BFDisch*	0.308	0.168	0.140	0.0029
Rock BP	= 3.75 *StrucDen*	0.309	0.027	0.282	0.0259
Rock BP	= 4.50 *ProjLen*	0.308	0.032	0.276	0.0319

Stacked BP scored significantly higher than unstacked BP (Figure 3.43). The linear regression relationship indicates that stacked BP scored 12.2% higher than unstacked BP, which is equivalent to 2 points on the structure assessment (n = 127, adj. $r^2 = 0.040$, p-value = 0.0133; Table 3.7). Of the 127 BP structures used to develop this relationship, 89 were stacked and 38 were unstacked. This relationship only explains 4% of the variability in the data, which is reasonable since this relationship was developed using a categorical variable with two options.

Field observations (and fundamental physics) demonstrated there were inherent differences in how unstacked and stacked BP were constructed. Unstacked BP was frequently designed as stone toe using smaller boulders. Mann-Whitney 2-sample tests verified that stacked BP has significantly larger values of boulder width (*BouldWid*) than unstacked BP. Stacked BP was also constructed with significantly higher wall heights (*WallHeight*) than unstacked BP (n = 127, adj. $r^2 = 0.58$, p-value = < 0.0001). The average *WallHeight* of unstacked BP was 0.5 bankfull depths whereas stacked BP was constructed to an average *WallHeight* of 1.9 bankfull depths (Figure 3.44).

Analysis of *BouldWid* versus stacked and unstacked BP indicated that stacked BP was constructed with significantly larger boulders than unstacked BP (n = 127, adj. $r^2 = 0.41$, p-value = < 0.0001). *BouldWid* of stacked BP ranged from 0.41 to 3.33 bankfull depths, whereas the *BouldWid* of unstacked BP ranged from 0.31 to 0.77 bankfull depths. On average, unstacked BP was constructed with boulders that were 0.4 bankfull depths in diameter whereas stacked BP was constructed with boulders that were 1.2 bankfull depths in diameter (Figure 3.44). These results clearly indicate significant design differences between stacked and unstacked BP: stacked BP was constructed four times taller than unstacked BP using boulders that were three times larger.

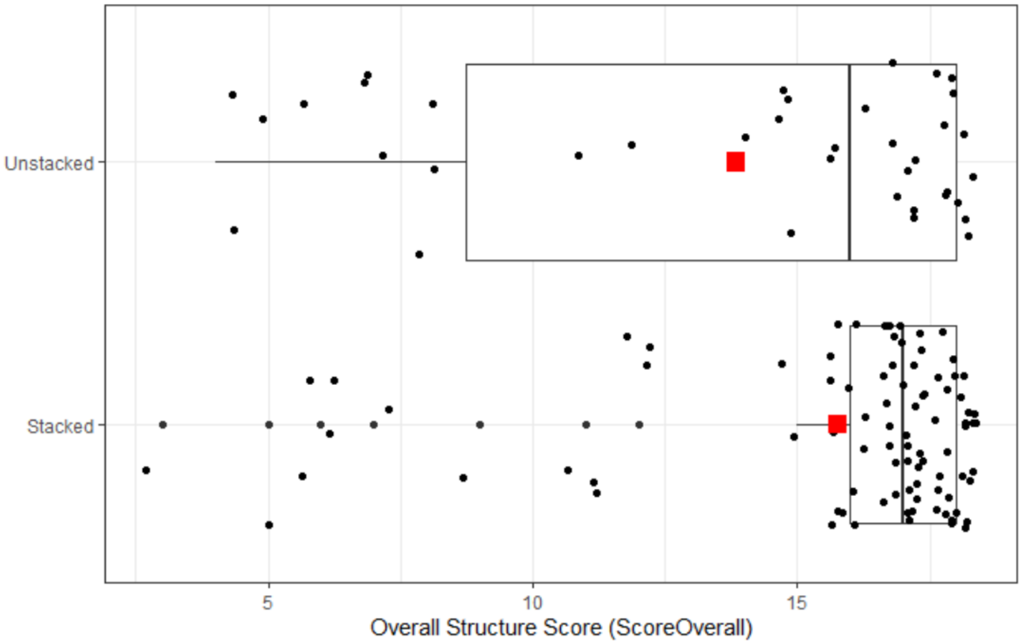


Figure 3.43 Differences between overall structure score for stacked versus unstacked bank protection.

Given that stacked and unstacked BP have very different designs, they were analyzed separately. For stacked BP, there was a significant positive relationship between *ScoreOverall* and *WallHeight* (n = 89, adj. $r^2 = 0.305$, p-value = < 0.0001). The significance of *WallHeight* suggests that a major failure mechanism for rock BP is overtopping and erosion behind the structure; field observations confirmed this. For unstacked BP, there were no significant relationships between *ScoreOverall* and other structure-scale predictors that could provide insight into possible design factors related to the failure of unstacked BP.

A statistical analysis was also performed for unstacked and stacked BP versus the structure assessment subcategory scores. These results indicated that stacked BP had fewer issues with unintended scour or erosion and overall structure function, indicating that stacked BP, which is constructed taller and using larger rocks, functions and prevents erosion to a greater degree than unstacked BP.

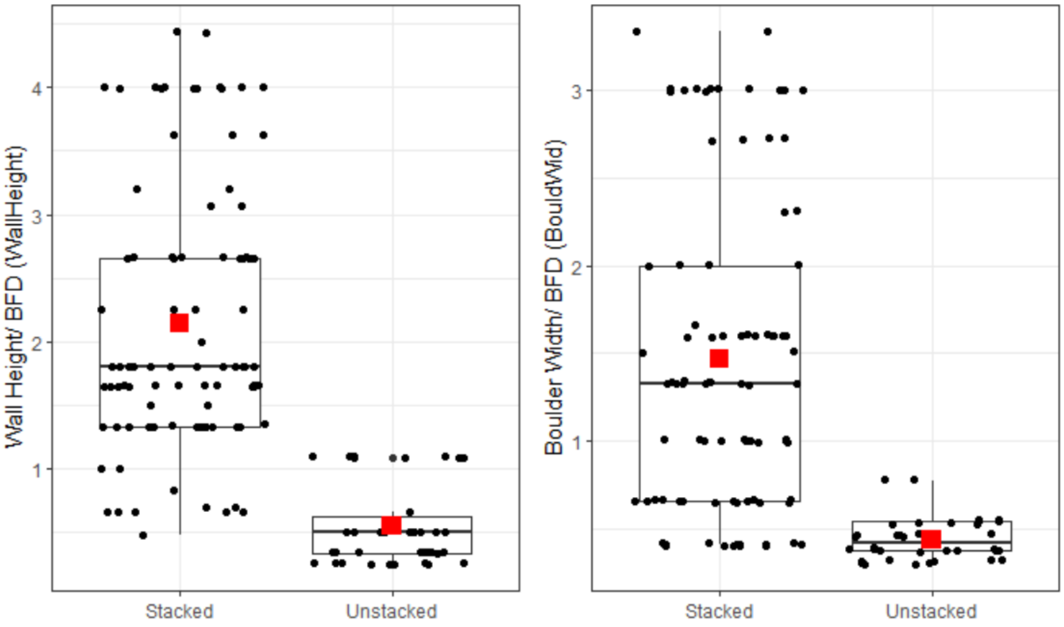


Figure 3.44 Differences in scaled wall height and boulder width between stacked and unstacked bank protection.

For all rock BP, there was a positive relationship between *ScoreOverall* and *WallHeight* (n = 127, adj. r^2 = 0.132, p-value = < 0.001; Table 3.7; Figure 3.45). As discussed previously, this relationship was significant for the subset of this dataset consisting of stacked BP but not for unstacked BP. Further analysis was performed to investigate the relationship between the structure assessment subcategory scores and wall height. There were positive relationships between *WallHeight* and all subcategory scores except *ScoreAggrad*, which was the subcategory that rock BP scored highest in (average score of 97%; Table 3.6). This finding indicates that *WallHeight* is positively correlated with high scores in all subcategories. *WallHeight* ranged from 0.25 to 4.44 bankfull depths. From Figure 3.45, there appears to be a threshold above 1 bankfull depth (0.0 in figure) where rock BP scored higher. This threshold is the upper-bound of wall height for unstacked BP; all structures above this threshold were stacked.

For all rock BP, there was a negative relationship between *ScoreOverall* and *BFDisch* (n = 116, adj. r^2 = 0.308, p-value = 0.0029; Table 3.7; Figure 3.46). *BFDisch* ranged from 7 to 1519 cubic feet per second (cfs). Of the variability in the data explained by this linear mixed-effects model (30.8%), slightly more than half was explained by the fixed effect, *BFDisch* (16.8%), as compared to the random effect, *Project* (14.0%; see r^2 values in Table 3.8). Higher bankfull discharge is more likely to dislodge individual stones in a rock structure and rock structures scored lowest for material movement overall (Table 3.6).

There was a positive relationship between *ScoreOverall* and *ProjLen* for rock BP (n = 116, adj. r^2 = 0.309, p-value = 0.0259; Table 3.8; Figure 3.47). *ProjLen* ranged from 19.5 to 450.2 bankfull widths. Of the variability in the data explained by the linear mixed-effects model (30.8%), nearly all of it was explained by the random effect (27.6%), *Project*, as compared to the fixed effect (3.2%), *ProjectLen* (see r^2 values in Table 3.8). Similarly, there was a positive relationship between *OverallScore* and *StrucDen* (number of structures/

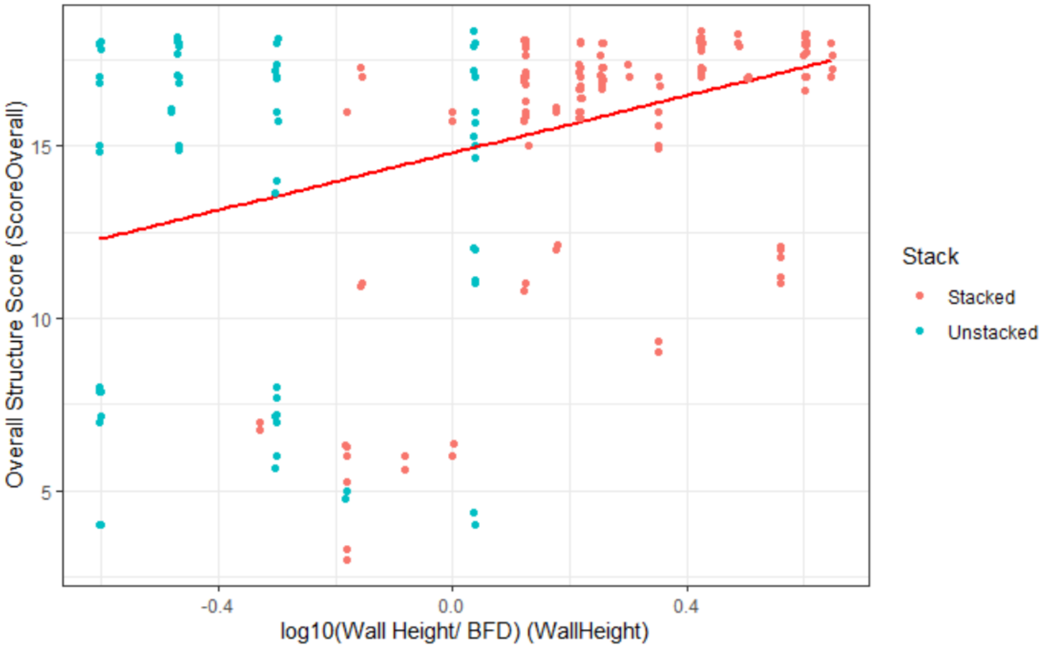


Figure 3.45 Relationship between overall structure score and scaled wall height for rock bank protection structures (n = 127).

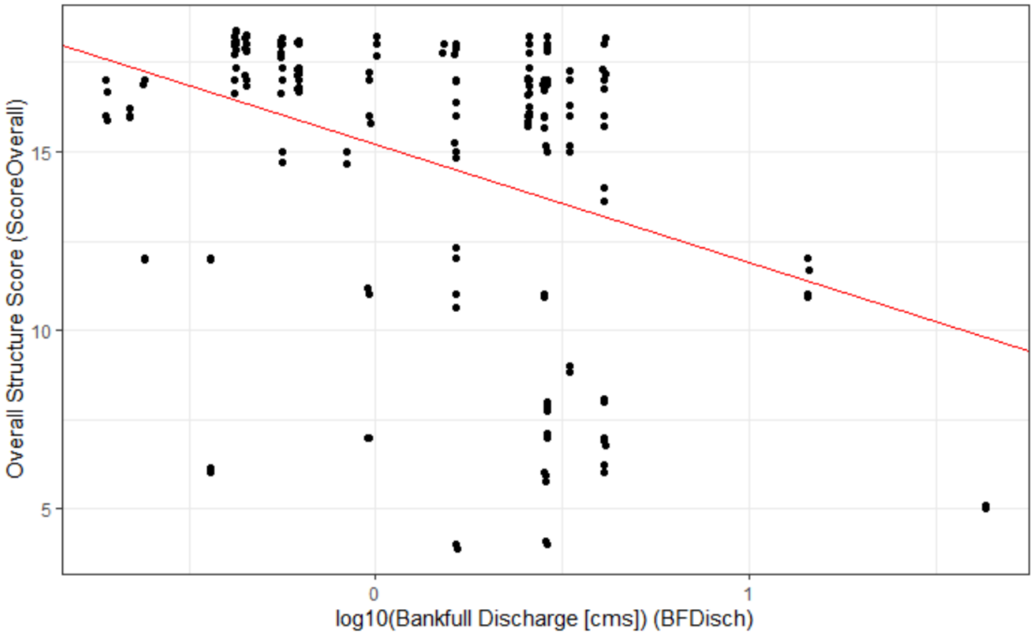


Figure 3.46 Relationship between overall structure score and bankfull discharge for bank protection (n = 116).

1000 ft.) for rock BP (n = 116, adj. $r^2 = 0.308$, p-value = 0.0319; Table 3.8; Figure 3.48). *StrucDen* ranged from 2 to 119 structures per 1000 ft. Of the variability explained by the linear mixed-effects model (30.8%), nearly all of it was explained by the random effect (28.2%), *Project*, rather than the fixed effect (2.7%), *StrucDen*. The large fraction of the variance in *ScoreOverall* explained by the specific restoration project indicates that the overall differences between projects play a greater role in structure scores than differences in *ProjLen* or *StrucDen*. The random effect, *Project*, likely encompasses a variety of hidden variables that account for structure performance such as design and construction quality, construction oversight, and whether repairs were made.

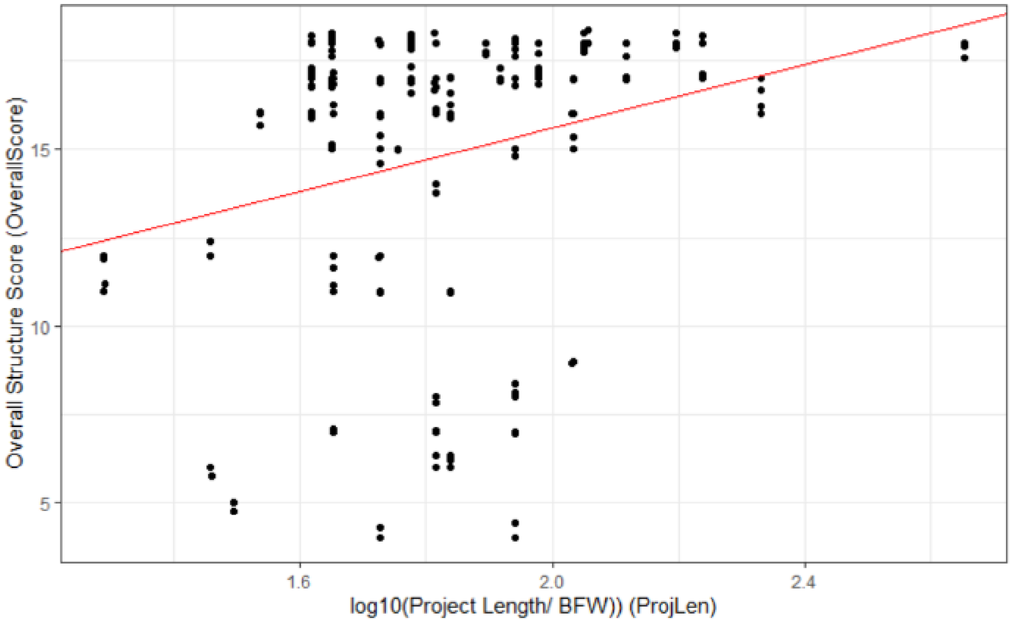


Figure 3.47 Relationship between overall structure score and scaled project length (n = 116).

3.3.3 Full Span Vanes

The average score in each structure assessment subcategory was determined for log and rock FSVs (Table 3.9). Log FSVs scored highest in *ScorePCTRemain*, a result that also occurred for all log structures and log PSVs (Tables 3.6 and 3.12). However, log FSVs scored the lowest in *ScoreAggrad*, which was also the result for PSVs (Table 3.12). An aggraded wood FSV is pictured in Figure 3.49a. Rock FSV scored highest in *ScorePCTRemain* but scored similarly to log FSVs in every other assessment subcategory (Table 3.9).

Mann-Whitney nonparametric 2-sample tests were conducted to determine if log or rock FSVs scored significantly differently in any of the structure assessment subcategories. The results of these tests indicate that rock and log FSVs did not score significantly differently in any of the structure assessment subcategories, indicating structure material does not account for significant differences in subcategory scores. However, the sample size for log FSVs was very small.

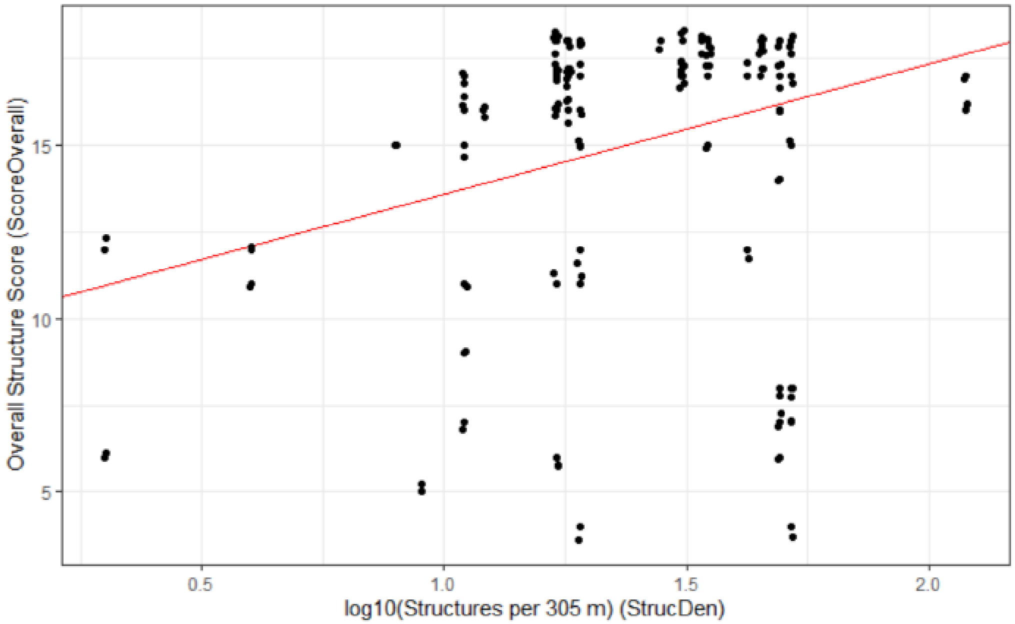


Figure 3.48 Relationship between overall structure score and scaled project length (n = 116).

Table 3.9 Average structure subcategory score, as a fraction of the maximum score for log (n = 8) and rock (n = 99) full span vanes (FSVs).

	Average Fraction of Highest Possible Score	
Subcategory Score	**Log FSVs**	**Rock FSVs**
ScorePCTRemain	0.97	0.94
ScoreMatMove	0.88	0.82
ScoreErosion	0.84	0.82
ScoreAggrad	0.78	0.83
ScoreFunction	0.83	0.82

Two significant models were developed for FSVs using *ScoreOverall* (Tables 3.10 and 3.11). One model included a structure-scale predictor, *KeyAng* (Table 3.10), and the other included a watershed-scale predictor, *MedDenCh* (Table 3.11). No significant models were developed for log FSVs, likely due to the small sample size. Moreover, project- and watershed-scale predictors could not be analyzed for log FSVs because there were too few projects and structures to develop linear mixed-effects models.

Table 3.10 Significant linear regression equation for rock full span vanes (FSVs; n = 36).

Structure Family	**Linear Regression Equation** (*ScoreOverall* = …)	**Adjusted r^2**	**Predicted r^2**	**Regression p-value**
Rock FSVs*	= 2.24 *KeyAng* - 1.74 *KeyAng* ^2	0.385	0.282	0.0001

* Regression coefficients for this multiple linear model are expressed as standardized regression coefficients.

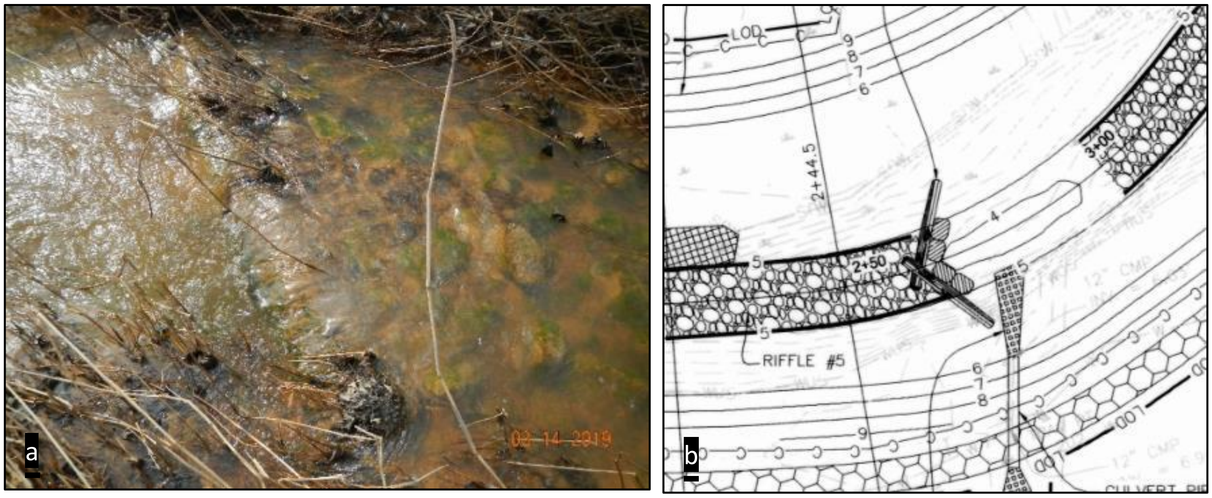


Figure 3.49 Log full span vane at restoration project 9, where the left arm is completely buried (a). The design drawing for the structure is provided in (b).

Table 3.11 Equation for linear mixed-effects model for rock full span vanes (FSVs; n = 91).

Structure Family	**Fixed Effect Regression Equation** (*ScoreOverall* = …)	**Model r^2**	**Fixed Effect r^2**	**Random Effect r^2**	**Fixed Effect p-value**
Rock FSVs	= -18.64 *MedDenCh*	0.172	0.172	0.00	< 0.001

There is a downward parabolic relationship between *ScoreOverall* and *KeyAng* for rock FSVs (n = 36, adj. r^2 = 0.385, p-value = 0.0001; Table 3.10; Figure 3.50). Given the pattern of the data, a logarithmic model was investigated (r^2 = 0.303); however, the fit was not as good as the final quadratic model. *KeyAng* ranged from 12° to 90°. The only structures included in the dataset of this model were FSVs with bank keys. The peak of the parabolic relationship occurs at 74°; however, key angles between 35° and 90° are within one point of this maximum, suggesting the optimal range of key-in angle is between 35° and 90°, with lower key angles corresponding to lower scores.

Finally, there was a negative relationship between *ScoreOverall* and *MedDenCh* for rock FSVs (n = 91, adj. r^2 = 0.172, p-value = < 0.001; Table 4-8; Figure 3.51). *MedDenCh* ranged from 1.8% to 5.6%. Of the variability in the data explained by this linear mixed-effects model (17.2%), all of it was explained by the fixed effect, *MedDenCh* (17.2%), rather than the random effect, *Project* (0.0%; see r^2 values in Table 3.11), indicating the relationship in Figure 3.51 was due solely to changes in land cover following construction.

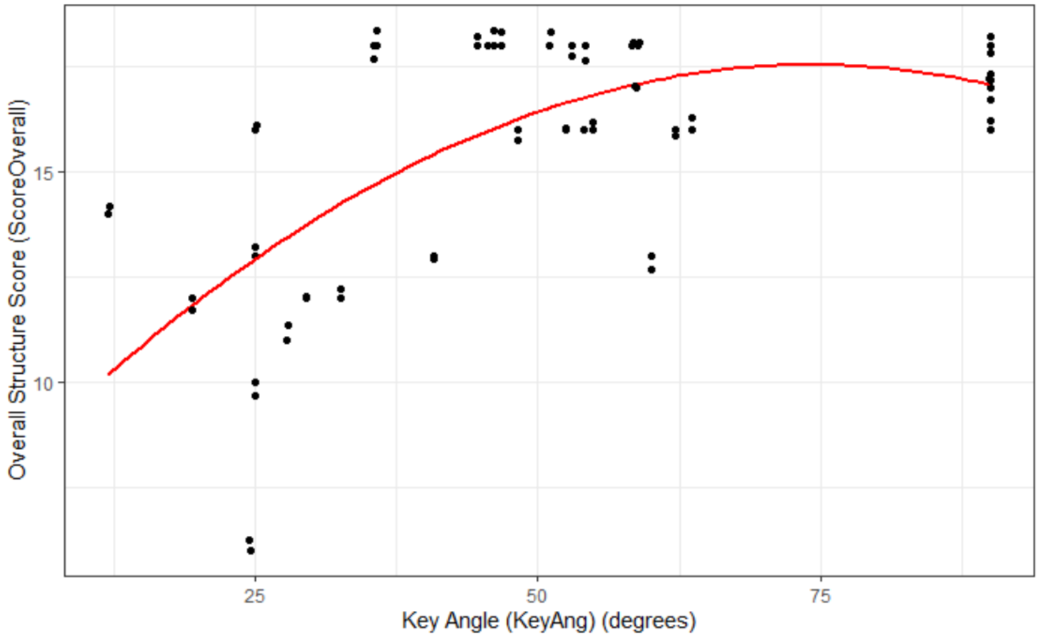


Figure 3.50 The influence of bank key angle on structure score for rock full span vanes.

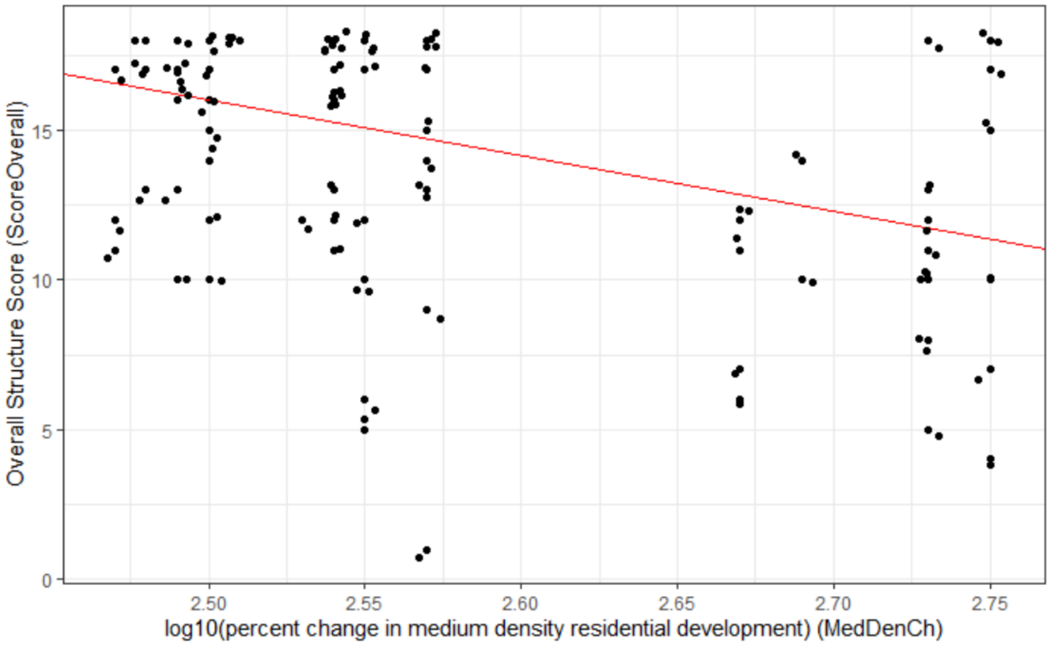


Figure 3.51 Changes in structure score for rock full span vanes with changes in medium density development following stream restoration project completion.

3.3.4 Partial Span Vanes

The average assessment subcategory scores of log and rock PSVs are summarized in Table 3.12. Log PSVs scored highest in *ScorePCTRemain* and lowest in *ScoreAggrad*. Rock PSVs scored lowest in *ScoreFunction* and highest in *ScoreAggrad*.

Table 3.12 Average subcategory score, as a fraction of the maximum score for log (n = 12) and rock (n = 51) partial span vanes (PSVs).

	Average Fraction of Highest Possible Score	
Subcategory Score	**Log PSVs**	**Rock PSVs**
*ScorePCTRemain**	1.00	0.82
*ScoreMatMove**	0.98	0.72
ScoreErosion	0.92	0.85
*ScoreAggrad**	0.71	0.92
ScoreFunction	0.75	0.68

* Assessment subcategory scores are significantly different ($\alpha < 0.05$) between log and rock partial span vanes using Mann-Whitney nonparametric 2-sample test.

Mann-Whitney nonparametric 2-sample tests were performed on log and rock PSVs to determine if they scored significantly differently in any structure assessment subcategory. Log PSVs scored significantly higher than rock PSVs in the structure structural stability categories: *ScorePCTRemain* and *ScoreMatMove*. However, rock PSVs scored significantly higher than log PSVs in *ScoreAggrad*. These results indicate that log PSVs may be more structurally stable than their rock counterparts, but more prone to unintended sedimentation or burial.

One significant model was developed for log PSVs using the *ScoreOverall* (Table 3.13). For log PSVs, *ScoreOverall* was negatively correlated to *USFlo* (n = 10, adj. $r^2 = 0.443$, p-value = 0.0214; Table 3.13; Figure 3.52). *USFlo* ranged from 1.6 to 12.9 bankfull widths. This relationship explains nearly half the variance in the structure scores for log partial span vanes. Given the small dataset, these results clearly indicate that log PSVs should be constructed in a series of vanes. Project- and watershed-scale predictors were not analyzed for log PSVs because there were too few projects and structures to develop linear mixed-effects models. Rock PSVs were analyzed but no significant linear models or linear mixed-effects models were developed for the *ScoreOverall*.

Table 3.13 Significant linear regression equation for log partial span vanes (PSVs; n = 10).

Structure Family	**Linear Regression Equation** (structure score = …)	**Adjusted r^2**	**Predicted r^2**	**Regression p-value**
Log PSV	= -7.13 *USFlo*	0.443	0.346	0.0214

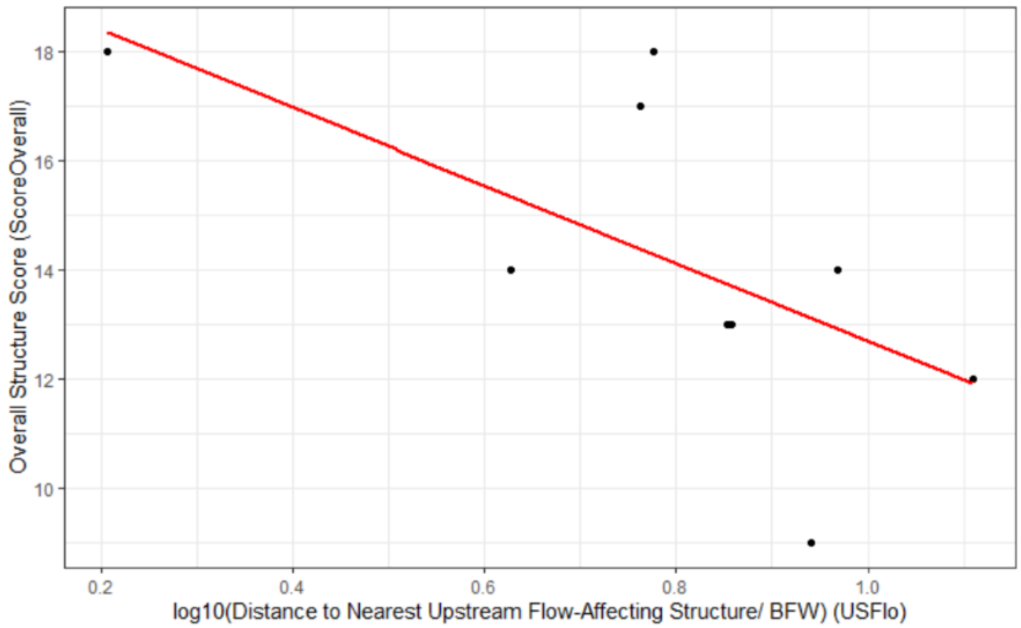


Figure 3.52 Relationship between the distance to an upstream flow-affecting structure and structure score for partial span vanes constructed of logs.

Further analyses were performed to determine if there were significant relationships between subcategory and other structure-scale predictor variables. For rock PSVs, there was one significant relationship for *ScoreMatMove* and two significant relationships for *ScoreAggrad* (Table 3.14). There was a positive relationship between *ScoreMatMove* and *ArmLen* (n = 58, adj. r^2 = 0.294, p-value = <0.0001). *ArmLen* ranged from 0.1 to 2.1 bankfull widths. This relationship suggests that as structure arm length increases, rock displacement occurs less frequently. Arm length increases as bank angle decreases; thus, PSVs with small bank angles may experience lower shear stresses because the frontal area perpendicular to the stream flow is minimized. For the *ScoreAggrad*, the first model indicated that *ScoreAggrad* increased as *ArmLen* decreased and as *ArmVert* increased (n = 58, adj. r^2 = 0.240, p-value = 0.0002). *ArmVert* ranged from 0.1 to 2.1 bankfull depths. The second model indicated that *ScoreAggrad* increased as *ArmLen* decreased and as *SillLen* increased (n = 58, adj. r^2 = 0.240, p-value = 0.0002). *SillLen* ranged from 0.0 to 0.5 bankfull widths. These relationships illustrate how the geometry of individual vane features are interdependent. Arm length increases as the bank angle decreases. This finding suggests that lower bank angles result in increased unintended aggradation (i.e. full or partial structure burial). Vane arms that are keyed into the bank at higher levels relative to bankfull depth and shorter j-hooks reduce aggradation.

3.3.5 Constructed Riffles

Structure assessment subcategory scores were analyzed and RFs scored highest in *ScoreFunction* and lowest in *ScoreMatMove* (Table 3.15). RFs typically failed by washing out but continued to function despite some material movement.

Table 3.14 Significant linear regressions developed using scores from structure assessment subcategories for partial span vanes (PSVs; n = 58).

Structure Family	Subcategory Score	Linear Regression Equation (subcategory score = …)	Adjusted r^2	Predicted r^2	Regression p-value
Rock PSVs	*ScoreMatMove*	= 1.82 *ArmLen*	0.294	0.257	< 0.0001
Rock PSVs *	*ScoreAggrad*	= -0.67 *ArmLen* + 0.33 *ArmVert*	0.240	0.199	0.0002
Rock PSVs *	*ScoreAggrad*	= -0.34 *ArmLen* - 0.27 *SillLen*	0.240	0.179	0.0002

* Regression coefficients for this multiple linear model are expressed as standardized regression coefficients.

Table 3.15 Average subcategory score, as a fraction of the maximum score for constructed riffles (n = 100).

Subcategory Score	Average Fraction of Highest Possible Score
ScorePCTRemain	0.73
ScoreMatMove	0.58
ScoreErosion	0.72
ScoreAggrad	0.69
ScoreFunction	0.74

There were three significant models for RFs using *ScoreOverall*: two corresponding to structure-scale predictors (Table 3.16) and one corresponding to a watershed-scale predictor (Table 3.17). RFs with downstream grade control scored 32% (equivalent to 6 points) higher than RFs lacking grade control (n = 100, adj. r^2 = 0.187, p-value = <0.0001; Figure 3.53). Of the RFs in this dataset, 36 out of 100 had downstream grade control. Moreover, the presence of downstream grade control significantly increased the score of RFs in every structure assessment subcategory.

Table 3.16 Significant linear regression equations for constructed riffles (RF).

Structure Family	Sample Size	Linear Regression Equation (structure score = …)	Adjusted r^2	Predicted r^2	Regression p-value
RF	100	= 8.47 for no downstream grade control = 14.20 for downstream grade control	0.187	0.166	< 0.0001
RF*	75	= 0.40 *RFLenWid* + 0.23 *RFSubDep*	0.259	0.228	< 0.0001

* Regression coefficients for the multiple linear model are expressed as standardized regression coefficients.

Table 3.17 Linear regression equations linear mixed-effects models for constructed riffles (RF; n = 100).

Structure Family	Fixed Effect Regression Equation (structure score = …)	Model r^2	Fixed Effect r^2	Random Effect r^2	Fixed Effect p-value
RF	= 9.50 + 18.72 *FracAg*	0.333	0.177	0.156	0.0205

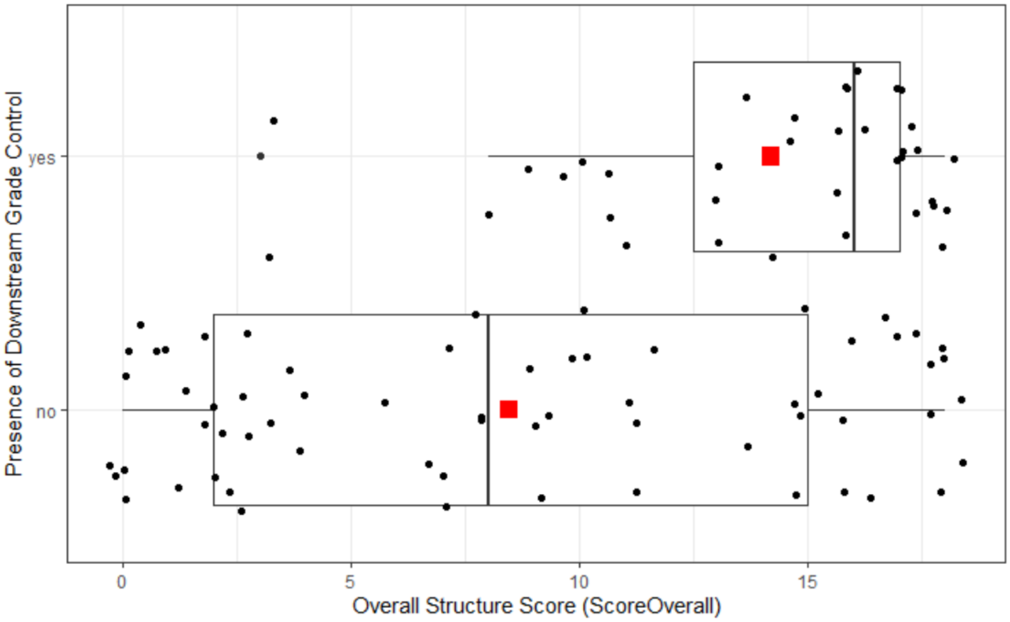


Figure 3.53 Influence of downstream grade control on structure scores for constructed riffles.

A multivariable linear regression developed for RFs indicated a positive relationship between *ScoreOverall* and *RFLenWid* and a positive relationship between *ScoreOverall* and *RFSubDep* (n = 75, adj. r^2 = 0.259, p-value = <0.0001; Table 3.16). *RFLenWid* ranged from 0.8 to 15.9 and *RFSubDep* ranged from 0.3 to 2.0 bankfull depths. The magnitude of the standardized regression coefficients indicates that *RFLenWid* carries more weight for predicting *ScoreOverall* than *RFSubDep*. Further analysis was performed to determine the relationship between the structure assessment subcategory scores and these two predictor variables. *RFLenWid* had significant, positive relationships with every structure assessment subcategory score. Furthermore, *RFSubDep* had a significant positive relationship with every structure assessment subcategory score except *ScoreMatMove*.

There was a positive relationship between *ScoreOverall* and *FracAg* for RFs (n = 100, adj. r^2 = 0.333, p-value = 0.0205; Table 3.17; Figure 3.54). *FracAg* ranged from 0.00 to 0.27. Of the variability in the data explained by this model (33.3%), roughly equal amounts were explained by the fixed effect, *FracAg* (17.1%), and the random effect, Project (15.6%; see adjusted r^2 values in Table 3.17). These results indicate that *FracAg* and differences between projects carry equal weight in predicting the performance of constructed riffles.

3.3.6 RSC Weirs

Each weir in an RSC-project was rated separately. The evaluated RSC weirs scored well overall and in all structure assessment categories, with some issues noted for material movement, erosion, and overall function (Table 3.18).

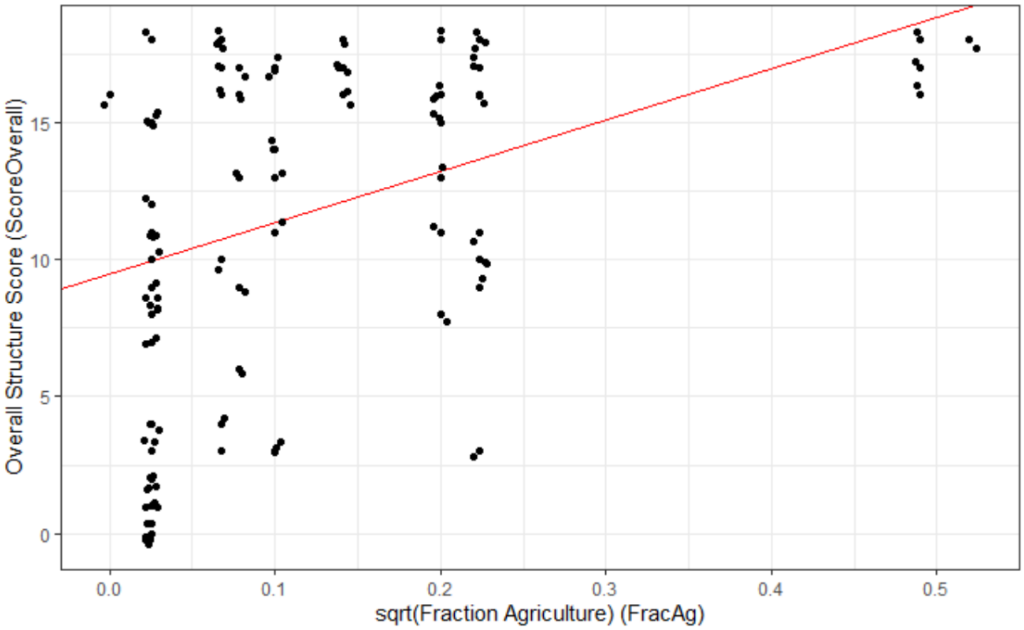


Figure 3.54 Relationship between the fraction of agricultural land cover in the watershed and the structure score for constructed riffles.

Table 3.18 Average subcategory score, as a fraction of the maximum score for the subcategory for regenerative stream conveyance (RSC) weirs (n = 59).

Subcategory Score	Average Fraction of Highest Possible Score
ScorePCTRemain	1.00
ScoreMatMove	0.97
ScoreErosion	0.96
ScoreAggrad	1.00
ScoreFunction	0.99

No significant models were developed for RSCs. The major factor that contributed to this was a lack of variability in *ScoreOverall*. Of the RSC weirs assessed, 49 out of 57 received scores of 18 out of 18. A possible reason for these high scores is that Anne Arundel County routinely performs maintenance on RSC structures when problems arise; therefore, relationships between RSC weir design and performance could not be established. Project- and watershed-scale predictors were not analyzed for RSC weirs because there were too few projects and structures to develop linear mixed-effects models.

3.3.7 Step Pools

Scores in each of the structure assessment subcategories were summarized for log and rock SPs (Table 3.19). Log SPs scored highest in *ScoreAggrad* and lowest in *ScoreErosion*. It should be noted that only three log SPs were assessed, so few conclusions should be draw about their performance. Rock SPs scored highest in *ScorePCTRemain* and lowest in *ScoreAggrad*. These results indicate that rock SPs exhibited good structural stability but were prone to unintended sedimentation/burial.

Table 3.19 Average subcategory score, as a fraction of the maximum score for the subcategory for log (n = 3) and rock (n = 27) step pools (SPs).

	Average Fraction of Highest Possible Score	
Subcategory Score	**Log SPs**	**Rock SPs**
ScorePCTRemain	0.75	0.93
ScoreMatMove	0.75	0.86
ScoreErosion	0.58	0.85
ScoreAggrad	1.00	0.84
*ScoreFunction**	0.67	0.90

* Assessment subcategory scores are significantly different ($\alpha < 0.05$) between log and rock PSVs using Mann-Whitney nonparametric 2-sample test.

Mann-Whitney nonparametric 2-sample tests were conducted to determine if there were significant differences between the subcategory scores of log and rock SPs. These tests indicated that log SPs scored significantly lower than rock SPs in *ScoreFunction*. Although the Mann-Whitney nonparametric 2-sample tests take sample size into account, it should be noted that log (n = 3) and rock (n = 26) SPs had very different sample sizes.

No significant models were developed for SPs. The major factor that contributed to this were small sample sizes: n = 26 for rock SPs and n = 3 for log SPs. Project- and watershed-scale predictors were not analyzed for SPs because there were too few projects and structures to develop linear mixed-effects models.

3.4 Discussion

3.4.1 Project Differences

Linear mixed-effects models were used to develop models for project- and watershed-scale predictors. These statistical models accounted for the fact that multiple structures could occur within a single project and would therefore have similar design characteristics. For many of these models, a large proportion of the variability in the data was explained by the random effect, *Project*, as opposed to a project- or watershed-scale predictor (the fixed effect; Table 3.20). Therefore, differences between individual projects can play a significant role in the performance of instream structures. Factors that could affect the performance of structures between projects are overall project design quality, construction quality, and project maintenance. Moreover, structures within a given project would have been affected by the same weather conditions during and immediately after construction, when the project and structures are especially sensitive to disturbance.

Table 3.20 Complete list of linear mixed-effects models developed for this project, where RF = constructed riffle, BP = bank protection, and FSV = full span vane.

Structure Family	**Fixed Effect Regression Equation** (structure score = …)	**Model r^2**	**Fixed Effect r^2**	**Random Effect r^2**	**Fixed Effect p-value**
All log structures	= -45.88 *DrainageK*	0.121	0.121	< 0.001	0.0379
All rock structures, excluding RFs	= -15.67 *MedDenCh*	0.207	0.080	0.126	0.0024
Rock BP	= -3.30 *BFDisch*	0.308	0.168	0.140	0.0029
Rock BP	= 3.75 *StrucDen*	0.309	0.027	0.282	0.0259
Rock BP	= 4.50 *ProjLen*	0.308	0.032	0.276	0.0319
Rock FSVs	= -18.64 *MedDenCh*	0.172	0.172	< 0.001	< 0.001
RFs	= 18.72 *FracAg*	0.333	0.177	0.156	0.0205

3.4.2 All Structures

When interpreting the results of this study, it should be noted that there was tremendous variability in the data. Even for significant relationships, high structure scores were often found along the entire range of a design variable. In many cases, relationships were strongly influenced by changing densities of low-scoring structures across the range of a predictor variable. This indicated that there are a range of design techniques that are effective and that other unquantified factors played a significant role in structure performance. Furthermore, streams are highly dynamic systems, which complicates any associated engineering design and scientific investigation.

In the structure assessment, log structures performed significantly higher than rock structures in the subcategories related to structural stability: *ScorePCTRemain* and *ScoreMatMove*. This finding could indicate that log structures are more stable than their rock counterparts, perhaps because entire tree boles require a greater amount of energy to mobilize compared to individual boulders. However, the sample size of rock structures (n = 492) was 10 times larger than the sample size of log structures (n = 36). Another explanation is that rock structures were generally preferred by designers in more urban watersheds, so existing log structures were applied in more rural watersheds with less flashy hydrology. Mann-Whitney nonparametric 2-sample tests confirmed that land use is significantly different between the watersheds of log and rock structures (p-value < 0.001), with log structures being constructed in watersheds with twice as much rural land cover and four times less urban land cover.

For all log structures, there was a negative relationship between structure performance and drainage network streambank erodibility (*DrainageK*), likely riparian soils in the watershed were more susceptible to bank erosion or bed scour. Project bank erodibility (*ProjectK*) is highly correlated to *DrainageK* (0.72), so *DrainageK* is related to the erodibility of the local channel boundaries through a given project reach.

There was a negative relationship between the overall performance of rock structures and change in medium density development since construction (*MedDenCh*). Increased *MedDenCh* resulted in poor structure performance related to unintended aggradation, unintended erosion, and impaired structure function. Medium density residential development includes lot sizes between 1/8 and 1/2 acres and encompasses common residential construction in the Baltimore-DC area (MDP, 2010). The impact of this development in a watershed may stem from hydrologic and sediment regime changes associated with increased impervious area. Impervious areas in a watershed rapidly conveys runoff to streams with little or no entrained sediment (Brown, 2000). This results in significant increases in peak discharges and the sediment transport capacity of streams, which often results in channel incision in urban environments (Brown, 2000). This finding suggested that these changes in hydrologic and sediment regime did not result in changes significant enough to affect structural stability, but that they did affect sediment transport and the overall function of structures. Therefore, increases in medium density development within a watershed after a restoration project has been constructed can alter stream hydrology and sediment transport such that instream structures used in stream restoration projects are negatively impacted. As a result, stream restoration designers should consult landuse plans to consider the impact of future land use on stream restoration designs.

3.4.3 Bank Protection

There was a positive relationship between the performance of rock bank protection (BP) and structure height. Pictures of low-scoring rock BP indicate that a major failure mechanism was overtopping, which causes erosion behind the structure (Figures 3.55-3.58). Taller rock BP likely experienced overtopping at a lower frequency, resulting in increased structure durability and overall performance.

Figure 3.55 Two bank protection structures from restoration project 7 that illustrate how overtopping contributed to structure degradation. In both cases, the bank above the structure is eroded and the structure is destabilized.

Tie-backs are a common design technique for BP to increase resiliency by preventing flanking behind the structure (Figure 3.58; NRCS, 2007e; Baird et al., 2015). None of the structures assessed in this project included tie-backs of any kind. There are two types of tie-backs: terminal and intermediate. Terminal tie-backs are located on the upstream or downstream end of BP, are angled into the bank at 30°, and stabilize the ends of the structure where flow expansion and turbulence occur (NRCS, 2007e; Baird et al., 2015). Failure often occurred at the ends of BP and was frequently observed with structures in this project, as depicted in Figures 3.56b, 3.57, and 3.58. Intermediate tie-backs occur at intervals along the length of BP, extend perpendicularly from the structure into the bank, and are spaced 1 to 2 channel widths (Baird et al., 2015). Given that flanking was a common issue for BP, tie-backs should be investigated as a design technique to increase durability.

Figure 3.56 Two examples of BP structures from restoration project 24, one that is functioning (a) and one that is failing (b). The failing rock wall is the downstream end of a longer structure, and failure seems to have stemmed from overtopping leading to structure destabilization.

Figure 3.57 Two stone toe structures from restoration project 33. Both structures illustrate that the ends of these bank protection structures are compromising structure function. The structure in picture (b) is experiencing bank erosion on both ends.

Figure 3.58 Two bank protection structures from restoration project 12 with erosion above the structures.

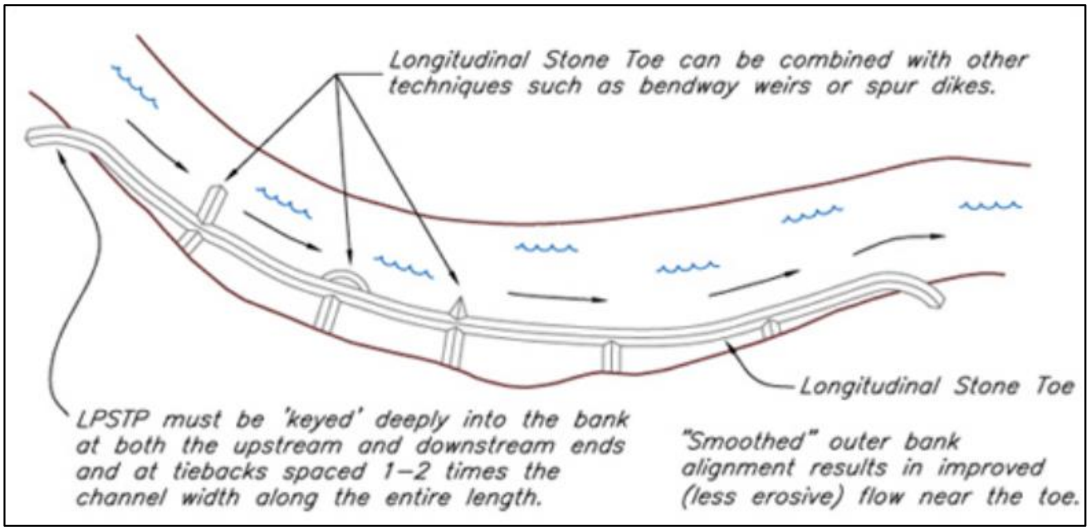


Figure 3.59 Use of tiebacks at ends and at intermediary points along stone toe bank protection (Baird et al., 2015).

A range of structures fall under the category of rock BP. These structures were grouped as either "stacked" or "unstacked". Stacked BP structures are generally imbricated rock walls, which are constructed by stacking rectangular stones that are between 0.67 - 3 ft. in diameter and weigh upwards of 500 lb. (King County WA, 1993; NRCS, 2007f). Stacked BP in this study was constructed out of rocks of intermediate diameter between 2- 3 ft. or 0.41- 3.33 bankfull depths. The recommended maximum height for imbricated rock walls is between 5- 10 ft. (MDE, 2000; NRCS, 2007f). However, the material specifications and design techniques of imbricated rock walls can, and were, applied to shorter rock toe protection as seen in Figure 3.60. Thus, actual wall heights in this study ranged from 1.4 - 8.0 ft. or 0.25 - 4.44 bankfull depths. For examples of stacked BP, see Figures 3.60-3.62.

Figure 3.60 Example of stacked rock toe from restoration project 9. Although not visible in this photograph, there is a layer of footers below the stones.

Figure 3.61 Examples of stacked bank protection from restoration project 16.

Unstacked BP in this study generally consisted of angular stones that were placed along the lower part of the streambank and are often referred to as stone toe protection. Stone toe generally utilizes riprap to provide reinforcement of the streambank toe against erosion and geotechnical failure (Massachusetts DEP, n.d.; MDE, 2000; Iowa DNR, 2018b; Bigham, 2020). The riprap used to construct stone toe is sized to resist a given design discharge or using general design guidelines developed for riprap revetments, such as being a minimum of the D100 or 1.5 times the D50 of native sediment (NRCS, 2007e; Baird et al., 2015). Although "stone toe" is consistent with the naming convention used in every design plan for unstacked BP, some projects also used stone toe to refer to short, stacked BP structures. Therefore, to avoid confusion and differentiate these design practices, unstacked BP will not be referred to as stone toe. The recommended height of unstacked BP ranges from baseflow depth to the height of vegetation or another stabilizing feature (NRCS, 2007e; Iowa DNR, 2018b). For examples of unstacked BP, see Figures 3.63 and 3.64.

Figure 3.62 Stacked BP from restoration project 3.

Figure 3.63 Example of unstacked BP from an unassessed restoration project in Maryland.

Figure 3.64 Examples of unstacked bank protection from restoration project 22.

Stacked BP performed significantly better than unstacked BP, likely because there were significant differences between the boulder size and wall height for each of these types of BP. Compared to unstacked BP, stacked BP was constructed four times taller using boulders that were three times larger. Given that there were positive relationships between rock BP performance and wall height, it is reasonable that stacked BP was more durable than unstacked BP given that the former was generally taller. Moreover, stacked BP experienced significantly fewer incidences of erosion and provided a greater degree of erosion resistance than unstacked BP. Although stacked BP outperformed unstacked BP, it should be noted that there were still successful instances of unstacked BP. As shown in Figure 3.43, the variability of performance of unstacked BP is much higher than that of stacked BP. Therefore, successful BP can be constructed using both design approaches, but unstacked BP is associated with a higher risk of failure.

Stacked and unstacked BP were analyzed separately, and wall height was only significant for stacked BP. This gives further credence to the conclusion that a major failure mechanism for rock walls is erosion behind the structure due to overtopping. Stacked BP had a range of wall heights (0.5-4.4 bankfull depths) four times greater than unstacked BP (0.3- 1.1 bankfull depths). Thus, shorter rock BP, which included both unstacked and stacked BP, was less durable than taller BP, which only included stacked BP due to its larger range of wall heights (see Figure 3.45).

Finally, there was a negative relationship between rock BP performance and bankfull discharge (*BFDisch*). Increased bankfull discharge is related to increased stream energy, which could increase the likelihood that materials would be mobilized, resulting in failure. Thus, BP structures in higher energy systems were more prone to failure.

3.4.4 Full Span Vanes

For rock full span vanes (FSVs), there was a downward parabolic relationship between performance and key angle (*KeyAng*), with the apex of this relationship occurring at 74° and angles between 35° and 90° being within one point of the apex. There were similar relationships between key angle and every assessment subcategory score except *ScorePCTRemain*, likely because structure keys are not in the active channel. The key, or tie-in, of a FSV is designed to prevent flanking around the arms, especially following construction before vegetation is established (Doll et al., 2003). Existing design guidance for FSV keys only state that bank keys should be utilized (Rosgen, 2001; Doll et al., 2003; Puckett, 2007; Gordon & Collins, 2016) or indicate generally how far keys should extend into the bank (MDE, 2000; VDSWC, 2004; MT DNRC, 2020). Most of the guidance for the orientation of keys is found in the sample images of FSVs provided in design resources. In these depictions, there are two distinct types of keys: extended-arm keys and cut-off sills (Figure 3.65). Extended-arm keys are shown as an extension of the vane arms that extends into the bank (Figure 3.12). Cut-off sills are labeled as such, occur where the vane arm meets the bank, and extend perpendicularly into the bank (Figure 3.12). Structures in this study with high key angles had both cut-off sills and extended-arm sills. Traditional cross vanes with high key angles utilized cutoff sills while v-vanes with large a large angle between the arms typically utilized extended-arm sills. The results of this study indicate that high key angles are positively correlated to structure performance, regardless of what type of key a structure has. High key angles may benefit structures by orienting keys more perpendicularly to overbank flows, thus, forcing erosive overbanks flows over bank keys instead of around them, which could cause flanking. Another possible explanation of this finding is that higher key angles place bank keys farther away from the edge of the channel bank, reducing the likelihood that the bank key is undermined if bank erosion occurs.

Similar to all rock structures, there was a negative relationship between the performance of rock FSVs and the percent change in medium density land use since project construction (*MedDenCh*), which was correlated to increased erosion rates and decreased structure function. This correlation is likely due to changes in hydrology and sediment transport regime that occur as impervious surface area increases in watersheds as residential neighborhoods are constructed. These changes include increased peak discharges

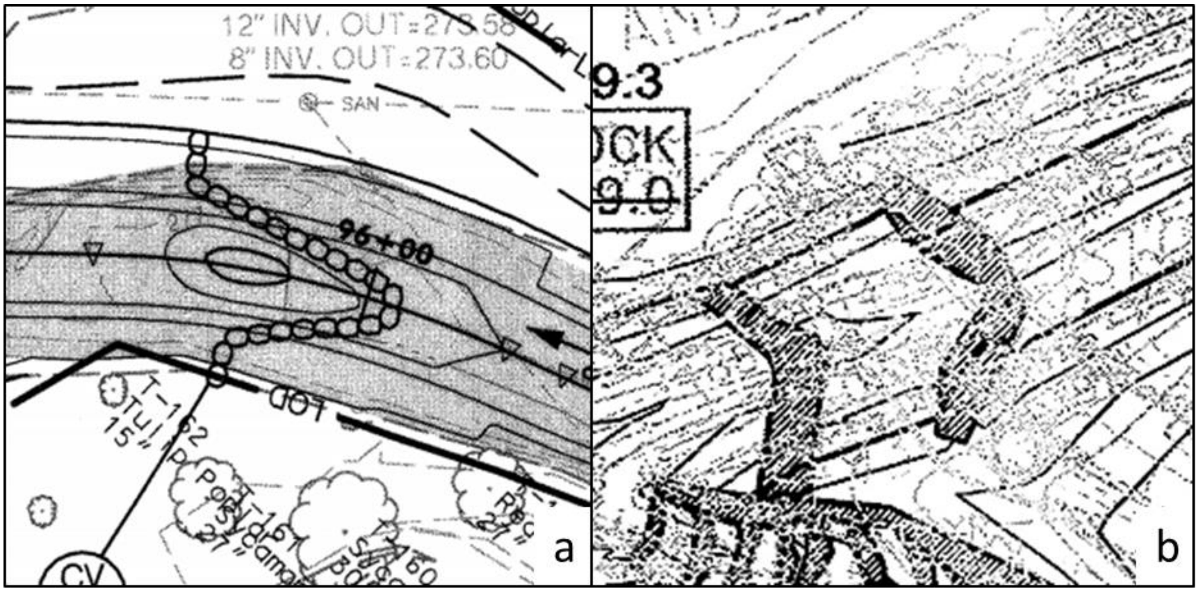


Figure 3.65 Examples of full span vanes with high key-in angles: a traditional cross vane from restoration project 28 that utilized cut-off sill keys (a) and two v-vanes from restoration project 37 that had extended arm keys (b).

and sediment transport capacity, which can impair FSV function by causing erosion. This relationship was likely present for FSVs because they are located within the active channel and are highly affected by streamflow and sediment transport.

3.4.5 Partial Span Vanes

There was a positive relationship between the performance of log partial span vanes (PSVs), particularly related to aggradation and overall function, and the distance to the nearest upstream flow-affecting structure (*USFlo*). This result is consistent with existing design literature. PSVs are often constructed in series along the outside of meander bends (McCullah & Gray, 2005). Moreover, NRCS (2007a) states that placing PSVs in series may increase individual structure durability.

Design guidance from MDE (2000) recommends a spacing of 5 to 7 channel widths for meander development and a minimum spacing of 1 channel width for habitat creation. Rosgen (2001) recommends spacing between 1.5 and 2.5 bankfull widths, depending on bank angle (referred to as departure angle) and radius of curvature/bankfull width. In contrast, Sotiropoulos & Diplas (2014) recommend a vector-based spacing method which, instead of utilizing constant spacings, involves placing PSVs based on relative angles to the apex of the meander and other PSVs (for a full discussion, see Section 3.13 and Figure 3.18). This vector-based method generally yields structure spacings between 1 to 3 bankfull widths. Using numerical and scale hydraulic models, Siefken et al. (2021) recommend an optimal spacing for PSVs of 0.75 channel widths. The range of distances to other structures (FSV, PSV, RSC, SP) recorded in this study was 1.6 to 12.9 bankfull widths, and it appears that log PSV performance was improved when they were located less than 6 bankfull widths away from other structures. This consistent with the aforementioned design recommendations, which recommend spacing PSVs at the lower end of the range that was assessed.

Study results also indicated that less material movement occurred with longer vane arms, which are also associated with smaller angles between the vane arm and the bank. Both bank angle and arm length are important, interdependent design factors for PSVs. Longer arm lengths were associated with reduced dislocation of the vane rocks and but a greater risk of sedimentation. PSVs with small bank angles may experience lower shear stresses because the frontal area perpendicular to the stream flow is minimized, decreasing the shear stress on individual rocks and potentially encouraging sedimentation. Longer sills, which are associated with j-hook vanes, can also increase sedimentation around the structure. Additionally, increased vertical distance in the channel occupied by the structure could have resulted in a greater drop height, reducing the risk of sedimentation around the structure.

3.4.6 Constructed Riffles

The presence of grade control directly abutting the downstream end of constructed riffles (RFs) had a positive effect on their performance. RFs typically “fail” when the RF material is washed downstream (Radspinner et al., 2010). Having larger rocks or logs at the downstream end of RFs discourages RF substrate from washing away. Walker (2002) recommends constructing RFs with large particles at the crest and downstream end to provide stability. The results of this study support this design recommendation.

RFs scored higher if they had a larger length to width ratio (i.e. were longer; *RFLenWid*) and if they were composed of deeper substrate (*RFSubDep*). These results indicate that RFs should be constructed such that there is sufficient material to allow them to adjust in the channel. It is likely that longer RFs scored higher because, even if some of the riffle washed out, elements of the structure were still present and functional. Similarly, RFs constructed out of deeper substrate could lose more material and adjust to a greater degree, increasing the likelihood that a stable functional bedform remained in the channel. Natural riffle length-width ratios are between 1.3 and 1.8 (Grant et al., 1990; Carling & Orr, 2000). Prior design guidance recommended riffle length to width ratios of 1 to 3 (Gore & Petts, 1989). Interestingly, the findings of this study indicate that RFs with high length to width ratios, especially above a threshold of 4.5, score higher. Given that length to width ratios greater than 4.5 are significantly larger than what occurs in natural riffles, long RFs could have performed well by armoring the channel bed rather than emulating the function/ form of natural riffles. This observation is supported by instances of RFs constructed in close proximity to one another, also effectively armoring the bed. For example, in Figure 3.66 there is an exceptionally long RF and four other RFs, all spaced far less than the five to seven bankfull widths observed in natural conditions (Montgomery & Buffington, 1997; Walker, 2002). While these RFs performed uniformly well (scores of 15 and 16), their function was more comparable to bed armor than natural bedforms. Given the increasing use of RFs, additional research on the spacing and the length to width ratio of these structures is recommended.

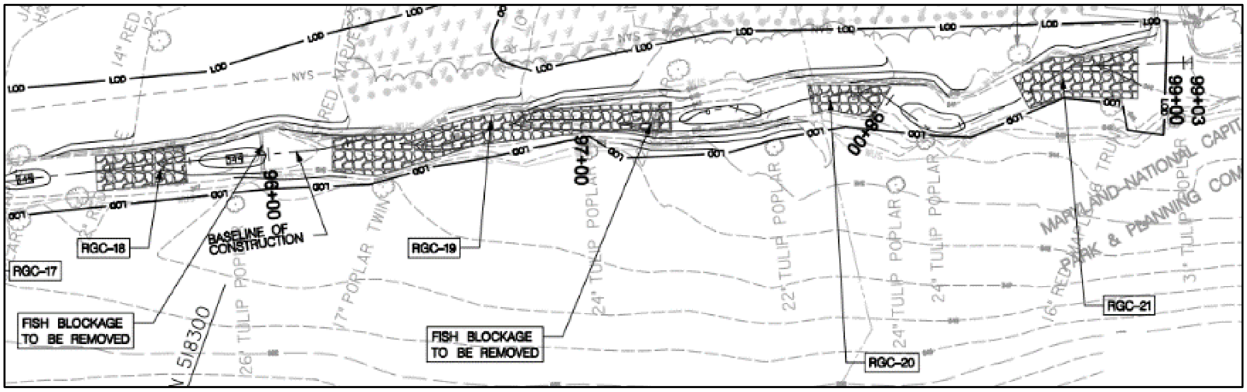


Figure 3.66 Closely-spaced and high length:width RFs from restoration project 10.

3.4.7 Step Pools

There were no significant results for step pools (SPs). Further studies need to be performed. All statistical relationships developed for SPs in this study were weak, likely due to the small sample size. It is recommended that a larger sample size be utilized in future studies. Although there was more variability in the scores of SPs than RSC weirs, two thirds of the assessed SPs scored within two points of the highest possible score. High scores for SPs could have been the result of conservative designs which utilized large materials and effectively armored the channel. Moreover, SPs consist of multiple structures in proximity, all of which could have a protective effect on one another, resulting in better structure function.

3.5 Study Limitations

There are certain limitations in the experimental design of this study that may affect the strength and interpretation of the results. A potential source of error in this study is that there was no way to tell if structures had been repaired unless such activities were described in monitoring reports. Moreover, structures were evaluated under the assumption that they were constructed as indicated in the design drawings or as-builts. Some error was likely the result of differences in the design drawings (when as-builts were not available) and actual construction.

The study results only relate to the engineering performance of the assessed instream structures, rather than ecological improvement or degradation that resulted from them. In some cases, structures may have been constructed solely to create pool-riffle or other habitat, but these functions were not assessed. Finally, these results are most applicable to the mid-Atlantic United States and may not carry over to other regions, such as where there is snowmelt-influenced hydrology or transport-limited streams.

3.6 Instream Structures Conclusions

Stream restoration is an expanding multibillion-dollar industry and instream structures are a common element of many designs, particularly in urban watersheds where natural channel migration is limited by floodplain encroachment. Similar to stream restoration itself, instream structures aim to locally address degradation that is frequently linked to watershed-scale issues. Long-term failure of instream structures is common, there are no formal design standards, and there is little consensus about whether structures designed to create habitat actually provide ecological value. However, instream structures are necessary to limit bank retreat and channel incision, to protect infrastructure and to limit additional channel degradation.

This study aimed to improve the application and design of instream structures by determining what design parameters and site and watershed conditions were correlated to structure success. Instream structures located in restoration projects in the state of Maryland were assessed based on their structural stability, impact on sediment transport, and geomorphic function. In total, 536 structures from 39 completed projects were assessed. These structures were grouped into six families of structures that are common in stream restoration in the Mid-Atlantic United States: bank protection (BP), full span vanes (FSV), partial span vanes (PSV), constructed riffles (RF), regenerative stream conveyances (RSC), and step pools (SP).

Some general observations were made for all structure types. Greater rates of structure failure occurred in watersheds with more erodible streambank soils. Greater rates of medium density development in a watershed after a restoration project was completed were correlated with lower structure success for all structures, especially rock FSVs. Residential development in this area typically occurs on rural lands and the increase in impervious surface area causes increased runoff volume and peak flows. Stream restoration projects implemented in watersheds where future development is anticipated will require a higher degree of planning and more robust structure designs.

For rock BP, taller walls increased structure success because the frequency of overtopping and scour behind the structure was reduced. These results are consistent with the finding that stacked BP (also referred to as imbricated rock walls) performed better than unstacked BP (also referred to as stone toe), because stacked BP is typically constructed four times taller with boulders that are three times larger compared to unstacked BP. BP success was also negatively related to bankfull discharge, indicating that greater flow energy decreases structure performance.

For log PSVs, there was evidence that upstream flow-affecting structures (FSV, PSV, RSC, SP) had a protective effect on downstream structures. Additionally for FSVs, the installation of a bank key or cutoff sill at angles between 35° and 90° improved structure performance.

Several design factors for RFs were correlated with structure success. RFs were more durable when constructed with downstream grade control, which likely stabilize the RF against scour and material migration. Moreover, RFs that were relatively longer (L:W>4.5) and constructed with deeper substrate were more durable. Longer RFs effectively armored the channel bed, making complete structure failure unlikely. Similarly, RFs constructed using deeper substrate likely performed better because they could experience greater scour before the structure function was compromised. Given that natural riffles have L:W of less than 2.0 and occur at greater spacings than observed in several stream restoration projects, it is apparent that some constructed riffles essentially serve as channel armor/riprap instead of replicating natural stream bedforms. More focus should be placed on correctly siting constructed riffles in the planform and designing riffles with L:W of less than 3.0.

Although this study developed several statistically significant correlations, it should be noted that a range of design techniques can be effective and that other factors play significant roles in structure success such as design quality, construction quality, weather conditions during and immediately after construction, and structure maintenance. Structure evaluation in this project did not assess the ecological function/ value of structures, so future studies should explore whether structures, particularly those that have stated habitat functions (FSV, PSV, RF, SP), are ecologically beneficial.

4.0 Comparison of 1D and 2D HEC-RAS Models for Stream Restoration Design

The Hydrologic Engineering Center (HEC) River Analysis System (HEC-RAS) is hydraulic software which allows the calculation of one-dimensional (1D) steady and 1D and 2D unsteady flow hydraulics in river systems, as well as 1D sediment transport and water quality modeling. The latest version, HEC-RAS 6.0 Beta, also allows 2D sediment transport modeling. HEC-RAS is approved for use by the U.S. Federal Emergency Management Agency (FEMA) for flood insurance studies (FIS); therefore, HEC-RAS is commonly used in stream restoration design because a FEMA-approved hydraulic model is required to evaluate potential changes to base flood elevations resulting from restoration projects in areas participating in the National Flood Insurance Program (NFIP).

Traditionally, a 1D steady state model is developed to calculate water surface elevations for flood insurance studies. Because these models also provide velocity and shear stress, they can be used for stream restoration design. Two-dimensional models calculate stream flow both downstream and across the channel, allowing evaluation of cross-channel flows in meander bends and at structures. However, 2D models require high resolution topographic data and the development of a flood hydrograph, as opposed to just the peak discharges. With the greater availability of high resolution topographic data and improved utilities for handling spatial data in HEC-RAS, the time and effort required to develop 2D HEC-RAS models has decreased in recent years. Therefore, the goal of this study was to compare 1D and 2D models of stream restoration projects to determine if the 2D model allows the identification of potential areas of high velocity and shear stress that are not revealed using a 1D model, thus justifying the additional time and expense to develop a 2D model.

4.1 HEC-RAS

In a river reach setting, the 1D HEC-RAS analysis considers flow velocity perpendicular to the channel cross section. Stream cross sections are input at locations that are representative of the channel and floodplain geometry, at road crossings, and where the channel slope, roughness, or discharge change and the remaining channel geometry is then interpolated between the cross sections. Typical cross section spacings range from 100 ft. along steep streams to 5000 ft. for large, flat rivers, although spacings on the order of a few feet are recommended near structures (Figure 4.1a; USACE, 2016). Resistance to flow is typically specified using Manning's roughness coefficients. Because there is typically a large difference in both land slope and roughness between the main channel and the floodplains, HEC-RAS calculates the "conveyance" of the main channel and floodplains separately, essentially viewing the river and floodplain as three parallel channels (Figure 4.1a). For FEMA studies, water surface elevations are determined for peak flood discharges with recurrence intervals of 10, 50, 100, and 500 years.

In contrast, the 2D analysis models velocity along and down the channel, which facilitates simulating more complex flow patterns. Rather than relying on interpolated water surface elevation between channel cross sections, as is the case on 1D modeling, 2D modeling allows representing the stream as a mesh consisting of small elements (Figure 4.1b; ShahiriParsa et al. 2016).

The 2D modeling allows flow to vary along and across the flow path. This feature is advantageous within boundaries of natural stream channels where there is extensive meandering or abrupt changes in the flow direction that cause uneven lateral elevation of the water surface. In general, 2D modeling provides better estimates of parameters such as flow depth, velocity, and shear stress where flow patterns are complex.

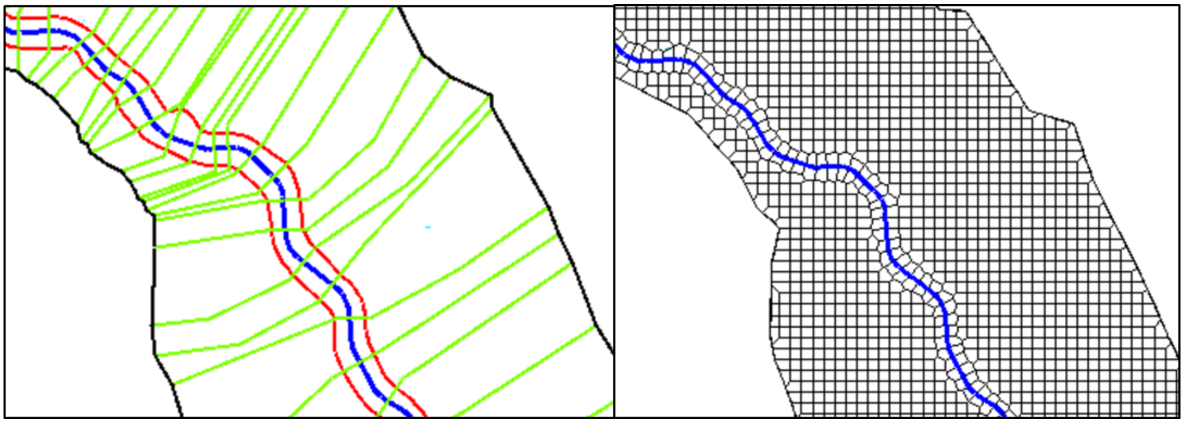


Figure 4.1   Stream channel (blue lines), main channel banks (red lines), and cross sections (green lines) in a 1D HEC-RAS model (a) and grids (black lines) in a 2D model of the same stream reach.

The newer updates of HEC-RAS (5.0 and higher) offer the option to run the full 2D momentum equations (full St. Venant) of the 2D diffusion wave equations depending on flow relation to critical state. When flow is supercritical (Froude Number > 1), the inertial terms are ignored and the 2D momentum equation is reduced to the diffusion wave form. Subcritical flows are controlled by downstream obstructions such as bridges, culverts, or instream structures and the model simulates the surface elevation of water ponding behind the obstructions (i.e. backwater). While HEC-RAS has routines for modeling inline stream structures, these routines are limited to gated spillways and traditional weirs (broad crested, Ogee, and sharp crested).

While FEMA FISs focus on water surface elevations to define the 100-yr floodplain extent, stream restoration design also utilizes velocity and shear stress predictions. Shear stress is estimated as a function of water specific weight, the channel hydraulic radius, and the slope of the energy grade line (Equation 4-1):

$$\tau = \gamma R S_f \tag{4-1}$$

where: γ = specific weight of water (62.43 lbf/ft.^{3});

R = hydraulic radius (ft.); and

S_f = slope of the energy grade line (friction slope).

The default option for determining S_f in the 1D model is the discharge (Q) divided by the conveyance (K), although multiple calculation options are available, depending on flow conditions (USACE, 2016). For 1D modeling, HEC-RAS estimates a shear stress value for each cross section using user-defined slices within the cross section. In the 2D model, an average shear stress is estimated across each face in a cell and then interpolated between faces, providing more detailed resolution of the shear stress.

4.2 Modeling Methods

4.2.1 Site Selection

For the comparison of 1D/2D HEC-RAS models, six stream restoration sites were chosen from over 60 projects in the overall research. The site selection was based on multiple characteristics: project designs scores, structure variety and number, and availability of existing information. The six project sites modelled and information on the projects are shown in Tables 4.1 and 4.2. Two projects were selected from high, mid ranged and low design scores. The second criteria used for project selection was the variety and number of structures used during restoration. Projects were selected to provide a range of different instream structures, including step-pools, pool-riffles, cross-vanes, j-hooks, and rock walls. The final, but not limiting criterion, was the existing information about the restoration, which included if a 1D HEC-RAS model was available and the comprehensiveness of the design plans. Two projects had existing FEMA 1D HEC-RAS models. Because these models did not explicitly represent the instream structures, the 1D FEMA models were rebuilt to include the instream structures. were selected to allow comparison between a HEC-RAS model completed for a floodplain study and a similar model that explicitly modeled instream structures based on the design plans. For the four projects that did not have current FEMA models, both 1D and 2D models were developed using GIS data, USGS stream gage flow data and the design plans.

4.2.2 1D Model Development

4.2.2.1 Geometry

The geometry of 1D HEC-RAS is developed using cross sections; the user inputs a series of cross-sections that represent the land surface at stations along the reach and the model completes calculations at each cross-section with the given flow and boundary conditions. It should be noted that the geometry created for the 1D model was also used in the 2D terrain model.

There were three starting conditions for the 1D models: a 1D model existed with structures (Project 50); a 1D model existed without structures (Project 24); or, no model existed (4 projects). These conditions affected the methodology used in constructing the cross-sections. The 1D model with structures did not need to be altered to run, but the model was reconstructed so it could be easily converted into a 2D model. For the 1D model without structures, the design plans were utilized to represent the structures in the model. The number of cross sections needed to capture flow hydraulics through the structures was investigated. While increasing the number of structures improved the model output, the increased detail made model development time-consuming and more prone to errors. Ultimately, four cross sections per instream structure was selected to balance modeler time with model accuracy.

Using the typical cross-sections and structures tables in the design plans, each structure was represented with three to four cross-sections placed at significant gradient changes in the longitudinal profile or to represent the structure complexity, size, and upstream and downstream terrain. For example, for a

Table 4.1 Project sites selected for modelling.

Project Number	County	Watershed Area (mi^2)	Project Length (ft.)	Design Score	Cross Sections	Channel Slope (ft/ft)	100-yr Discharge (cfs)	Year Constructed	Grid Size (ft)	Cells per Channel Width	2D Run Time (min)
24	Baltimore	0.22	1572	87	234	0.0261	606	2004	3.28	12	41
25	Calvert	0.04	671	36	98	0.017	43	2009	1.64* 3.28	2	6
41	Harford	54	1500	33	47	0.0071	20100	2004	3.28	8	85
47	Howard	0.08	1259	100	160	0.0354	729	2014	3	2	20
50	Howard	0.54	1500	75	73	0.0094	1088	2013	5	4	86
55	Montgomery	0.37	850	84	120	0.016	557	2012	3.28	2	35

* Smaller grid size used in main channel and larger grid size used on floodplain.

Table 4.2 Structures included in each project

Project Number	Number of Structures	Structure Types
24	45	Step pool, imbricated rock wall, j-hook, cross vane
25	27	Cross vane, j-hook, step pool
41	9	Single arm vane, stone toe, riffle grade control, cross vane, j-hook
47	141	Riffle grade control with weirs, step pool, stone toe, imbricated rock wall
50	49	Step pool, riffle grade control, stone toe
55	35	Riffle grade control, stone toe

typical single step pool, at least four cross-sections were needed: the first to represent the top of the step, the second to capture the step drop, the third for the pool, and the fourth to transition out of the pool appropriately. If the step-pool was followed by another step-pool, the fourth cross-section of the first step-pool would be replaced with a cross-section representing the top of the next step. If the design plans showed that the stream bed transitioned into and was flush with the first step, no transitional cross-section was needed preceding the structure. On the other hand, if the structure had a sudden terrain change, as some rock structures do, an upstream cross-section was placed to better represent the abrupt transition at that point.

Four of the restoration projects did not have available HEC-RAS models, so both 1D and 2D models were developed. Once the projections were set, a DEM of the surrounding area was downloaded and input into HEC-RAS as a terrain. Using both the terrain and design plans, the stream thalweg/centerline was drawn into RAS Mapper. Generally this was done by turning on the terrain contour lines and following the stream bed and then comparing the shape and stationing of the thalweg to the design plans. If there was a significant difference, the centerline was edited to match the design plans as closely as possible. Then, cross-sections were added for the structures as described above. Additional cross-sections were added at each given cross-section in the design plans and at every significant change in channel slope. Cross-sections placed at changes in slope did not usually have a plan cross-section so the typical cross-section of the design plan was used. In these cross-sections, the design longitudinal profile was used to determine elevations.

4.2.2.2 Roughness

HEC-RAS requires a roughness coefficient associated with the geometry to run. Options include Manning's n values or k roughness coefficients. Manning's n was used for this project. In 1D, roughness values are assigned per cross-section for the left-of-bank (LOB), channel, and right-of-bank (ROB). A Manning's roughness of 0.035 was used for the channel and 0.15 for out of bank areas.

4.2.2.3 Flow Data

1D HEC-RAS can be run using both steady and unsteady flows. Since floodplain models are 1D, steady-state, the 1D models were conducting using a steady flow analysis. For this, the peak flow for a 100-year storm event was entered into the steady flow data editor tool in HEC-RAS as a boundary condition. This requires a flow rate input (cfs) at the first upstream cross section in the HEC-RAS model. In addition to the flow rate, a normal depth at the downstream end of the 1D model was entered as a boundary condition. This was entered as a friction slope which was determined at the last cross section by plotting a profile line against the model terrain. For any subsequent inflow at the project site, including tributaries and stormwater culverts, additional flow rates were added to cross sections corresponding to these confluences. For instances where 1D HEC-RAS models were available and included flow data, the 100-year storm event steady flow was used. In the case that no 1D HEC-RAS was present and/or lacked flow data, 100-year flow data was retrieved using Streamstats, a USGS streamflow statistic and spatial analyst tool for water resource applications (USGS, 2016).

4.2.3 2D Model

4.2.3.1 Generating 2D Terrain

A critical part of constructing a 2D model was creating the channel geometry, which is referred to as the terrain in HEC-RAS. The typical process of building a terrain is to access a digital elevation model (DEM) of the study area and then add the stream/river bathymetry either in HEC-RAS or a separate software such as AutoCAD. In this study, HEC-RAS itself was used for terrain modifications to build the stream bathymetry and structures. The HEC-RAS terrain modification system functions through the creation and manipulation of cross-sections. Essentially, one creates a new geometry and adds cross-sections in RASMapper, and then alters the cross-sections in the Geometry window. This process for the input and manipulation of cross-sections is the same as for creating the 1D channel geometry. Once the cross-sections are edited, HEC-RAS has a function to create a terrain from these cross-section by interpolating between them. The bathymetry can also be made in other software and exported into HEC-RAS. For example, a surface can be created in AutoCAD/Civil3D using survey data and then exported into HEC-RAS as a GeoTIFF file. This new terrain can then be merged with the project site DEM to create a final terrain for the 2D model. For this project, Maryland statewide DEMs were retrieved from the Maryland Mapping and GIS Data Portal and utilized the North American Datum of 1983 (NAD83) and North American Vertical Datum of 1988 (NAVD 88).

As stated above, there were three starting conditions in terms of a 1D model: a 1D model existed with structures; a 1D model existed without structures; or, no 1D model existed. These conditions affected the methodology used in constructing the stream bathymetry. Although the existence of a 1D model with structures was convenient because all the cross-sections needed to create the bathymetry already existed, two main issues arose when the 2D model was developed. The first issue was the lack of or incorrect reach shape and projections. Since 1D modelling assumes a straight reach between cross-sections, there is no need to input the correct shape of a reach as long as the stationing of the cross-sections is correct. To correct the reach shape, a new 1D model was created with the correct the reach shape while maintaining the same cross-sections and stationing. A bathymetry terrain was then created and merged with the wider area terrain. The second issue with the existing 1D model was a lack of or incorrect projections. Usually projections are not needed for a 1D model, but they are necessary when building a bathymetric terrain by interpolating cross-sections. An issue arose when the 1D models, even when the correct projection was input, would yield bathymetry terrains that were in the wrong location and/or the wrong size. To correct this, the terrains were translated and/or rescaled in GIS software, input back into HEC-RAS, and then merged with the area terrain. When a 1D model existed but without structures, the design plans were used to add the missing structures. After the structure cross sections were added, the cross-sections were interpolated and merged with the area terrain. The longitudinal profile of the bathymetry was then checked against the design plan longitudinal profile. Four of the selected projects did not an existing 1D model. In this case, both the 1D and 2D were constructed based on the design plans.

4.2.3.2 Computational Mesh

Once the terrain was constructed, the 2D flow area was delineated and breaklines were added. Breaklines can be included in the 2D model flow area so that, when recomputed, the mesh aligns with the breakline. The size of grids surrounding the breaklines can also be changed. The usual practice is to enter a breakline along the thalweg so that the grids representing the channel can be aligned and grids altered in size. This practice was done for each restoration project modeled.

Once the flow area and breaklines were constructed, the computational mesh was created. The appropriate grid size varies with each project and even between areas in a single project. Complex terrain, such as found around instream structures, is represented best with small grid sizes; however, as the number of grids in the model overall increases, so does the computational time required to run the model. To assess appropriate grid sizes, Project 25 was repeatedly run with various floodplain and channel grid sizes and with or without a thalweg breakline, shown in Table 4.3. The water surface elevation (WSE) and shear stress (SS) outputs were examined in the longitudinal direction along the thalweg. Visually comparing outputs showed three things: 1) WSE and SS outputs were more sensitive to changes in channel (i.e. breakline) grid size than floodplain grid size ; 2) the SS outputs did not converge to a consistent profile as grid sizes decreased, which emphasized that the SS output should be viewed as an estimate; and, 3) the WSE profile did converge to a sing profile as grid sizes decreased, which was estimated well when the breakline cell size was 3.28 ft or, alternatively, when there were two cells per channel width. Given these results, the meshes were generally set with either a minimum breakline cell size of 3.28 ft or minimum of two cells per channel width. The exception to this was Project 41, which was changed due to the project being a large river with an extensive floodplain.

Table 4.3 Grid configurations tested.

Grid Size (ft)	Breakline Size (ft)	Cells per Channel Width	Grid Size (ft)	Breakline Size (ft)	Cells per Channel Width
13.12	None	0.5	6.56	0.82	8
13.12	13.12	0.5	3.28	None	2
13.12	6.56	1	3.28	3.28	2
13.12	3.28	2	3.28	1.64	4
13.12	1.64	4	3.28	0.82	8
13.12	0.82	8	1.64	None	4
6.56	None	1	1.64	1.64	4
6.56	6.56	1	1.64	0.82	8
6.56	3.28	2	0.82	None	8
6.56	1.64	4	0.82	0.82	8

4.2.3.3 Flow Data

2D HEC-RAS models need to be computed with unsteady flow. For this analysis, two boundary conditions are required in the unsteady flow data editor tool. First, a flow hydrograph (Q vs time) for a 100-year storm was entered at the first cross section in the HEC-RAS model. Since these data were not available in the existing 1D HEC-RAS models, a standard NRCS dimensionless unit hydrograph (DUH) was used to create a flow hydrograph; a spreadsheet developed by Natural Resources Conservation Service (NRCS) was applied in these cases (NRCS, 2016). This tool required the entry of the watershed area, peak discharge and time of concentration. The time of concentration was calculated using the Kirpich equation as shown below in Equation 4-2, where T_c is the time of concentration in minutes, L is the longest flow path in feet and S is the average watershed slope. The longest flowpath and average watershed slope were determined using GIS. This flow hydrograph boundary condition also required the input of an energy slope to compute the normal depth. The project channel slope, determined from the design plans, was used as the energy slope.

$$T_c = 0.0078\left(\frac{L^{0.77}}{S^{0.385}}\right) \tag{4-2}$$

Because the maximum watershed size to which the NRCS DUH should be applied is 25 mi^2, alternative methods of developing an inflow hydrograph were used for Project 41. For this project, an upstream USGS gaging station (USGS gage 1581700 near Benson, Maryland) was used. A large peak flow event was identified in June 2006 and then scaled by watershed size to represent the hydrograph from a large flood for this restoration project. Although this flood event did not reach the 100-year peak discharge determined by Streamstats, the flows were scaled by the ratio between 100-year peak flow from StreamStats and the actual peak flow for the June 2006 flood.

The second boundary condition used was normal depth. For this, a friction slope was needed at the last downstream cross section, representing flow leaving the 2D area . The friction slope was initially estimated as the bed slope of the last cross-section, but was then updated to be the water surface slope at the last cross-section after each iteration of the unsteady hydrograph. This boundary condition can only be used for flow leaving a 2D area.

The methods described above were also used for additional inflow locations, such as tributaries or significant stormwater infrastructure. For tributary inflows, break lines along the tributary centerline were added to the 2D flow area mesh to better represent confluences.

4.2.3.4 Manning's Roughness Layer

A Manning's roughness layer (Manning's n) was developed for each 2D model representing = the spatial variation of land cover throughout each project site. Manning's roughness layers were created for the flow areas using GIS and the 2011 National Land Cover Dataset (NLCD). The 2011 NLCD was used because most of the modelled projects were completed around this time. In GIS, the NLCD layer was clipped to the model flow area. The river channel and floodplain were estimated for each site based on the model centerline/thalweg and satellite imagery. Channel and floodplain polygons were created and superimposed over the clipped NLCD layer. A Manning's roughness value was associated with each land cover types, as shown in Table 4.4. The polygon with these roughness values for the flow area was imported into HEC-RAS and associated with the terrain layer for computation.

Table 4.4 Land cover and associated Manning's roughness values.

Land Cover Class	**Manning's Roughness**	**Suggested Literature Values (Janssen, 2016)**
Channel	0.035	N/A
Floodplain	0.15	N/A
Forest	0.16	0.10 - 0.16
High Density Residential	0.15	0.12 - 0.20
Medium Density Residential	0.12	0.06 - 0.14
Low Density Residential	0.10	0.08 - 0.12
Institutional	0.08	N/A
Industrial	0.10	N/A
Commercial	0.08	N/A
Agricultural	0.10	N/A

4.2.3.5 Running the 2D Models

There are two computational options for running 2D HEC-RAS: the diffusion wave equations, and the full momentum equations. The full momentum equation is the full-form of the 2D, depth-averaged Navier-Stokes equations, while the diffusion wave equation is a simplification of the full momentum equation which ignores the convective and local accelerations terms. Due to this, the diffusion wave has a shorter computation time than the full momentum equations, but is less accurate. In this study, all computations were done using the full momentum equation so the greatest possible difference in 1D and 2D model output could be evaluated.

Another feature of 2D HEC-RAS is the variable time-step, which was used in this study. The variable time-step essentially allows the time-step to be controlled by the Courant number (Equations 4-3 and 4-4).

$$C = V \frac{\Delta T}{\Delta X} \leq 1.0 \tag{4-3}$$

$$\Delta T \leq \frac{\Delta X C}{V} \tag{4-4}$$

where, C is the Courant number, V is the flood wave velocity, ΔT is the computational time step, and ΔX is the average cell size. The Courant number is essentially a measure of how many grid cells the flow will travel through in each computational time-step. Generally, the lower Courant number, the more accurate and unstable the model. The HEC-RAS manual recommends a Courant number of 1 for the full momentum equations. The variable time-step option in HEC-RAS allows the user to set a maximum and minimum Courant number such that the time-step of the model will be changed to keep computations within the set range. The maximum and minimum Courant numbers set were 1 and 0.45 with time-steps ranging between 0.03 and 16.00 seconds.

4.2.3.6 Floodplain Mapping

The RAS Mapper permits the display of model values on top of the terrain layer. For comparison of the 1D and 2D models, the 100 yr storm WSE and boundary shear stress was compared at each HEC-RAS cross section. For the boundary shear stress both the maximum and average values were compared. These data were retrieved from the RAS Mapper by creating profile lines at each cross section and plotting these profile lines against both the WSE and boundary shear stress maps. The WSE was determined directly from this plot. Generally, the 1D models had a level WSE across the terrain, while the 2D models showed more variation across the terrain. For the boundary shear stress, the data from the plot were tabulated and processed in Microsoft Excel to determine the maximum and average values.

4.3 Model Comparison Results

Because discharge and velocity data were not available for the modeled projects, none of the HEC-RAS models were calibrated. Therefore, comparisons differences between the different models is more important than the absolute value of the water surface elevations, velocities, and boundary shear stresses.

4.3.1 Comparison of 1D Models With and Without Structures

Because Projects 24 and 50 had existing HEC-RAS 1D models, comparisons can be made between the original 1D HEC-RAS models and 1D models with instream structures specifically simulated. To simulate the rapidly changing flow conditions near an instream structure, multiple cross sections were added to the models. Figure 4.2 illustrates the increase in model cross sections with the terrain for project 24, which was a steep, confined channel with multiple step pool and cross vane structures. Representing the instream structures increased the number of cross sections from 45 to 234. Increasing the number of cross sections in the 1D model was the most time-consuming task in model development.

The most conspicuous difference between the 1D models with and without structures is the shape of the floodplain. Improving the model resolution around the instream structures resulted in a jagged floodplain boundary, as backwater behind steps and cross vanes expanded across the floodplain and then concentrated over the sills. Figure C.3 shows the difference in the water surface elevations for Project 24. Upstream of cross vanes near a tributary confluence, the water surface elevation for the 1D model with structures included is 2.5 ft. higher than for the model without structures. Similarly, Figure C.23 shows how

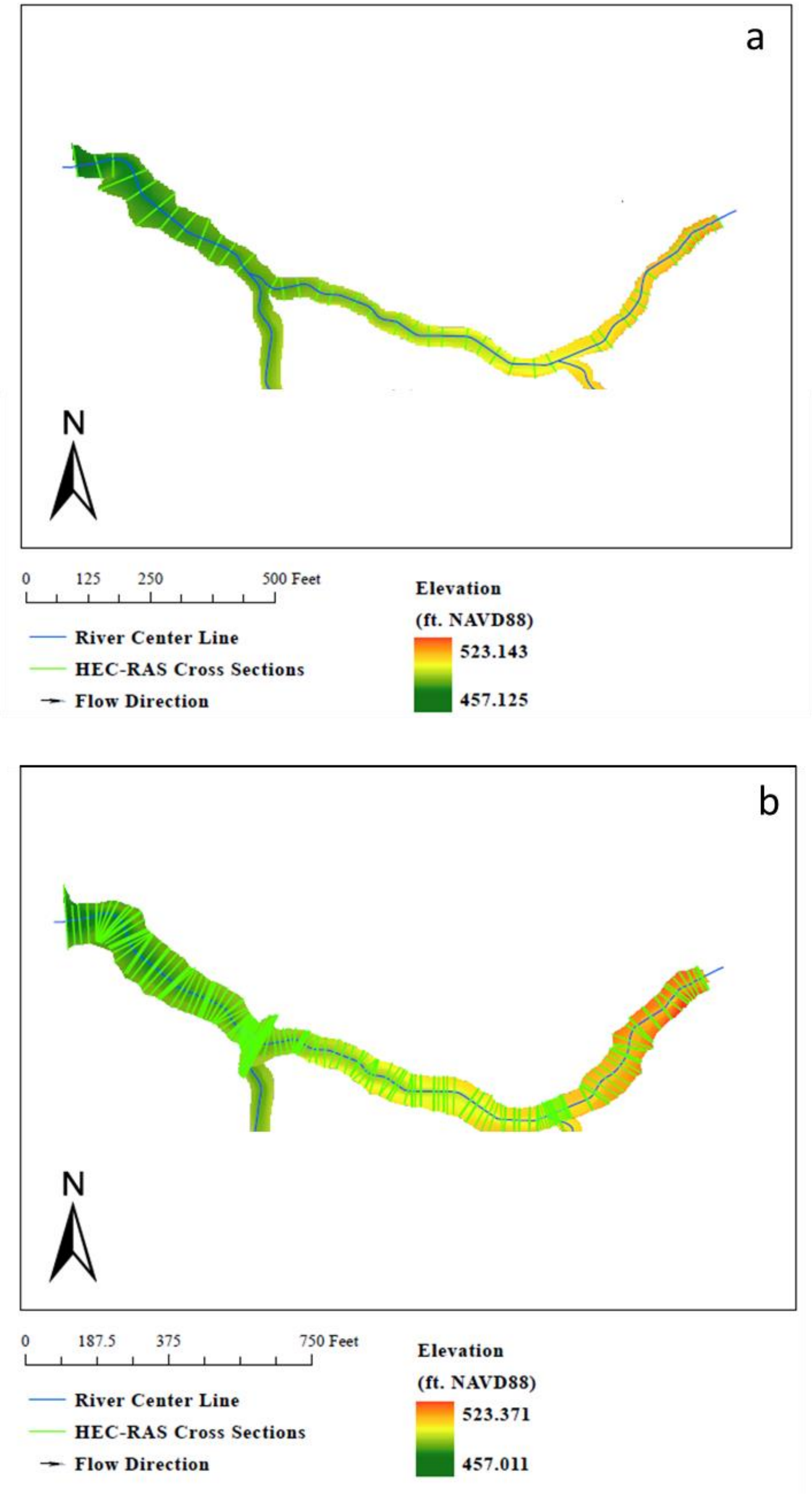


Figure 4.2 Cross sections with terrain for original FEMA HEC-RAS model (a) and model with structures (b) for Project 24.

the model with structures captures fluctuations of the water surface over the riffle grade controls in Project 50. The differences in the water surface elevations creates differences in both the modeled velocities and boundary shear stresses. In general, the models with structures predict higher velocities and boundary shear stress. A specific example is evident in Figure C.5, where the predicted SS downstream of the cross vane is over 8 psf higher than the SS predicted by the standard FEMA model. This difference in SS could result in sizing a 6-in. diameter stone versus a 24-in diameter stone (USACE, 2001).

4.3.2 Comparison of 1D and 2D Models

Use of the 2D model captures the impact of the instream structures on WSEs, velocities, and SS without the development of the jagged flood extents. For steep projects with numerous step pools and cross vanes (projects 24 and 47), the 1D model generally predicts higher WSE than the 2D model. In contrast, the 2D model predicts higher WSE for projects that consist mainly of riffle grade controls (projects 50 and 55). Figure 4.2 shows plots of the 2D WSE versus the 1D WSE for projects 24 and 50.

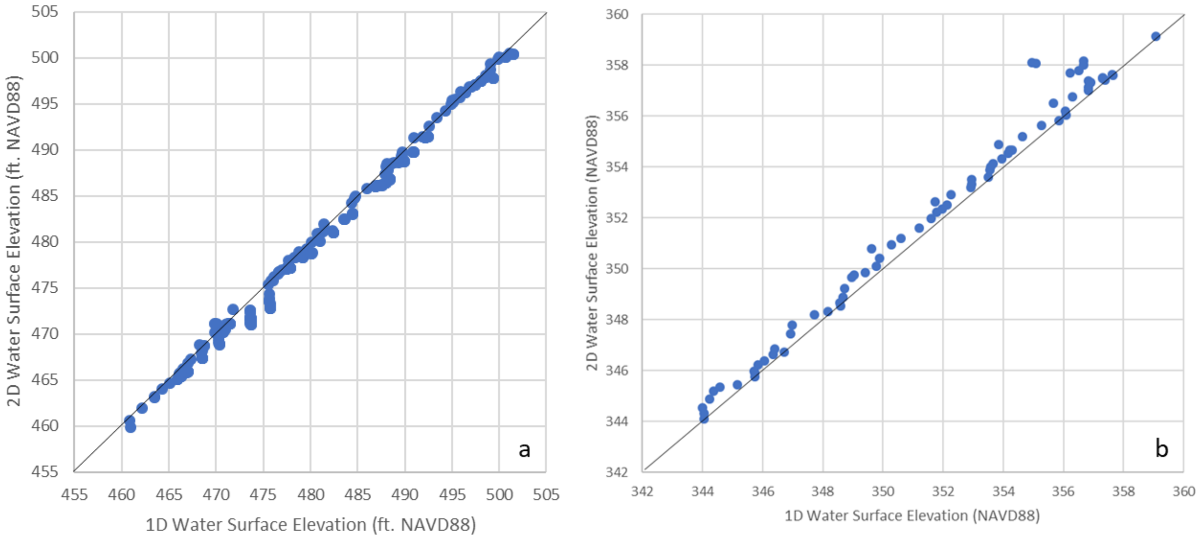


Figure 4.2 Comparison of 2D water surface elevations versus 1D for a stream restoration project with step pools and cross vanes (Project 24, a) and a project with riffle grade controls (Project 50, b).

In general, differences in the predicted velocities and shear stresses for the 1D and 2D models are similar, although the 2D model better represented the higher velocities in the center of the main channel (Figure C.7). The most significant difference between the models is evident in plots of shear stress. The 1D models indicated peaks in shear stress in the center of the channel, where the changes in velocities through the structures are greatest. In contrast, the 2D models indicated the highest shear stresses would occur at the interface between the main channel and the floodplain, which better represents actual stream hydrodynamics.

While the overall differences in SS are small, the 2D model indicates small areas of high shear stress that are not captured in the 1D model. An example can be seen in Project 25. This project consists of both cross vanes and step pools. A step pool structure is located at the confluence of a small intermittent tributary. Figure 4.3 shows the design plans and pictures from the project. From the images, the loss of the upstream and downstream steps and pools are missing from the structure. Figure 4.4 shows the shear stress from both the 1D and 2D models for that structure. The 1D model shows that the peak in shear stress will be downstream of the steps in the center of the channel; however, the 2D model indicates the high shear stress occurs along the channel banks. The eroding channel banks in the images clearly show the 2D model did a better job of predicting bank erosion at each end of the step pool structure.

4.3.3 Model Development and Run Times

Explicitly modeling instream structures in both the 1D and 2D models greatly increased the number of cross sections in the 1D model, which significantly increased model development time, as the elevations for each cross section had to be read from the design plans. However, once the cross sections were input in the 1D model, creating a 2D model was relatively straightforward. The 2D model terrain construction may be even easier if one uses surfaces imported from AutoCAD that are based on already existing design plans, or with the new terrain modification of HEC-RAS 6.0.

One limitation in the use of 2D models for stream restoration design is the increased time required to run the 2D models. Table 4.1 provides the time required to run each 2D model. Run times ranged from 6 minutes to 86 minutes. If the HEC-RAS model is being updated and run with each modification to the design, these times could increase the time required for design. However, these models utilized grid sizes that were smaller than typically used and employed the full momentum equation to fully capture the capabilities of the 2D version of HEC-RAS. Increasing the grid sizes, particularly on the floodplain and/or utilizing the diffusive wave equation may reduce model run times.

4.4 Model Comparison Conclusions

Comparison of the predicted water surface elevations, velocities, and shear stresses for 1D and 2D models of a range of stream restoration projects indicates the 2D model better represents stream hydrodynamics overall. Additionally, the 2D model captures areas of high shear along the channel boundary that could cause structure flanking. Given the improved spatial data tools in HEC-RAS 5.0 and 6.0 and the increased availability of high resolution topographic data, the development of a 2D model is not significantly greater than the time required for a 1D model.

Figure 4.3 Design plan drawings and field pictures of a step pool structure in Project 25. The orange arrows indication the direction the photographer was facing.

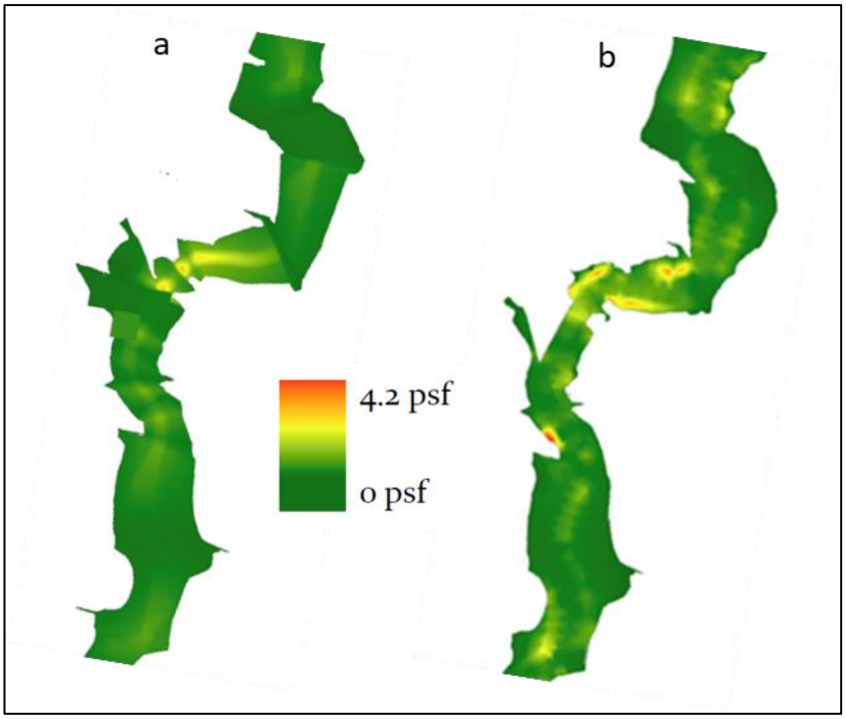


Figure 4.4 Shear stress for the 1D (a) and 2D (b) models of project 25 through a step pool structure.

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Appendix A. Assessment Forms from Methods Summarized in Chapter 2

A.1 Stream Visual Assessment Protocol (USDA-NRCS, 1998)

(1) Channel Condition

Natural channel; no structures, dikes. No evidence of downcutting or excessive lateral cutting.	Evidence of past channel alteration, but with significant recovery of channel and banks. Any dikes or levies are set back to provide access to an adequate floodplain	Altered channel; <50% of the reach with riprap and/or channelization. Excess aggradation; braided channel. Dikes or levees restrict floodplain width.	Channel is actively downcutting or widening. >50% of the reach with riprap or channelization. Dikes or levees prevent access to the floodplain.
10	7	3	1

(2) Hydrologic Alteration

Flooding every 1.5–2 yr. No dams, no water withdrawals, no dikes or other structures limiting the stream's access to the floodplain. Channel is not incised.	Flooding occurs only once every 3–5 yr; limited channel incision, or Withdrawals, although present, do not affect available habitat for biota.	Flooding only once every 6–10 yr; channel deeply, or Withdrawals significantly affect available low flow habitat for biota.	No flooding; channel deeply incised or structures prevent access to floodplain or dam operations prevent flood flows, or Withdrawals have caused severe loss of low flow, or Flooding occurs on a 1-year rain event or less.
10	7	3	1

(3) Riparian Zone

Natural vegetation extends at least two active channel widths on each side.	Natural vegetation extends one active channel width on each side, or If less than one width, covers entire flood-plain.	Natural vegetation extends 1/2 of the active channel width on each side.	Natural vegetation extends 1/3 of active channel width on each side, or Filtering function moderately compromised.	Natural vegetation less than 1/3 of active channel width on each side, or Lack of regeneration, or Filtering function severely compromised.
10	8	5	3	1

(4) Bank Stability

Banks are stable; banks are low (at elevation of active flood plain); 33% or more of eroding surface area of banks in outside bends is protected by roots that extend to the base-flow elevation.	Moderately stable; banks are low (at elevation of active flood plain); less than 33% of eroding surface area of banks in outside bends is protected by roots that extend to the base-flow elevation.	Moderately unstable; banks may be low, but typically are high (flooding occurs 1 yr. out of 5 or less frequently); outside bends are actively eroding (overhanging vegetation at top of bank, some mature trees falling into stream annually, some slope failures apparent).	Unstable; banks may be low, but typically are high; some straight reaches and inside edges of bends are actively eroding as well as outside bends (overhanging vegetation at top of bare bank, numerous mature trees falling into stream annually, numerous slope failures apparent).
10	7	3	1

(5) Water Appearance

Very clear, or clear but tea-colored; objects visible at depth 3–6 ft. (less if slightly colored); no oil sheen or foaming on surface; no noticeable film on submerged objects or rocks.	Occasionally cloudy, especially after storm event, but clears rapidly; objects visible at depth 1.5–3 ft.; may have slightly green color; no oil sheen on water surface.	Considerable cloudiness most of the time; objects visible to depth 0.5–1.5 ft.; slow sections may appear pea-green; bottom rocks or submerged objects covered with heavy green or olive-green film, or Moderate odor of ammonia or rotten eggs.	Very turbid or muddy appearance most of the time; objects visible to depth <1/2 ft.; slow moving water may be bright-green; other obvious water pollutants; floating algal mats, surface scum, sheen or heavy coat of foam on surface, or Strong odor of chemicals, oil, sewage, other pollutants
10	7	3	1

(6) Nutrient Enrichment

Clear water along entire reach; diverse aquatic plant community includes low quantities of many species of macrophytes; little algal growth present.	Fairly clear or slightly greenish water color along entire reach; moderate algal growth on stream substrates.	Greenish water color along entire reach; overabundance of lush green macrophytes; abundant algal growth, especially during warmer months.	Pea green, gray, brown water along entire reach; dense stands of macrophytes clog stream; severe algal blooms create thick algal mats in stream.
10	7	3	1

(7) Barrier to Fish Movement

No barriers	Seasonal water withdrawals inhibit movement within the reach.	Drop structures, culverts, dams, or diversions (<1 foot drop) within the reach	Drop structures, culverts, dams, or diversions (>1 foot drop) within 3 miles of the reach.	Drop structures, culverts, dams, or diversions (>1 foot drop) within the reach.
10	8	5	3	1

(8) Instream Fish Cover

>7 cover types available	6 to 7 cover types available	4 to 5 cover types available	2 to 3 cover types available	None to 1 cover type available
10	8	5	3	1

(9) Pools

Deep and shallow pools abundant; greater than 30% of the pool bottom is obscure due to depth, or the pools are at least 5 feet deep.	Pools present but not abundant; between 10–30% of the pool bottom is obscure due to depth, or the pools are at least 3 feet deep.	Pools present but shallow; between 5–10% of the pool bottom is obscure due to depth, or the pools are less than 3 feet deep.	Pools absent or the entire bottom is discernible.
10	7	3	1

(10) Insect/Invertebrate Habitat

At least 5 types of habitat available. Habitat is at a stage to allow full insect colonization (woody debris and logs not freshly fallen).	3–4 types of habitat. Some potential habitat exists, such as overhanging trees, which will provide habitat but have not yet entered the stream.	1–2 types habitat. The substrate is often disturbed, covered, or removed by high stream velocities and scour or by sediment deposition.	None to 1 type of habitat.
10	7	3	1

(11) Canopy Cover (if applicable): Coldwater Fishery

>75% of water surface shaded and upstream. 2–3 miles generally well shaded.	>50% shaded in reach, or >75% in reach, but upstream 2–3 miles poorly shaded.	20–50% shaded.	<20% of water surface in reach shaded.
10	7	3	1

(11) Warmwater Fishery

25–90% of water surface shaded; mixture of conditions.	>90% shaded; full canopy; same shading condition throughout the reach.		<25% water surface shaded in reach.
10	7	3	1

(12) Manure Presence (if applicable)

Evidence of livestock access to riparian zone.	Occasional manure in stream or waste storage structure located in the flood plain.	Extensive amount of manure on banks or in stream, or Untreated human waste discharge pipes present.
5	3	1

(13) Salinity (if applicable)

Minimal wilting, bleaching, leaf burn, or stunting of aquatic vegetation; some salt-tolerant streamside vegetation.	Aquatic vegetation may show significant wilting, bleaching, leaf burn, or stunting; dominance of salt- tolerant streamside vegetation.	Severe wilting, bleaching, leaf burn, or stunting; presence of only salt-tolerant aquatic vegetation; most streamside vegetation salt tolerant.
5	3	1

(14) Riffle Embeddedness (if applicable)

Gravel or cobble particles are <20% embedded.	Gravel or cobble particles are 20–30% embedded.	Gravel or cobble particles are 30–40% embedded.	Gravel or cobble particles >40% embedded.	Riffle is completely embedded.
10	8	5	3	1

(15) Macroinvertebrates Observed (Optional)

Community dominated by Class 1 or intolerant species with good species diversity. Examples include: caddisflies, mayflies, stoneflies, hellgrammites.	Community dominated by Class 2 or facultative species such as damselflies, dragonflies, aquatic sowbugs, blackflies, crayfish.	Community dominated by Class 3 or tolerant species such as midges, craneflies, horseflies, leeches, aquatic earthworms, tubificid worms.	Very reduced number of species or near absence of all macroinvertebrates.
15	6	2	-3

A.2 Pfankuch (1975) Channel Stability Index

UPPER BANKS	**EXCELLENT**		**GOOD**		**FAIR**		**POOR**	
Landform slope	Bank slope gradient <30%	2	Bank slope gradient 30-40%	4	Bank slope gradient 40-60%	6	Bank slope gradient >60%	8
Mass-wasting (existing or potential)	No evidence of post or any potential for future mass-wasting into channel.	3	Infrequent and/or very small. Mostly healed over. Low future potential.	6	Moderate frequency and size, with some raw spots eroded by water during high flows.	9	Frequent or large, causing sediment OR imminent danger of same.	12
Debris jam potential (floatable objects)	Essentially absent from immediate channel area.	2	Present but mostly small twigs and limbs.	4	Present, volume and size are both increasing,	6	Moderate to heavy amounts, mainly larger sizes.	8
Vegetative bank protection	>90% plant density. Vigor and variety suggests a deep, dense, soil binding root mass.	3	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass.	6	50-70% density. Lower vigor and species form a somewhat shallow and discontinuous root mass.	9	<50% density plus fewer species and vigor indicate discontinuous and shallow root mass.	12
Channel capacity	Ample for present plus some increases. Peak flows contained. Width to Depth (W/D) ratio <7.	1	Adequate. Overbank flows rare. W/D ratio 8 to 15.	2	Barely contains present peaks. Occasional over-bank floods. W/D ratio 15 to 25.	3	Inadequate. Overbank flows common. W/D ratio >25.	4
LOWER BANKS								
Bank rock content	65% with large, angular boulders 30cm numerous.	2	40 to 65'%, mostly small boulders to cobbles 15-30cm.	4	20 to 401, with most in the 7.5-15cm diameter class.	6	<20% rock fragments of gravel sizes, 2.5-7.5 cm or less.	8
Obstructions (flow deflectors Sediment traps)	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	2	Some present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm.	4	Moderately frequent, unstable obstructions and deflectors move with high water causing bank cutting and filling of pools.	6	Frequent obstructions and deflectors cause bank erosion. Sediment traps' full channel migration occurring.	8
Undercutting	Little or none evident. Infrequent raw banks <150cm high.	4	Some, intermittently at outcurves and constrictions. Raw banks <30cm.	8	Significant. Cuts 15-30cm high. Root mat overhangs and sloughing evident.	12	Almost continuous cuts, some >30cm high. Failure of overhangs	16
Deposition	Little or no enlargement of channel or point bars.	4	Some new increase in bar formation, mostly from coarse gravels.	8	Moderate deposition of new gravel and coarse sand on old and some new bars.	12	Extensive deposits of predominantly fine particles. Accelerated	16
STREAM BED								
Rock angularity	Sharp edges and corners, plane surfaces roughened.	1	Rounded corners and edges. Smooth and flat.	2	Corners and edges wel1 rounded in two dimensions.	3	Well rounded in all dimensions.	4
Brightness	Surfaces dull, darkened or stained. Not "bright".	1	Mostly dull, but may have up to 35% bright surfaces.	2	Mixture, 50-50% dull and bright i.e. 35-65%.	3	Predominantly bright, 65%, exposed surfaces.	4
Consolidation or particle packing	Assorted sizes tightly packed and/or overlapping.	2	Moderately packed with some overlapping.	4	Mostly a loose assortment with no apparent overlap.	6	No packing evident. Loose, easily moved.	8
Bottom size distribution & stable	No change in sizes evident. Stable materials 80-100%	4	Distribution shift slight. Stable materials 50-80%.	8	Moderate change in sizes. Stable materials 20-50%	12	Marked change. Stable materials 0-20%	16
Scouring and deposition	<5% of the bottom affected by scouring and deposition.	6	5-30% affected. Scour at constrictions and where steep. Pool deposition.	12	30-50% affected. Deposits and scour at obstructions, constrictions, and bends.	18	> 50% of bed in a state of flux or change nearly year-long.	24
Clinging aquatic vegetation (moss and algae)	Abundant, growth largely moss, dark green, perennial. In swift water too.	1	Common. Algal forms in low velocity and pool areas. Moss and swifter waters.	2	Present but spotty, mostly in backwater areas. Seasonal blooms	3	Perennial types scarce or absent. Yellow-green, short term bloom present.	4
COLUMN TOTALS								

A.3 Bank Erosion Hazard Index

BEHI category	A		B		C		D		E	
	Bank height	Score	Root depth	Score	Root density	Score	Surface protection	Score	Bank angle	Score
Very low	1.0 – 1.1	1.45	90 - 100	1.45	80 - 100	1.45	80 - 100	1.45	0 - 20	1.45
Low	1.1 – 1.2	2.95	50 - 89	2.95	55 - 79	2.95	55 - 79	2.95	21 - 60	2.95
Moderate	1.3 – 1.5	4.95	30 - 49	4.95	30 - 54	4.95	30 - 54	4.95	61 - 80	4.95
High	1.6 – 2.0	6.95	15 - 29	6.95	15 - 29	6.95	15 - 29	6.95	81 - 90	6.95
Very high	2.1 – 2.8	8.50	5 -14	8.50	5 - 14	8.50	10 - 14	8.50	91 - 119	8.50
Extreme	> 2.8	10.00	< 5	10.00	< 5	10.00	< 14	10.00	> 119	10.00

F - Material adjustment	
Bedrock - automatically	Very low
Boulder - automatically	Low
Cobble	(-) 10
Gravel or mostly gravel	(+) 5
Sand or mostly sands	(+) 10
Silt/loam	No adjustment
Clay	(-) 20

(2b)

G - Stratification adjustment	
No layer	No adjustment
Single layer	(+) 5
Multiple layers	(+) 10

(2c)

BEHI category	Total score by category
Very low	≤ 7.25
Low	7.26 – 14.75
Moderate	14.76 – 24.75
High	24.76 – 34.75
Very high	34.76 – 42.50
Extreme	42.51 - 50

(2d)

A.4 Riparian, Channel, and Environmental Inventory

Landuse

		Score
Land-use pattern beyond the immediate riparian zone	Undisturbed, consisting of forest, natural wetlands, bogs and/or mires	30
	Permanent pasture mixed with woodlots and swamps, few row crops	20
	Mixed row crops and pasture	10
	Mainly row crops	1
Width of riparian zone from stream edge to field	Marshy or woody riparian zone >30 m wide	30
	Marshy or woody riparian zone varying from 5 to 30 m	20
	Marshy or woody riparian zone 1 - 5 m	5
	Marshy or woody riparian zone absent	1
Completeness of riparian zone	Riparian zone intact without breaks in vegetation	30
	Breaks occurring at intervals of >50 m	20
	Breaks frequent with some gullies and scars every 50 m	5
	Deeply scarred with gullies all along its length	1
Vegetation of riparian zone within 10 m of channel	> 90% plant density of non-pioneer trees or shrubs, or native marsh plants	25
	Mixed pioneer species along channel and mature trees behind	15
	Vegetation of mixed grasses and sparse pioneer tree or shrub species	5
	Vegetation consisting of grasses, few trees shrubs	1

Physical stream structure

		Score
Retention devices	Channel with rocks and old logs firmly set in place	15
	Rocks and logs present but back filled with sediment	10
	Retention devices loose; moving with floods	5
	Channel of loose sandy silt; few channel obstructions	1
Channel structure	Ample for present and annual peak flows, width/depth < 7	15
	Adequate, overbank flows rare, W/D 8 to 15	10
	Barely contains present peaks, W/D 15 to 25	5
	Overbank flows common, W/D >25 or stream is channelized	1
Channel sediments	Little or no channel enlargement resulting from sediment accumulation	15
	Some gravel bars of coarse stones and well-washed debris present, little silt	10
	Sediment bars of rocks, sand and silt common	5
	Channel divided into braids or stream is channelized	1
Stream-bank structure	Banks stable, of rock and soil held firmly by grasses shrubs and tree roots	25
	Banks firm but loosely held by grass and shrubs	15
	Banks of loose soil held by a sparse layer of grass and shrubs	5
	Banks unstable, of loose soil or sand easily disturbed	1
Bank undercutting	Little or none evident or restricted to areas with tree root support	20
	Cutting only on curves and at constrictions	15
	Cutting frequent, undercutting of banks and roots	5
	Severe cutting along channel, banks falling in	1
Stony substrate; feel and appearance	Stones clean, rounded without sharp edges; may have blackened color	25
	Stones without sharp edges and with slight sand, silt, gritty feel	15
	Some stones with sharp edges, obvious gritty cover	5
	Stones bright; silt, grit cover and sharp edges common	1

Physical stream structure, continued.

		Score
Stream bottom	Stony bottom of several sizes packed together, interstices obvious	25
	Stony bottom easily moved, with little silt	15
	Bottom of silt, gravel and sand, stable in places	5
	Uniform bottom of sand and silt loosely held together, stony substrate absent	1
Riffles and pools, or meanders	Distinct, occurring at intervals of 5 - 7x stream width	25
	Irregularly spaced	20
	Long pools separating short riffles, meanders absent	10
	Meanders and riffles/pools absent or stream channelized	1

Biota

		Score
Aquatic vegetation	When present consists of moss and patches of algae	15
	Algae dominant in pools, vascular plants along edge	10
	Algal mats present, some vascular plants, few mosses	5
	Algal mats cover bottom, vascular plants dominate channel	1
Fish	Rheophilous fish present, native population, present in most pools	20
	Rheophilous fish scarce and difficult to locate	15
	No rheophilous fish, some lentic fish present in pools	10
	Fish absent or scarce	1
Detritus	Mainly consisting of leaves and wood without sediment	25
	Leaves and wood scarce; fine flocculent organic debris without sediment	10
	No leaves or woody debris; coarse and fine organic matter with sediment	5
	Fine, anaerobic sediment, no coarse debris	1
Macrobenthos	Many species present on all types of substrate	20
	Many species but only in well-aerated habitats	15
	Few species present but found in most habitats	5
	Few if any species and only in well-aerated habitats	1
	Total Score =	

Summary and Recommendations

Class	Score	Evaluation	Recommended Action
I	293 - 360	Excellent	Biomonitoring and protection of the existing status
II	224 - 292	Very Good	Selected alterations and monitoring for changes
III	154 - 223	Good	Minor alterations needed
IV	86 - 153	Fair	Major alterations needed
V	16 - 85	Poor	Complete structural reorganization

A.5 Stream Performance Assessment

Bedforms

#	Description	Range
1	Riffles and pools (or step-pools) are present and appear in a regular alternating sequence	0 - 3
2	Bedform features are properly located (pools in bends or downstream of bedrock, boulders or logs and riffles in straight stretches)	0 - 3
3	Riffles (or steps) are adequate in length and have a suitable slope (not overly steep)	0 - 3
4	Riffles (or steps) have clean washed coarse material (no accumulation of fines)	0 - 3
5	Pools are of adequate length, are deep and have gently sloped point bars (wide meandering stream types only)	0 - 3

Channel Pattern

#	Description	Range
6	Free-forming meander pattern appropriate to the valley slope and width supporting an appropriate riffle-pool sequence. (Note: Meanders may not be present in steep confined valley system). Pattern is not restricted by utilities, structures or other manmade boundary conditions.	6 - 10
	OR	
6	Clear evidence of pattern restrictions and/or immature pattern formation as a result of channelization, armoring, utilities, other man-made boundary conditions or natural disturbances.	0 - 5

In-stream Habitat

#	Description	Range
7	Large woody debris (LWD) is present in the channel (excluding rootwads)	0 - 3
8	Leaf Packs are present	0 - 3
9	Stable undercut banks are present	0 - 3
10	Rootmats and/or fine roots are present along toe of streambanks	0 - 3
11	Overhanging vegetation is present	0 - 3
12	Rootwads and/or large root masses are present along the streambanks	0 - 3
13	Bedrock, boulders or boulder clusters are present	0 - 2

Sediment Transport

#	Description	Range
14	Stream appears to be transporting bedload efficiently with no obvious signs of degradation (bed incision) or deposition (i.e. no mid channel bars or obvious sediment accumulation in pools, structures are not buried or exposed, etc.). Pool depths are maintained and deposition is occurring on innerberm benches, point bars & other appropriate depositional areas only.	11 - 15
	OR	
14	Stream is having some trouble with sediment transport. There are indications of degradation (bed incision and/or undercutting of boulder structures). Or there are clear indicators of deposition (i.e. mid channel bars starting to form or sediment accumulation in pools, structures buried, etc.).	6 - 10
	OR	
14	Stream is having significant trouble with sediment transport. There are substantial obvious signs of degradation (bed incision, headcutting) and associated streambank undercutting. Or there is extensive indications of deposition including mid channel bars, sediment accumulation in pools, or structures and/or riffles are buried).	0 - 5

Streambank Condition

#	Description	Range
15	< 10% of the banks exhibit obvious signs of erosion or sloughing.	16 -20
	OR	
15	11-30% of the banks exhibit signs of erosion, sloughing and instability. Remaining banks are stable.	11 - 15
	OR	
15	31-50% of the banks exhibit signs of erosion, sloughing and instability. Remaining banks are stable.	6 - 10
	OR	
15	> 50% or more of banks are eroding and unstable.	0 -5

Streambank Vegetation

#	Description	Range
16	Streambank vegetation is lush on all banks and consists of a diverse native plant community. Presence of exotics is very minor to nonexistent.	11 - 15
	OR	
16	Good vegetative cover on streambanks, however some bank areas are bare and/or exotic vegetation is fairly prevalent.	6 - 10
	OR	
16	Numerous bare areas with poor vegetative cover on streambanks and/or banks are dominated by exotic vegetation.	0 - 5

Floodplain Function

#	Description	Range
17	Bankfull is at or very near top of bank with a substantial available floodplain at the bankfull stage. Clear indications that large storms are accessing design bankfull benches or floodplain (i.e. deposition of sand and other fine material, rack lines, photo documentation, anecdotal observations, etc.).	11 - 15
	OR	
17	Moderate floodplain available at the bankfull stage, however, floodplain irregularities (i.e. high spots) are present that do not show signs of floodplain access.	6 - 10
	OR	
17	Little to no available floodplain at bankfull stage or no obvious signs of floodplain access on designed bankfull stage.	0 - 5
	OR	
17	Unable to score as no large storms have occurred since restoration project was installed.	N/A

A.6 USEPA Rapid Bioassessment Protocols for use in streams and wadable rivers

HABITAT ASSESSMENT FIELD DATA SHEET—LOW GRADIENT STREAMS (FRONT)

STREAM NAME	LOCATION	
STATION #________ RIVERMILE________	STREAM CLASS	
LAT ____________ LONG ____________	RIVER BASIN	
STORET #	AGENCY	
INVESTIGATORS		
FORM COMPLETED BY	DATE ________ TIME ________ AM PM	REASON FOR SURVEY

	Habitat Parameter	**Condition Category**			
		Optimal	**Suboptimal**	**Marginal**	**Poor**
Parameters to be evaluated in sampling reach	**1. Epifaunal Substrate/ Available Cover**	Greater than 50% of substrate favorable for epifaunal colonization and fish cover; mix of snags, submerged logs, undercut banks, cobble or other stable habitat and at stage to allow full colonization potential (i.e., logs/snags that are not new fall and not transient).	30-50% mix of stable habitat; well-suited for full colonization potential; adequate habitat for maintenance of populations; presence of additional substrate in the form of newfall, but not yet prepared for colonization (may rate at high end of scale).	10-30% mix of stable habitat; habitat availability less than desirable; substrate frequently disturbed or removed.	Less than 10% stable habitat; lack of habitat is obvious; substrate unstable or lacking.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	2. Pool Substrate Characterization	Mixture of substrate materials, with gravel and firm sand prevalent; root mats and submerged vegetation common.	Mixture of soft sand, mud, or clay; mud may be dominant; some root mats and submerged vegetation present.	All mud or clay or sand bottom; little or no root mat; no submerged vegetation.	Hard-pan clay or bedrock; no root mat or vegetation.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	3. Pool Variability	Even mix of large-shallow, large-deep, small-shallow, small-deep pools present.	Majority of pools large-deep; very few shallow.	Shallow pools much more prevalent than deep pools.	Majority of pools small-shallow or pools absent.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	4. Sediment Deposition	Little or no enlargement of islands or point bars and less than <20% of the bottom affected by sediment deposition.	Some new increase in bar formation, mostly from gravel, sand or fine sediment; 20-50% of the bottom affected; slight deposition in pools.	Moderate deposition of new gravel, sand or fine sediment on old and new bars; 50-80% of the bottom affected; sediment deposits at obstructions, constrictions, and bends; moderate deposition of pools prevalent.	Heavy deposits of fine material, increased bar development; more than 80% of the bottom changing frequently; pools almost absent due to substantial sediment deposition.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
	5. Channel Flow Status	Water reaches base of both lower banks, and minimal amount of channel substrate is exposed.	Water fills >75% of the available channel; or <25% of channel substrate is exposed.	Water fills 25-75% of the available channel, and/or riffle substrates are mostly exposed.	Very little water in channel and mostly present as standing pools.
	SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0

HABITAT ASSESSMENT FIELD DATA SHEET—LOW GRADIENT STREAMS (BACK)

Parameters to be evaluated broader than sampling reach

Habitat Parameter	Condition Category			
	Optimal	Suboptimal	Marginal	Poor
6. Channel Alteration	Channelization or dredging absent or minimal; stream with normal pattern.	Some channelization present, usually in areas of bridge abutments; evidence of past channelization, i.e., dredging, (greater than past 20 yr) may be present, but recent channelization is not present.	Channelization may be extensive; embankments or shoring structures present on both banks; and 40 to 80% of stream reach channelized and disrupted.	Banks shored with gabion or cement; over 80% of the stream reach channelized and disrupted. Instream habitat greatly altered or removed entirely.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
7. Channel Sinuosity	The bends in the stream increase the stream length 3 to 4 times longer than if it was in a straight line. (Note - channel braiding is considered normal in coastal plains and other low-lying areas. This parameter is not easily rated in these areas.)	The bends in the stream increase the stream length 1 to 2 times longer than if it was in a straight line.	The bends in the stream increase the stream length 1 to 2 times longer than if it was in a straight line.	Channel straight; waterway has been channelized for a long distance.
SCORE	20 19 18 17 16	15 14 13 12 11	10 9 8 7 6	5 4 3 2 1 0
8. Bank Stability (score each bank)	Banks stable; evidence of erosion or bank failure absent or minimal; little potential for future problems. <5% of bank affected.	Moderately stable; infrequent, small areas of erosion mostly healed over. 5-30% of bank in reach has areas of erosion.	Moderately unstable; 30-60% of bank in reach has areas of erosion; high erosion potential during floods.	Unstable; many eroded areas; "raw" areas frequent along straight sections and bends; obvious bank sloughing; 60-100% of bank has erosional scars.
SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
9. Vegetative Protection (score each bank) Note: determine left or right side by facing downstream.	More than 90% of the streambank surfaces and immediate riparian zone covered by native vegetation, including trees, understory shrubs, or nonwoody macrophytes; vegetative disruption through grazing or mowing minimal or not evident; almost all plants allowed to grow naturally.	70-90% of the streambank surfaces covered by native vegetation, but one class of plants is not well-represented; disruption evident but not affecting full plant growth potential to any great extent; more than one-half of the potential plant stubble height remaining.	50-70% of the streambank surfaces covered by vegetation; disruption obvious; patches of bare soil or closely cropped vegetation common; less than one-half of the potential plant stubble height remaining.	Less than 50% of the streambank surfaces covered by vegetation; disruption of streambank vegetation is very high; vegetation has been removed to 5 centimeters or less in average stubble height.
SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0
10. Riparian Vegetative Zone Width (score each bank riparian zone)	Width of riparian zone >18 meters; human activities (i.e., parking lots, roadbeds, clear-cuts, lawns, or crops) have not impacted zone.	Width of riparian zone 12-18 meters; human activities have impacted zone only minimally.	Width of riparian zone 6-12 meters; human activities have impacted zone a great deal.	Width of riparian zone <6 meters: little or no riparian vegetation due to human activities.
SCORE ___ (LB)	Left Bank 10 9	8 7 6	5 4 3	2 1 0
SCORE ___ (RB)	Right Bank 10 9	8 7 6	5 4 3	2 1 0

Total Score __________

Appendix B. Variables for Instream Structure Analysis

Table B.1 Complete list of variables used in instream structure analysis.

Variable Name/ Alias	Type	Categorical or Continuous	Family	Description
ScoreOverall	Response	Continuous	All	Overall structure score; 0-18
ScorePCTRemain	Response	Continuous	All	Percent remaining subcategory score: 0-3
ScoreMatMove	Response	Continuous	All	Material movement subcategory score: 0-3
ScoreErosion	Response	Continuous	All	Unintended erosion and scour subcategory score: 0-3
ScoreAggrad	Response	Continuous	All	Unintended aggradation subcategory score: 0-3
ScoreFunction	Response	Continuous	All	Function subcategory score: 0, 3, 6
ID	Structure	Categorical	All	Structure ID
Planform	Structure	Categorical	All	Planform location: straight, slight bend, bend
DSFlu	Structure	Continuous	All	Distance to nearest downstream flush structure/ BFW
USFlu	Structure	Continuous	All	Distance to nearest upstream flush structure/ BFW
DSFlo	Structure	Continuous	All	Distance to nearest downstream flow-affecting structure/ BFW
USFlo	Structure	Continuous	All	Distance to nearest upstream flow-affecting structure/ BFW
Type	Structure	Categorical	BP, FSV, PSV	BP – log structure: log meander protection or log toe FSV – cross vane, sill, modified j-hook PSV – single arm vane, j-hook
StackUnstack	Structure	Categorical	BP	Rock BP design approach: stacked or unstacked
Material	Structure	Categorical	BP, FSV, PSV, SP	Structure material: rock, log, or composite
FootDep	Structure	Continuous	BP, FSV, PSV, RSC, SP	Footer depth/ BFD

* BP = bank protection, FSV = full span vanes, PSV = partial span vanes, RF = constructed riffles, RSC = regenerative stream conveyance, and SP = step pools.

Table B.1, cont. Complete list of variables used in instream structure analysis.

Variable Name/ Alias	Type	Categorical or Continuous	Family	Description
WallHeight	Structure	Continuous	BP	Wall height/ BFD
WallLength	Structure	Continuous	BP	Wall length/ BFW
BouldWid	Structure	Continuous	BP, FSV, PSV, RSC, SP	Boulder width/ BFD or step distance
LogDia	Structure	Continuous	BP, FSV, PSV, SP	Log diameter/ BFD or step distance
KeyAng	Structure	Continuous	FSV, PSV	Key angle (degrees)
KeyDist	Structure	Continuous	FSV, PSV	Key normal distance into bank/ BFW
BankAng	Structure	Continuous	FSV, PSV	Bank angle (degrees)
ArmLen	Structure	Continuous	FSV, PSV	Arm length/ BFW
ArmNorm	Structure	Continuous	FSV, PSV	Arm normal distance in channel/ BFW
ArmSlp	Structure	Continuous	FSV, PSV	Arm slope
ArmVert	Structure	Continuous	FSV, PSV	Arm vertical distance in channel/ BFD
SillLen	Structure	Continuous	FSV, PSV	Sill length/ BFW
ProtHeight	Structure	Continuous	FSV, PSV	Sill protrusion height/ BFD
RFUSGC	Structure	Categorical	RF	Presence of upstream grade control: yes or no
RFDSGC	Structure	Categorical	RF	Presence of downstream grade control: yes or no
RFLenWid	Structure	Continuous	RF	RF length to width ratio
RFSubDep	Structure	Continuous	RF	RF substrate depth/ BFD
RFD50	Structure	Continuous	RF	RF median substrate size/ BFD
Perimeter	Structure	Categorical	RSC, SP	Presence of perimeter around pool: yes or no
WeirLenWid	Structure	Continuous	RSC	RSC weir length to width ratio
WeirWidBFW	Structure	Continuous	RSC	RSC weir width/ BFW
WeirWidValley	Structure	Continuous	RSC	RSC weir width/ valley bottom width
WeirSlp	Structure	Continuous	RSC	RSC weir slope

* BP = bank protection, FSV = full span vanes, PSV = partial span vanes, RF = constructed riffles, RSC = regenerative stream conveyance, and SP = step pools.

Table B.1, cont. Complete list of variables used in instream structure analysis.

Variable Name/ Alias	Type	Categorical or Continuous	Family	Description
WeirD50	Structure	Continuous	RSC	RSC weir cobble D_{50}/ step distance
WeirCobDep	Structure	Continuous	RSC	RSC weir cobble depth/ step distance
InfMedThick	Structure	Continuous	RSC	RSC infiltration media thickness/ step distance
PoolLenWid	Structure	Continuous	RSC, SP	Pool length to width ratio
PoolDep	Structure	Continuous	RSC, SP	Pool depth/ step distance
Number	Structure	Continuous	SP	Number of step pools
HLavg	Structure	Continuous	SP	Average of (step distance/ step pool length)
HLavgS	Structure	Continuous	SP	Average of (step distance/ step pool length)/ slope
SillWid	Structure	Continuous	SP	SP sill width/ BFW
TotalLen	Structure	Continuous	SP	SP total length/ BFW
PoolSubDep	Structure	Continuous	SP	SP pool substrate depth/ step distance
PoolSubD50	Structure	Continuous	SP	SP pool substrate D_{50}/ step distance
Project	Project	Categorical	All	Project name
DesignApproach	Project	Categorical	All	Project design approach (ex. NCD…)
RosgenType	Project	Categorical	All	Rosgen channel type
BFWBFD	Project	Continuous	All	Bankfull width/ bankfull depth
YearComp	Project	Continuous	All	Year completed
ProjLen	Project	Continuous	All	Project length/ BFW
MainChDSlp	Project	Continuous	All	Main channel design slope
Flood	Project	Continuous	All	Floodprone width/ BFW
BFDisch	Project	Continuous	All	Bankfull discharge (cms)
Sinuosity	Project	Continuous	All	Project sinuosity

* BP = bank protection, FSV = full span vanes, PSV = partial span vanes, RF = constructed riffles, RSC = regenerative stream conveyance, and SP = step pools.

Table B.1, cont. Complete list of variables used in instream structure analysis.

Variable Name/ Alias	Type	Categorical or Continuous	Family	Description
ProjectK	Project	Continuous	All	Project bank erodibility (K)
RiffD50	Project	Continuous	All	Median riffle particle size
StrucDen	Project	Continuous	All	Structure density (#/1000 ft)
USGC	Project	Continuous	All	Distance to nearest upstream grade control/ BFW
DSGC	Project	Continuous	All	Distance to nearest downstream grade control/ BFW
BMPDens	Watershed	Continuous	All	Number of BMPs/ urban watershed area
AreaK	Watershed	Continuous	All	Watershed area-weighted erodibility (K)
DrainageK	Watershed	Continuous	All	Drainage network bank erodibility (K)
LongChSlp	Watershed	Continuous	All	Longest channel slope
FracHighDen	Watershed	Continuous	All	Fraction high-density development land use
FracMedDen	Watershed	Continuous	All	Fraction medium-density development land use
FracLowDen	Watershed	Continuous	All	Fraction low-density development land use
FracForest	Watershed	Continuous	All	Fraction forested land use
FracAg	Watershed	Continuous	All	Fraction agricultural land use
FracWater	Watershed	Continuous	All	Fraction open water/ wetland land use
HighDenCh	Watershed	Continuous	All	High-density land use change since construction (%)
MedDenCh	Watershed	Continuous	All	Medium-density land use change since construction (%)
LowDenCh	Watershed	Continuous	All	Low-density land use change since construction (%)
ForestCh	Watershed	Continuous	All	Forested land use change since construction (%)
AgCh	Watershed	Continuous	All	Agricultural land use change since construction (%)
WaterCh	Watershed	Continuous	All	Open water/ wetland land use change since construction (%)
UrbanCh	Watershed	Continuous	All	Urban (high + medium density development) land use change since construction
RuralCh	Watershed	Continuous	All	Rural (forested + agricultural + low density development) land use change since construction

* BP = bank protection, FSV = full span vanes, PSV = partial span vanes, RF = constructed riffles, RSC = regenerative stream conveyance, and SP = step pools.

Table B.2 General information about watershed-scale variables.

Variable	Units	Category	Data Source	Acquisition Method
BMPDens	#/m^2	flow energy	county-level DEMs	GIS BMP analysis
AreaK	unitless	erosion resistance	web soil survey	GIS soil analysis
DrainageK	unitless	erosion resistance	web soil survey	GIS soil analysis
LongChSlp	m/m	flow energy	county-level DEMs	GIS slope analysis
FracHighDen	fraction	flow energy	NLCD 2016	GIS land use analysis
FracMedDen	fraction	flow energy	NLCD 2016	GIS land use analysis
FracLowDen	fraction	flow energy	NLCD 2016	GIS land use analysis
FracForest	fraction	flow energy	NLCD 2016	GIS land use analysis
FracAg	fraction	flow energy	NLCD 2016	GIS land use analysis
FracWater	fraction	flow energy	NLCD 2016	GIS land use analysis
HighDenCh	percent	flow energy	NLCD 2016	GIS land use analysis
MedDenCh	percent	flow energy	NLCD 2016	GIS land use analysis
LowDenCh	percent	flow energy	NLCD 2016	GIS land use analysis
ForestCh	percent	flow energy	NLCD 2016	GIS land use analysis
AgCh	percent	flow energy	NLCD 2016	GIS land use analysis
WaterCh	percent	flow energy	NLCD 2016	GIS land use analysis
UrbanCh	percent	flow energy	NLCD 2016	GIS land use analysis
RuralCh	percent	flow energy	NLCD 2016	GIS land use analysis

Table B.3 Ratios developed to scale watershed- and project-scale variables.

Variable	Numerator	Denominator	Meaning
ProjLen	(project-scale) Project length (m)	(structure-scale) Bankfull width (m)	Project length expressed in number of channel widths
Flood	(project-scale) Floodprone width (m)	(structure-scale) Bankfull width (m)	Floodplain width relative to channel width (also called entrenchment ratio)
RiffD50	(project-scale) Riffle D_{50} (m)	(structure-scale) Bankfull width (m)	Riffle median particle size relative to channel width
USGC	(project-scale) Distance to upstream grade control (m)	(structure-scale) Bankfull width (m)	Number of channel widths from the downstream end of project to nearest downstream grade control structure
DSGC	(project-scale) Distance to downstream grade control (m)	(structure-scale) Bankfull width (m)	Number of channel widths from the upstream end of project to nearest upstream grade control structure
FracHighDen	(watershed-scale) High density residential area (m^2)	(watershed-scale) Watershed area (m^2)	Fraction of watershed with high density residential area
FracMedDen	(watershed-scale) Medium density residential area (m^2)	(watershed-scale) Watershed area (m^2)	Fraction of watershed with medium density residential area
FracLowDen	(watershed-scale) Low density residential area (m^2)	(watershed-scale) Watershed area (m^2)	Fraction of watershed used as low density residential area
FracForest	(watershed-scale) Forested area (m^2)	(watershed-scale) Watershed area (m^2)	Fraction of watershed that is forested
FracAg	(watershed-scale) Agricultural area (m^2)	(watershed-scale) Watershed area (m^2)	Fraction of watershed used for agriculture
FracWater	(watershed-scale) Water/ wetland area (m^2)	(watershed-scale) Watershed area (m^2)	Fraction of watershed that is open water or wetland

Table B.4 Description of project land use categories and NLCD 2016 land use types (Maryland Department of Planning, 2010).

	Included NLCD 2016 Codes	**Description of NLCD 2016 Codes**
High density development	16 - institutional	Lands for educational facilities, military installations, churches, medical facilities, correctional facilities, and government offices.
	15 - industrial	Lands for manufacturing including industrial parks, warehouses, storage yards, research laboratories, and associated parking areas.
	14 - commercial	Buildings, yards, and parking areas associated with retail/ wholesale services that are used primarily for the sale of products or services.
	13 – high density residential	Areas of more than 90% high-density residential units, with more than eight dwelling units per acre.
Medium density development	12 – medium density residential	Areas of more than 90% single-family/ duplex dwelling units and attached single-row housing with lot sizes between 1/2 and 1/8 acre.
Low density development	11 – low density residential	Areas of more than 90% single-family/ duplex dwelling units with lot sizes between 5 and 1/2 acre.
Forest	44 – brush	Unused lands that do not produce timber and can include cleared timber-stands and abandoned agricultural/ pasture fields.
	43 – mixed forest	Forest dominated by neither evergreen nor deciduous species.
	42 – evergreen forest	Forest dominated by trees with foliage that persists throughout year.
	41 – deciduous forest	Forest dominated by trees that lose foliage at end of growing season.
Agriculture	25 – row and garden crops	Intensively managed truck and vegetable farms.
	24 – feeding operations	Feed lots, holding lots for animals, hog feeding lots, poultry houses.
	23 – orchards, vineyards, horticulture	Intensively managed commercial bush and tree crops.
	22 – pasture	Land used for pasture, both permanent and rotated.
	21 - cropland	Field and forage crops.
Water/ wetland	50 – water	Rivers, waterways, reservoirs, ponds, bays, estuaries, and ocean.
	60 - wetlands	Forested and non-forested wetlands.

Table B.5 General information about project-scale variables.

Variable	Units	Category	Data Source	Acquisition Method
YearComp	year	design approach	Monitoring reports	
ProjecLen	length	design approach	Design plans	
MainChDSlp	length/length	flow energy	Design plans	
Flood	length	flow energy	County-level DEMS	GIS slope analysis
BFDisch	cms	flow energy	Maryland Regional Curves	
Sinuosity	unitless	flow energy	Design plans	
ProjectK	unitless	erosion resistance	Web soil survey	GIS soil analysis
RFD50	m	erosion resistance	Design plans	
StrucDen	#/length	design approach	Design plans	
DesignApproach	NA	design approach	Design plans	
RosgenType	NA	design approach	Design plans	
USGC	length	erosion resistance	Google maps	
DSGC	length	erosion resistance	Google maps	

Table B.6 General information about common structure-scale variables.

Variable	Units	Structure Families	Data Source	Acquisition Method
Material	NA	BP*, FSV, PSV, SP	Design plans	Visual inspection
BouldWid	length	BP, FSV, PSV, RSC, SP	As-builts or design plans	Structure tables or design drawings
LogDia	length	BP, FSV, PSV, SP	As-builts or design plans	Structure tables or design drawings
FootDep	length	BP, FSV, PSV, RSC, SP	As-builts or design plans	Structure tables or design drawings
DSFlu	length	BP, FSV, PSV, RF, RSC, SP	As-builts or design plans	Structure tables or AutoCAD analysis
USFlu	length	BP, FSV, PSV, RF, RSC, SP	As-builts or design plans	Structure tables or AutoCAD analysis
DSFlo	length	BP, FSV, PSV, RF, RSC, SP	As-builts or design plans	Structure tables or AutoCAD analysis
USFlo	length	BP, FSV, PSV, RF, RSC, SP	As-builts or design plans	Structure tables or AutoCAD analysis
Planform	NA	BP, FSV, PSV, RF, RSC, SP	As-builts or design plans	Visual inspection

* BP = bank protection, FSV = full span vanes, PSV = partial span vanes, RF = constructed riffles, RSC = regenerative stream conveyance, and SP = step pools.

Table B.7 General information about bank protection-specific structure-scale variables.

Explanatory Variable	Units	Notes	Data Source	Acquisition Method
Type	NA	Only applied to log structures	Design plans and site photographs	Visual inspection
StackUnstack	NA	Only applied to rock structures	Site photographs	Visual inspection
WallHeight	length		As-builts or design plans	Structure tables or design drawings
WallLength	length		As-builts or design plans	Structure tables or design drawings

Table B.8 General information about full span vane-specific structure-scale variables.

Explanatory Variable	Units	Data Source	Acquisition Method
Type	NA	Design plans and site photographs	Visual inspection
KeyAng	degrees	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
BankAng	degrees	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
ArmLen	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
SillLen	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
ArmNorm	length	As-builts or design plans	Structure tables, design drawings, or mathematical analysis of arm length and bank angle
KeyDist	length	As-builts or design plans	Structure tables, design drawings, or mathematical analysis of key length and bank angle
ProtHeight	length	As-builts or design plans	Structure tables or design drawings
ArmVert	length	As-builts or design plans	Structure tables or design drawings
ArmSlp	percent	As-builts or design plans	Structure tables or design drawings.

Table B.9 General information about partial span vane-specific structure-scale variables.

Explanatory Variable	**Units**	**Data Source**	**Acquisition Method**
Type	NA	Design plans and site photographs	Visual inspection
KeyAng	degrees	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
BankAng	degrees	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
ArmLen	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
SillLen	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
ArmNorm	length	As-builts or design plans	Structure tables, design drawings, or mathematical analysis of arm length and bank angle
KeyDist	length	As-builts or design plans	Structure tables, design drawings, or mathematical analysis of key length and bank angle
ProtHeight	length	As-builts or design plans	Structure tables or design drawings
ArmVert	length	As-builts or design plans	Structure tables or design drawings
ArmSlp	percent	As-builts or design plans	Structure tables or design drawings.

Table B.10 General information about riffle-specific structure-scale variables.

Explanatory Variable	**Units**	**Data Source**	**Acquisition Method**
RFLenWid	dimensionless	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
RFSubDep	length	As-builts or design plans	Structure tables or design drawings
RFD50	length	As-builts or design plans	Structure tables or design drawings
RFUSGC	NA	As-builts or design plans	Visual inspection
RFDSGC	NA	As-builts or design plans	Visual inspection

Table B.11 General information about RSC-specific structure-scale variables.

Explanatory Variable	Units	Data Source	Acquisition Method
WeirLenWid	dimensionless	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
WeirWid	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
WeirSlp	percent	As-builts or design plans	Structure tables or design drawings
WeirD50	length	As-builts or design plans	Structure tables or design drawings
WeirCobDep	length	As-builts or design plans	Structure tables or design drawings
PoolLenWid	Dimensionless	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
PoolDep	length	As-builts or design plans	Structure tables or design drawings
Perimeter	NA	As-builts, design plans, and site photographs	Visual inspection
InfMedThick	length	As-builts or design plans	Structure tables or design drawings

Table B.12 General information about step pool-specific structure-scale variables.

Explanatory Variable	Units	Data Source	Acquisition Method
Number	dimensionless	As-builts or design plans	Visual inspection
HLavg	dimensionless	As-builts or design plans	Structure tables or design drawings
HLavgS	dimensionless	As-builts or design plans	Structure tables or design drawings
SillWid	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
PoolDep	length	As-builts or design plans	Structure tables or design drawings
PoolLenWid	dimensionless	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
TotalLen	length	As-builts or design plans	Structure tables, design drawings, or AutoCAD analysis
PoolSubDep	length	As-builts or design plans	Structure tables or design drawings
PoolSubD50	length	As-builts or design plans	Structure tables or design drawings
Perimeter	NA	As-builts, design plans, and site photographs	Visual inspection

Table B.13 Ratios developed to scale common structure-scale variables.

Variable	Numerator	Denominator	Meaning
BouldWid	Boulder width (meters)	BFD or step distance (meters)	Size of construction materials relative to channel depth
LogDia	Log diameter (meters)	BFD or step distance (meters)	Size of construction materials relative to channel depth
FootDep	Footer depth (meters)	BFD or step distance (meters)	Depth of structure foundation relative to channel depth
DSFlu	DS flush (meters)	BFW (meters)	Number of channel widths to a wall or riffle downstream of the structure
USFlu	US flush (meters)	BFW (meters)	Number of channel widths to a wall or riffle upstream of the structure
DSFlo	DS flow (meters)	BFW (meters)	Number of channel widths to a full or partial span vane, RSC, or step pool system downstream of the structure
USFlo	US flow (meters)	BFW (meters)	Number of channel widths to a full or partial span vane, RSC, or step pools system upstream of the structure
BFWBFD	BFW (meters)	BFD or step distance (meters)	Width to depth ratio of channel where structure is located

* BFD = bankfull depth. BFW = bankfull width. DS flush = downstream distance to the nearest flush structure. US flush = upstream distance to the nearest flush structure. DS flow = downstream distance to the nearest flow-affecting structure. US flow = upstream distance to the nearest flow-affecting structure.

Table B.14 Ratios developed to scale bank protection-specific structure-scale variables.

Variable	Numerator	Denominator	Meaning
WallHeight	Wall height (meters)	BFD (meters)	Wall height relative to channel depth
WallLength	Wall length (meters)	BFW (meters)	Wall length relative to channel width

* BFD = bankfull depth. BFW = bankfull width.

Table B.15 Ratios developed to scale full span vane-specific structure-scale variables.

Variable	Numerator	Denominator	Meaning
ArmLen	Arm length (meters)	BFW (meters)	Arm length relative to channel width
SillLen	Sill length (meters)	BFW (meters)	Sill width relative to channel width
ArmNorm	Arm normal distance (meters)	BFW (meters)	Width of channel occupied by arm relative to channel width
KeyDist	Key normal distance (meters)	BFW (meters)	Key-in normal distance relative to channel width
SillLen	Sill protrusion height (meters)	BFD (meters)	Protrusion height of sill into flow relative to flow depth
ArmVert	Vertical distance occupied by structure (meters)	BFD (meters)	Vertical distance in channel occupied by entire structure relative to flow depth

* BFD = bankfull depth. BFW = bankfull width.

Table B.16 Ratios developed to scale partial span vane-specific structure-scale variables.

Variable	Numerator	Denominator	Meaning
ArmLen	Arm length (meters)	BFW (meters)	Arm length relative to channel width
SillLen	Sill length (meters)	BFW (meters)	Sill width relative to channel width
ArmNorm	Arm normal distance (meters)	BFW (meters)	Width of channel occupied by arm relative to channel width
KeyDist	Key normal distance (meters)	BFW (meters)	Key-in normal distance relative to channel width
ProtHeight	Sill protrusion height (meters)	BFD (meters)	Protrusion height of sill into flow relative to flow depth
ArmVert	Vertical distance occupied by structure (meters)	BFD (meters)	Vertical distance in channel occupied by entire structure relative to flow depth

* BFD = bankfull depth. BFW = bankfull width.

Table B.17 Ratios developed to scale riffle-specific structure-scale variables.

Variable	Numerator	Denominator	Meaning
RFLenWid	Riffle length (meters)	Riffle width (meters)	Riffle length to width ratio
RFSubDep	Substrate depth (meters)	BFD (meters)	Depth of riffle substrate relative to channel depth
RFD50	Substrate D_{50} (meters)	BFD (meters)	Median particle size of riffle relative to channel depth

* BFD = bankfull depth. D_{50} = median particle size.

Table B.18 Ratios developed to scale RSC-specific structure-scale variables.

Variable	**Numerator**	**Denominator**	**Meaning**
WeirLenWid	Weir length (meters)	Weir width (meters)	Length to width ratio of riffle-weir
WeirWidBFW	Weir width (meters)	BFW (meters)	Width of riffle-weir relative to channel width
WeirWidValley	Weir width (meters)	Valley bottom width (meters)	Width of riffle-weir relative to width of floodplain where structure is located
WeirD50	Weir cobble D_{50} (meters)	Step distance (meters)	Median particle size of riffle-weir relative to step distance
WeirCobDep	Weir cobble thickness (meters)	Step distance (meters)	Thickness riffle weir cobbles relative to step distance
PoolLenWid	Pool length (meters)	Width (meters)	Length to width ratio of pool
PoolDep	Pool depth (meters)	Step distance (meters)	Pool depth relative to step distance
InfMedThick	Infiltration media thickness (meters)	Step distance (meters)	Thickness of infiltration media relative to step distance

* BFW = bankfull width.

Table B.19 Ratios developed to scale step pool-specific structure-scale variables.

Variable	Numerator	Denominator	Meaning
HLavg	Step distance (H) (meters)	Step length (L) (meters)	Average slope of each step comprising step pool system
HLavgS	(H/L)avg (unitless)	Channel slope (S) (unitless)	Relative slope of step pool system with respect to channel slope
SillWid	Sill width (meters)	BFW (meters)	Sill width relative to channel width
PoolDep	Pool depth (meters)	Average step distance (meters)	Pool depth relative to step distance
PoolLenWid	Pool length (meters)	Pool width (meters)	Length to width ratio of pool
TotalLen	Total length (meters)	BFW (meters)	Total length of step pool system relative to channel width
PoolSubDep	Pool substrate depth (meters)	Average step distance (meters)	Depth of pool substrate relative to step distance
PoolSubD50	Pool substrate D_{50} (meters)	Average step distance (meters)	Median particle size of pool substrate relative to step distance

* BFW = bankfull width. D_{50} = median particle size.

Table B.20 Descriptive statistics for bank protection structure- and project-scale predictors.

Variable	n	Min	Max	Mean	Median
ScoreOverall	147	0.00	18.00	15.10	17.00
ScorePCTRemain	147	0.00	3.00	2.68	3.00
ScoreMatMove	147	0.00	3.00	2.12	2.00
ScoreErosion	147	0.00	3.00	2.48	3.00
ScoreAggrad	147	0.00	3.00	2.93	3.00
ScoreFunction	147	0.00	6.00	5.10	6.00
FootDep	139	0.00	2.66	0.93	0.50
WallHeight	134	0.25	4.44	1.63	1.38
WallLen	140	0.39	23.80	3.35	2.50
BouldWid	121	0.31	3.33	1.18	1.00
LogDia	13	0.37	1.00	0.54	0.55
DSFlu	127	0.00	119.00	3.94	0.00
USFlu	123	0.00	285.88	6.72	0.70
DSFlo	93	0.00	250.00	12.19	1.72
USFlu	71	0.00	73.61	8.33	1.30
BFWBFD	147	4.41	32.00	11.10	10.00
YearComp	147	1999	2015	2007	2008
ProjLen	147	19.46	450.20	85.61	72.95
MainChDSlp	147	2.8e-3	3.0e-2	1.1e-2	9.4e-3
Flood	147	0.70	24.72	6.50	3.12
BFDisch	136	0.19	43.01	2.42	1.64
Sinuosity	147	1.01	2.25	1.24	1.18
ProjectK	147	0.29	0.43	0.38	0.37
RFD50	123	2.2e-3	1.2e-1	2.6e-2	2.0e-2
StrucDen	147	2	119	31	28
USGC	147	0.00	73.68	15.07	9.13
DSGC	147	0.00	284.65	48.92	0.60

Table B.21 Descriptive statistics for bank protection watershed-scale predictors.

Variable	n	Min	Max	Mean	Median
BMPDens	147	0.00	3.83e-5	6.82e-6	3.24e-6
AreaK	147	0.15	0.39	0.26	0.24
DrainageK	147	0.27	0.44	0.35	0.35
LongChSlp	147	3.5e-3	3.0e-2	1.1e-2	1.0e-2
FracHighDen	147	0.00	0.08	0.03	0.02
FracMedDen	147	0.01	0.32	0.11	0.13
FracLowDen	147	0.22	0.81	0.62	0.62
FracForest	147	0.03	0.55	0.18	0.17
FracAg	147	0.0	0.05	0.00	0.00
FracWater	147	0.0	0.00	0.00	0.00
HighDenCh	147	1.94	2.81	2.09	1.94
MedDenCh	147	1.36	3.87	2.51	2.30
LowDenCh	147	-1.00	4.73	1.81	1.70
ForestCh	147	-2.76	2.18	1.39	1.94
AgCh	147	0.00	2.18	1.79	1.94
WaterCh	147	1.82	1.94	1.94	1.94
UrbanCh	147	1.70	4.30	2.68	2.43
RuralCh	147	-3.18	2.18	1.25	1.70

Table B.22 Descriptive statistics for full span vane structure-scale predictors.

Variable	n	Min	Max	Mean	Median
ScoreOverall	105	1.00	18.00	14.00	15.00
ScorePCTRemain	105	0.00	3.00	2.77	3.00
ScoreMatMove	105	0.00	3.00	2.89	3.00
ScoreErosion	105	0.00	3.00	2.89	3.00
ScoreAggrad	105	0.00	3.00	2.29	3.00
ScoreFunction	105	0.00	6.00	4.37	6.00
KeyAng	83	12.00	90.00	69.00	75.00
KeyDist	101	0.00	1.40	0.20	0.14
BankAng	101	3.96	90.00	39.77	27.80
ArmLen	101	0.00	1.94	0.89	0.85
ArmNorm	101	0.00	0.87	0.44	0.48
ArmSlp	97	0.00	45.11	9.71	7.76
ArmVert	89	0.07	2.42	0.90	1.00
SillLen	101	0.00	0.77	0.25	0.28
ProtHeight	97	0.00	1.56	0.11	0.00
FootDep	97	0.36	7.05	2.17	1.81
BouldWid	91	0.54	6.00	1.72	1.42
LogDia	8	0.37	1.51	0.74	0.55
DSFlu	69	0.00	17.46	3.77	2.38
USFlu	61	0.00	25.18	4.79	2.62
DSFlo	94	0.50	65.29	6.22	4.04
USFlo	87	0.34	87.14	7.41	4.03

Table B.23 Descriptive statistics for full span vane project-scale predictors.

Variable	n	Min	Max	Mean	Median
BFWBFD	105	4.44	32.00	12.50	11.81
YearComp	105	1999	2015	2007	2004
ProjLen	105	14.74	450.20	79.24	74.00
MainChDSlp	105	2.8e-3	7.0e-2	1.4e-2	1.0e-2
Flood	105	0.61	23.40	5.49	2.72
BFDisch	97	0.02	43.01	3.30	0.45
Sinuosity	105	1.01	2.25	1.27	1.20
ProjectK	105	0.24	0.43	0.36	0.37
RFD50	88	2.0e-3	7.0e-2	1.8e-2	2.0e-2
StrucDen	105	3.00	53.00	27.00	27.00
USGC	105	0.00	59.30	7.45	5.85
DSGC	105	0.00	337.54	57.79	9.88

Table B.24 Descriptive statistics for full span vane watershed-scale predictors.

Variable	n	Min	Max	Mean	Median
BMPDens	105	0.00	127.00	25.00	8.00
AreaK	105	0.10	0.39	0.26	0.26
DrainageK	105	0.21	0.42	0.33	0.35
LongChSlp	105	4.0e-3	7.0e-2	1.3e-2	1.0e-2
FracHighDen	105	0.0	0.03	0.00	0.00
FractMedDen	105	0.0	0.03	0.01	0.01
FracLowDen	105	0.09	1.00	0.520	0.58
FracForest	105	0.0	0.06	0.02	0.02
FracAg	105	0.0	0.07	0.01	0.00
FracWater	105	0.0	4.0e-2	3.6e-3	0.0
HighDenCh	105	1.02	3.20	2.10	2.06
MedDenCh	105	1.82	5.64	3.22	2.81
LowDenCh	105	-0.79	6.12	1.96	1.82
ForestedCh	105	-2.76	2.06	1.29	1.94
AgCh	105	-5.00	3.33	1.21	1.94
WaterCh	105	1.82	1.94	1.93	1.94
UrbanCh	105	0.80	6.95	3.37	2.81
RuralCh	105	-7.23	3.33	0.56	1.82

Table B.25 Descriptive statistics for partial span vane structure-scale predictors.

Variable	n	Min	Max	Mean	Median
ScoreOverall	68	0.00	138.00	13.00	12.00
ScorePCTRemain	68	0.00	3.00	2.41	3.00
ScoreMatMove	68	0.00	3.00	2.07	2.00
ScoreErosion	68	0.00	3.00	2.46	3.00
ScoreAggrad	68	0.00	3.00	2.47	3.00
ScoreFunction	68	0.00	6.00	3.31	3.00
KeyAng	54	2.0	99.0	34.5	26.5
KeyDist	68	0.00	0.40	0.11	0.075
ArmLen	68	0.00	2.08	0.80	0.75
ArmNorm	68	0.00	0.86	0.33	0.31
BankAng	68	10.00	119.00	29.00	25.00
ArmSlp	68	2.37	35.94	10.13	7.50
SillLen	68	0.00	0.46	0.08	0.00
ArmVert	68	0.00	2.12	0.71	0.68
FootDep	68	0.00	2.30	0.95	0.66
BouldWid	63	0.54	3.33	0.89	0.66
LogDia	17	0.18	0.55	0.37	0.37
DSFlu	54	0.00	25.87	3.97	1.20
USFlu	55	0.00	24.75	4.18	0.37
DSFlo	66	0.37	26.33	3.88	2.13
USFlu	63	0.37	47.48	4.57	2.00

Table B.26 Descriptive statistics for partial span vanes project-scale predictors.

Variable	n	Min	Max	Mean	Median
BFWBFD	68	5.63	32.00	11.20	10.38
YearComp	68	1999	2015	2003	2003
ProjLen	68	31.25	157.20	74.58	76.68
MainChDSlp	68	0.0040	0.0300	0.0092	0.0056
Flood	68	1.15	18.42	4.83	2.89
BFDisch	49	0.24	43.01	4.80	1.64
Sinuosity	68	1.01	2.25	1.21	1.14
ProjectK	68	0.29	0.43	0.37	0.37
RFD50	39	0.0022	0.0300	0.0106	0.0055
StrucDen	68	7.00	53.00	28.00	19.00
USGC	68	0.00	27.57	6.48	1.56
DSGC	68	0.00	189.12	33.19	0.60

Table B.27 Descriptive statistics for partial span vane watershed-scale predictors.

Variable	n	Min	Max	Mean	Median
BMPDens	68	0.00	1.30e-5	4.03e-6	1.24e-6
AreaL	68	0.19	0.39	0.29	0.27
DrainageK	68	0.27	0.42	0.34	0.32
LongChSlp	68	0.0040	0.0300	0.0096	0.0085
FracHighDen	68	0.00	0.00	0.00	0.00
FracMedDen	68	0.01	0.22	0.09	0.11
FracLowDen	68	0.28	0.81	0.58	0.58
FracForest	68	0.08	0.39	0.21	0.20
FracAg	68	0.00	0.27	0.08	0.04
FracWater	68	0.00	0.01	0.00	0.00
HighDenCh	68	1.94	3.20	2.26	2.06
MedDenCh	68	1.94	5.64	3.24	2.81
LowDenCh	68	-0.61	6.12	3.09	2.43
ForestCh	68	-2.76	1.94	0.34	1.70
AgCh	68	-5.00	2.18	0.79	1.47
WaterCh	68	1.94	1.94	1.94	1.94
UrbanCh	68	1.94	6.95	3.55	2.81
RuralCh	68	-7.23	1.94	-0.80	0.70

Table B.28 Descriptive statistics for constructed riffle structure- and project-scale predictors.

Variable	n	Min	Max	Mean	Median
ScoreOverall	102	0.00	18.00	11.00	11.00
ScorePCTRemain	102	0.00	3.00	2.00	3.00
ScoreMatMove	102	0.00	3.00	1.37	1.00
ScoreErosion	102	0.00	3.00	1.90	2.00
ScoreAggrad	102	0.00	3.00	1.86	3.00
ScoreFunction	102	0.00	6.00	1.24	6.00
RFLenWid	101	0.80	15.86	2.33	0.96
RFSubDep	100	0.28	2.00	0.70	0.58
RFD50	83	0.09	0.75	0.37	0.31
DSFlu	96	0.00	285.88	4.74	0.00
USFlu	95	0.00	35.98	2.07	0.27
DSFlo	32	0.00	56.39	11.80	5.75
USFlo	25	0.00	25.73	5.46	2.80
BFWBFD	94	3.57	32.00	9.91	10.00
YearComp	94	2003	2015	2009	2012
ProjLen	94	31.25	450.20	79.96	87.25
MainChDSlp	94	5.40e-3	3.00e-2	8.56e-3	5.60e-3
Flood	94	1.15	19.28	6.28	4.03
BFDisch	94	0.22	43.01	2.66	2.88
Sinuosity	94	1.02	2.25	1.30	1.35
ProjetK	94	0.35	0.43	0.38	0.37
RFD50	94	6.94e-3	7.00e-2	3.45e-2	3.00e-2
StrucDen	94	8.00	52.00	35.00	42.00
USGC	94	0.30	73.68	11.98	0.97
DSGC	94	0.00	284.65	70.10	18.00

Table B.29 Descriptive statistics for constructed riffle watershed-scale predictors.

Variable	n	Min	Max	Mean	Median
BMPDens	94	0.00	3.83e-5	1.45e-5	7.45e-6
AreaK	94	0.15	0.39	0.29	0.27
DrainageK	94	0.32	0.44	0.36	0.36
LongChSlp	94	3.50e-3	3.00e-2	1.16e-2	1.00e-2
FracHighDen	94	0.00	0.05	0.01	0.02
FracMedDen	94	0.00	0.26	0.07	0.06
FracLowDen	94	0.28	0.80	0.64	0.74
FracForest	94	0.08	0.55	0.22	0.18
FracAg	94	0.00	0.27	0.02	0.00
FracWater	94	0.00	0.04	0.01	0.00
HighDenCh	94	1.94	2.30	1.97	1.94
MedDenCh	94	1.36	3.07	2.29	2.43
LowDenCh	94	1.02	2.81	2.03	2.18
ForestCh	94	0.80	2.06	1.41	1.25
AgCh	94	1.13	2.18	1.84	1.94
WaterCh	94	1.82	1.94	1.93	1.94
UrbanCh	94	1.70	3.46	2.32	2.43
RuralCh	94	0.49	1.82	1.28	1.25

Table B.30 Descriptive statistics for regenerative stream conveyance weirs.

Variable	n	Min	Max	Mean	Median
ScoreOverall	57	12.00	18.00	18.00	18.00
ScorePCTRemain	57	3.00	3.00	3.00	3.00
ScoreMatMove	57	1.00	3.00	2.86	3.00
ScoreErosion	57	0.00	3.00	2.85	3.00
ScoreAggrad	57	3.00	3.00	3.00	3.00
ScoreFunction	57	3.00	6.00	5.95	3.00
WeirLenWid	57	0.05	1.14	0.47	0.44
WeirWidBFW	57	0.35	3.64	1.64	1.43
WeirWidValley	46	0.18	1.00	0.62	0.53
WeirSlp	56	0.00	12.50	2.76	2.82
FootDep	55	0.00	6.66	1.91	1.87
BouldWid	41	0.66	4.16	2.21	1.87
WeirD50	46	0.00	1.66	0.60	0.62
WeirCobDep	55	0.00	6.00	1.94	1.36
PoolLenWid	46	0.31	12.14	2.37	1.39
PoolDep	47	0.00	6.00	2.07	1.62
InfMedThick	55	0.00	6.00	1.09	0.00
DSFlu	15	0.00	75.61	28.27	24.71
USFlu	7	0.00	19.17	6.59	3.58
DSFlo	42	0.33	20.67	4.76	3.25
USFlo	43	0.33	15.22	3.87	2.83

Table B.31 Descriptive statistics for regenerative stream conveyance weir project- and watershed-predictors.

Variable	n	Min	Max	Mean	Median
MainChDSlp	57	0.0030	0.0100	0.0075	0.0072
BFWBFD	55	7.00	113.33	40.15	50.00
YearComp	57	2006	2016	2011	2010
ProjLen	57	25.00	123.80	65.54	78.35
Flood	13	4.50	5.02	4.82	5.02
BFDisch	57	0.19	0.45	0.27	0.22
Sinuosity	57	1.04	1.52	1.18	1.10
RFD50	13	0.01	0.06	0.04	0.06
StrucDen	57	0.00	27.00	15.00	18.00
USGC	57	0.00	137.06	4.74	3.73
DSGC	57	0.00	185.16	29.39	0.00
BMPDens	57	7.19e-6	6.34e-5	3.09e-5	2.52e-5
AreaK	57	0.08	0.24	0.17	0.19
DrainageK	57	0.24	0.30	0.26	0.25
LongChSlp	57	0.0035	0.0100	0.0081	0.0098
FracHighDen	57	0.00	0.07	0.04	0.05
FracMedDen	57	0.00	0.24	0.15	0.18
FracLowDen	57	0.12	0.61	0.47	0.56
FracForest	57	0.09	0.87	0.22	0.09
FracAg	57	0.00	0.30	0.04	0.02
FracWater	57	0.00	0.28	0.07	0.01

Table B.32 Descriptive statistics for step pool structure-scale predictors.

Variable	n	Min	Max	Mean	Median
ScoreOverall	31	2.00	18.00	15.00	17.00
ScorePCTRemain	31	0.00	3.00	2.63	3.00
ScoreMatMove	31	0.00	3.00	2.40	3.00
ScoreErosion	31	0.00	3.00	2.30	3.00
ScoreAggrad	31	0.00	3.00	2.43	3.00
ScoreFunction	31	0.00	6.00	4.90	3.00
Number	31	1	20	5	4
HLavg	31	0.00	0.15	0.06	0.05
HLavgS	31	-0.13	5.95	2.30	2.06
SillWid	31	0.23	1.53	0.79	1.00
PoolDep	23	0.00	6.00	1.51	1.25
PoolLenWid	31	0.57	4.87	1.49	1.27
TotalLen	31	0.65	26.25	5.67	3.50
PoolSubDep	27	0.82	5.00	2.02	1.83
PoolSubD50	12	0.17	1.14	0.62	0.57
FootDep	30	0.00	12.25	3.48	3.34
BouldWid	27	1.20	7.82	4.09	4.00
LogDia	4	1.31	1.6	1.38	1.31
DSFlu	12	0.00	10.06	1.27	0.00
USFlu	18	0.00	17.20	3.26	0.00
DSFlo	19	0.25	35.00	6.40	3.50
USFlo	24	0.5-	40.25	9.21	4.63

Table B.33 Descriptive statistics for step pool project-scale predictors.

Variable	n	Min	Max	Mean	Median
MainChDSlp	30	0.0089	0.0600	0.0296	0.0200
BFWBFD	29	6.95	40.00	18.26	17.21
YearComp	30	2001	2015	2007	2004
ProjLen	30	4.34	213.95	79.71	61.51
Flood	30	1.00	19.28	6.46	6.72
BFDisch	30	0.02	4.10	0.52	0.24
Sinuosity	30	1.00	2.25	1.18	1.15
ProjectK	30	0.27	0.43	0.36	0.37
RFD50	30	0.006	0.070	0.037	0.020
StrucDen	30	6.00	119.00	38.00	41.00
USGC	30	0.00	73.68	25.70	10.24
DSGC	30	0.00	337.54	47.57	0.00

Table B.34 Descriptive statistics for step pool watershed-scale predictors.

Variable	**n**	**Min**	**Max**	**Mean**	**Median**
BMPDens	30	0.00	8.14e-5	7.63e-6	1.72-6
AreaK	30	0.10	0.39	0.25	0.25
DrainageK	30	0.27	0.44	0.347	0.35
LongChSlp	30	0.0022	0.0700	0.0268	0.0100
FracHighDen	30	0.00	0.32	0.02	0.00
FracMedDen	30	0.00	0.32	0.09	0.06
FracLowDen	30	0.22	1.00	0.73	0.66
FracForest	30	0.00	0.33	0.14	0.13
FractAg	30	0.00	0.05	0.00	0.00
FracWater	30	0.00	0.00	0.00	0.00
HighDenCh	30	1.70	2.30	1.99	1.94
MedDenCh	30	1.36	5.33	2.52	2.06
LowDenCh	30	-1.06	2.43	1.19	1.47
ForestCh	30	1.25	2.18	1.82	1.94
AgCh	30	1.13	1.94	1.91	1.94
WaterCh	30	1.94	1.94	1.94	1.94
UrbanCh	30	1.70	5.18	2.56	2.06
RuralCh	30	0.70	2.18	1.78	1.94

Appendix C. Diagrams of Maximum Boundary Shear Stress for Model Comparison

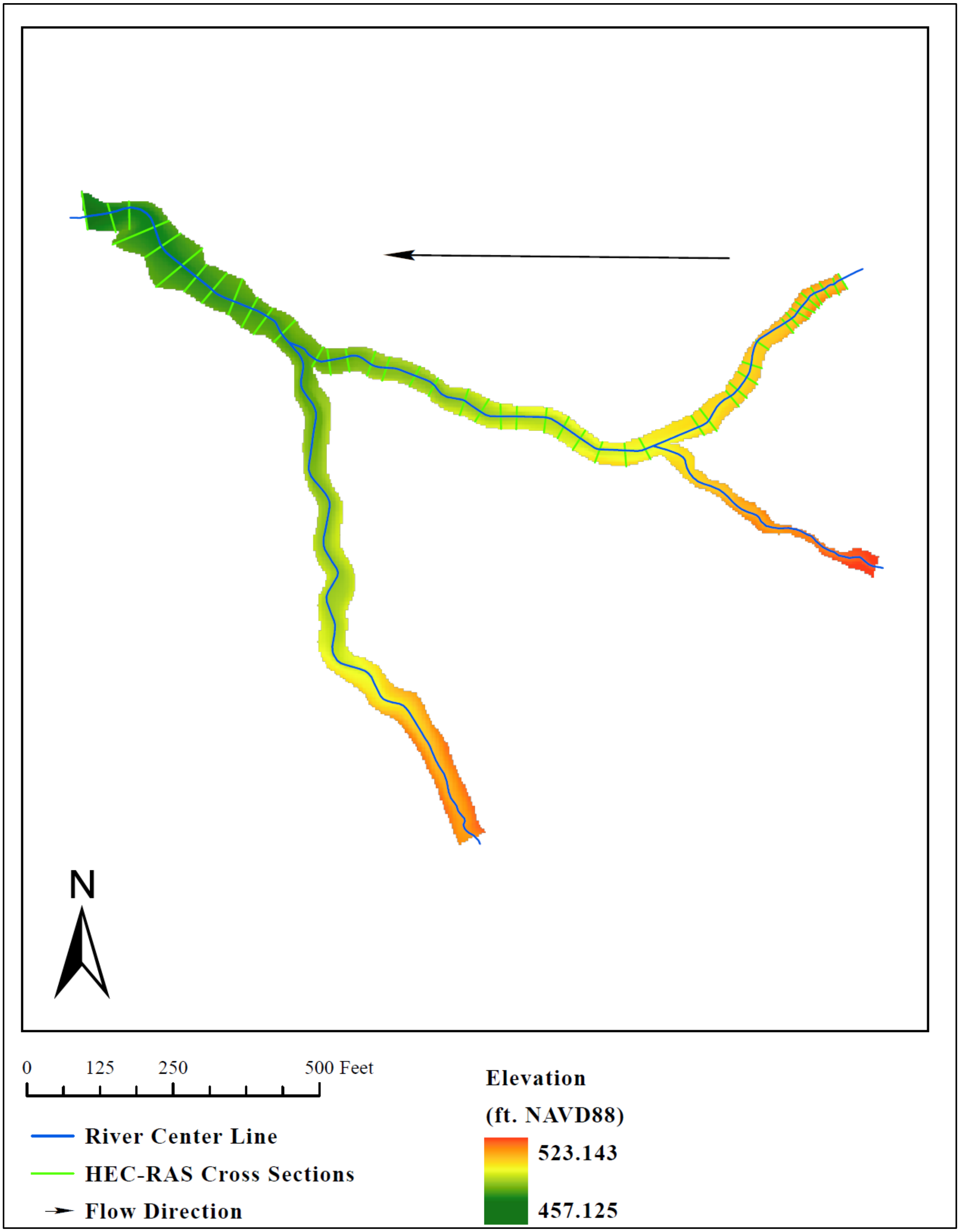

Figure C.1 Cross sections in FEMA 1D model for Project 24.

Figure C.2 Cross sections developed for 1D HEC-RAS model for Project 24.

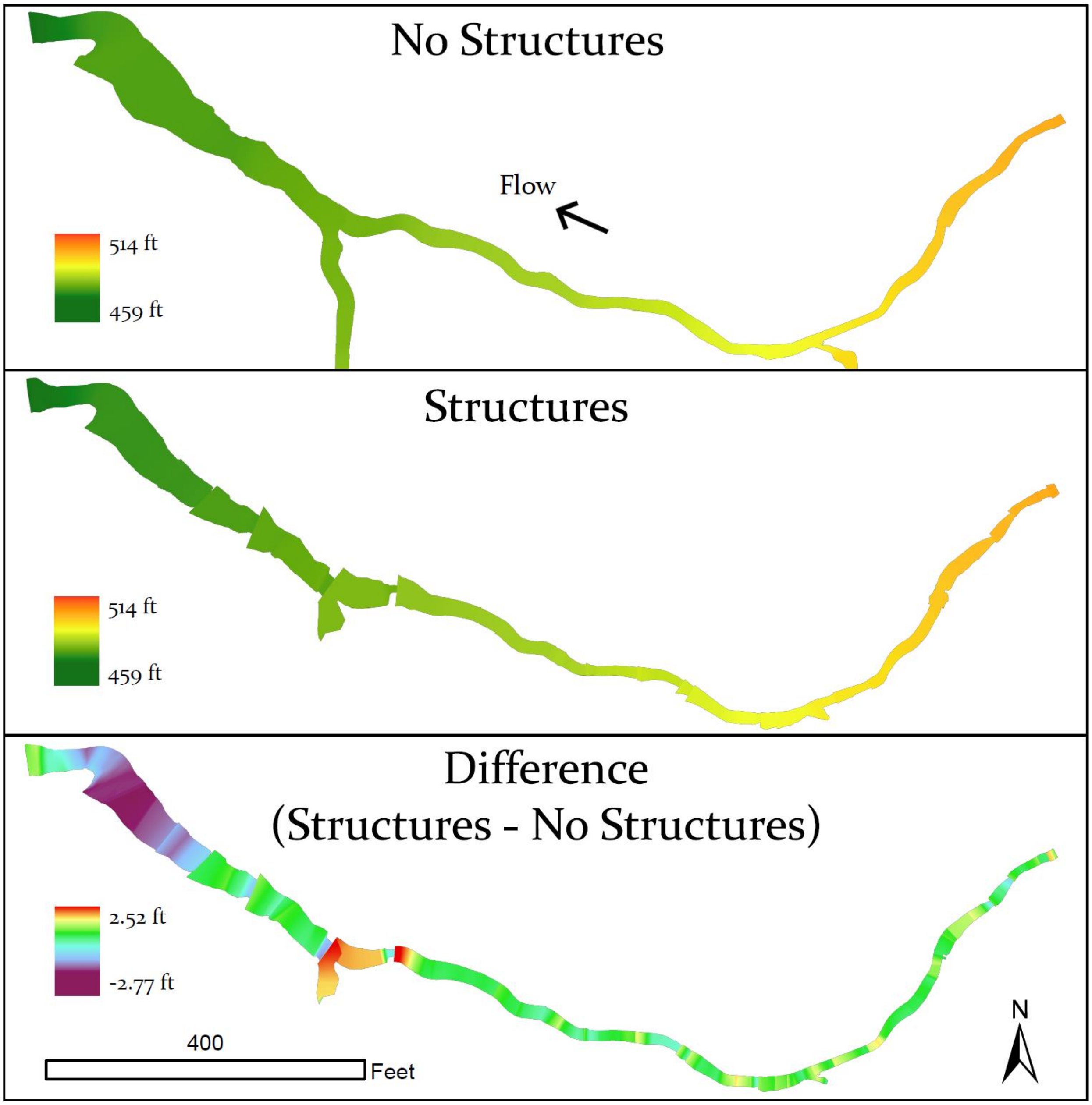

Figure C.3 100-yr water surface elevations for FEMA 1D and 1D model with structures for Project 24.

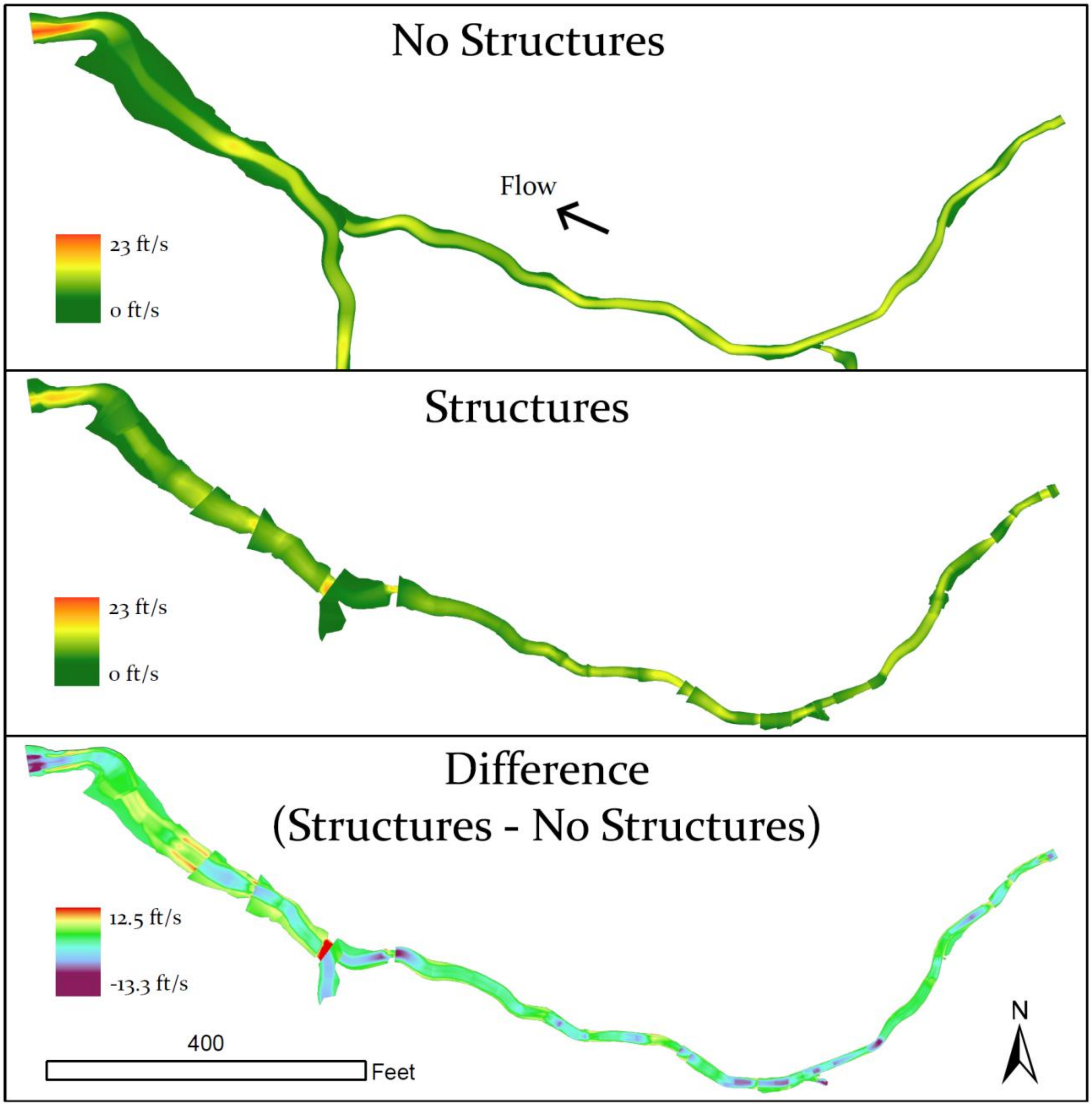

Figure C.4 Velocity for FEMA 1D and created 1D model with structures for Project 24.

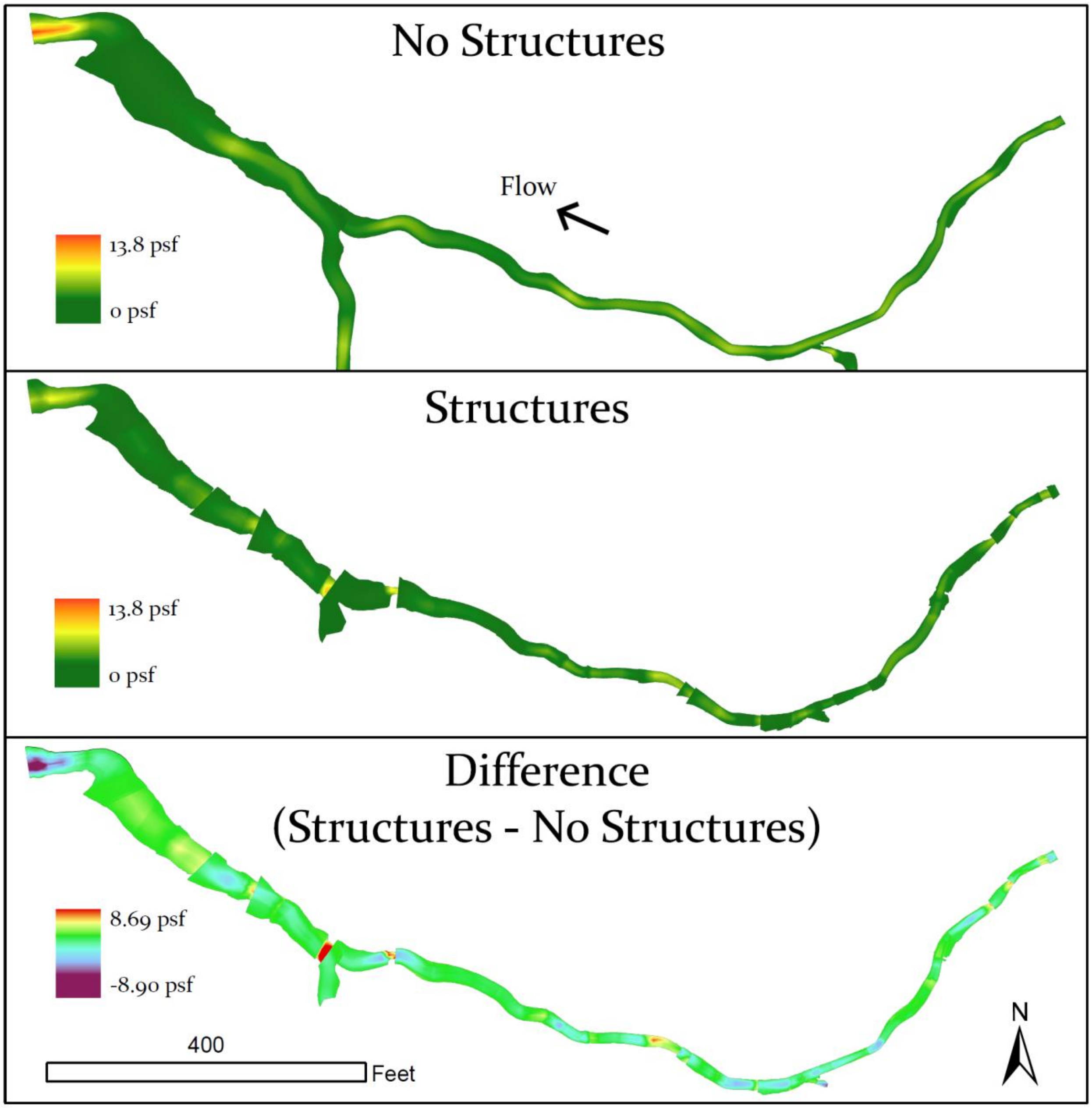

Figure C.5 Maximum boundary shear stress for FEMA 1D and created 1D model with structures for Project 24.

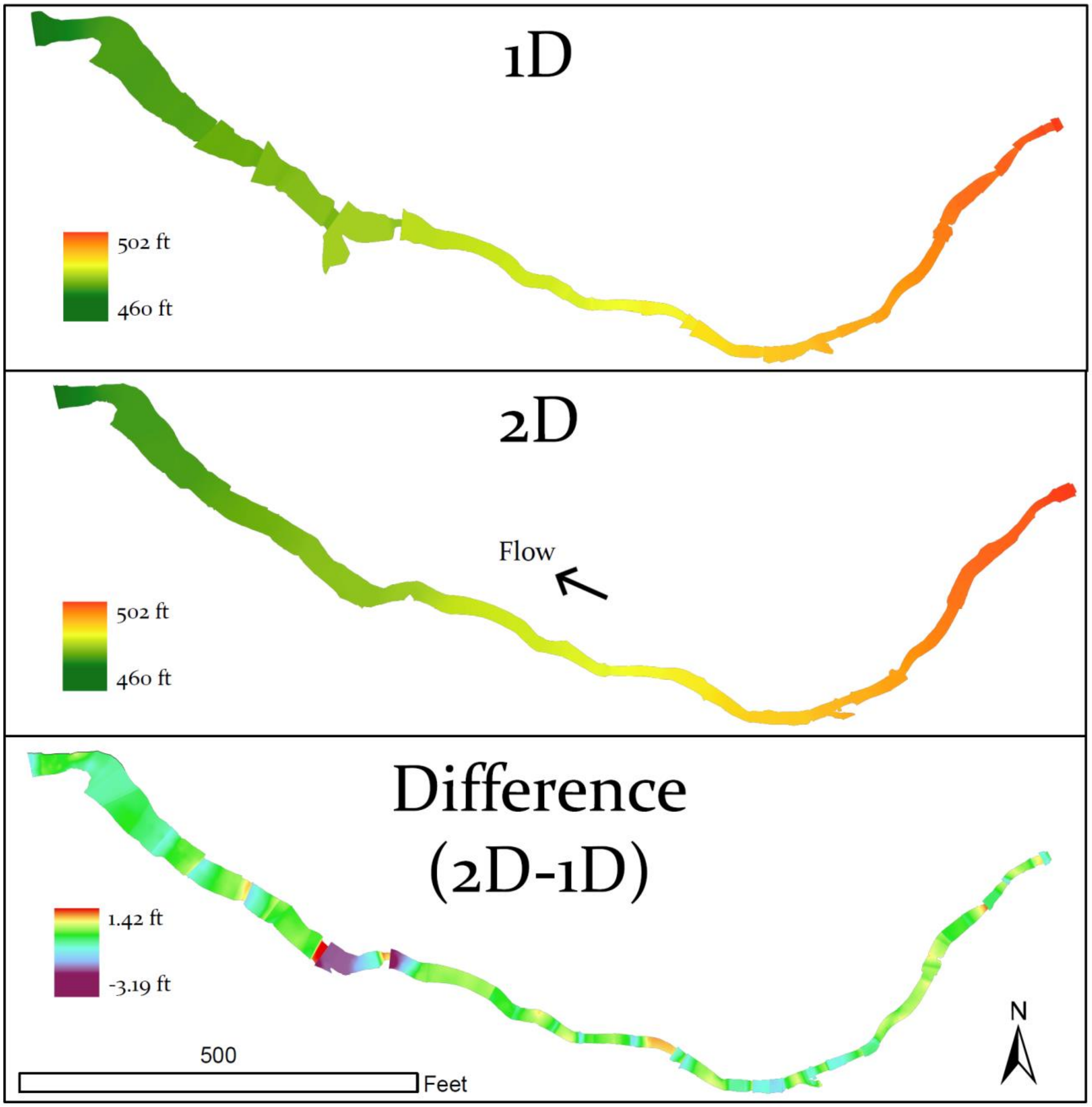

Figure C.6 Comparison of water surface elevations for 1D and 2D model for Project 25.

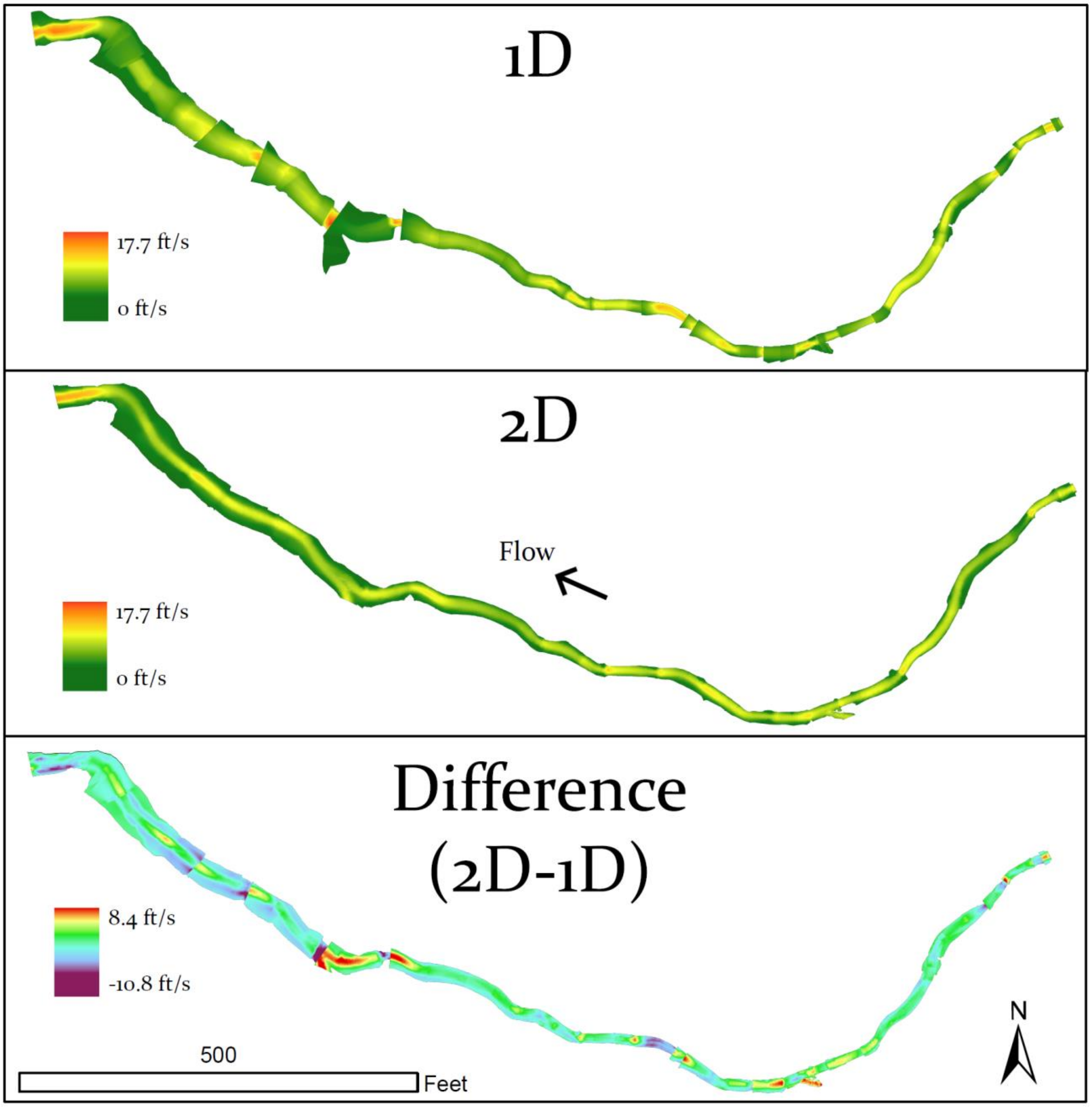

Figure C.7 Comparison of velocity for 1D and 2D model for Project 25.

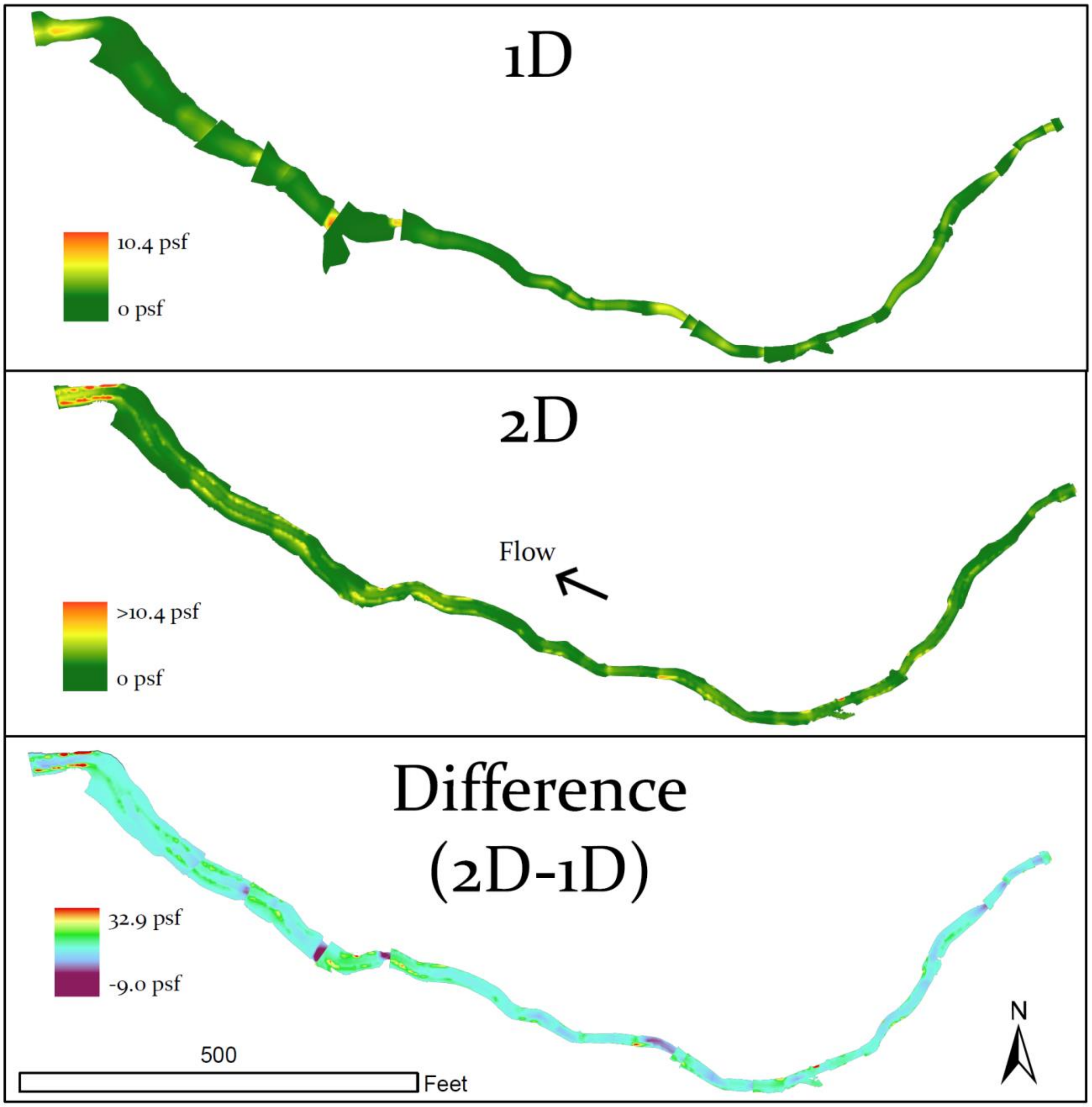

Figure C.8 Comparison of maximum boundary shear stress for 1D and 2D model for Project 25.

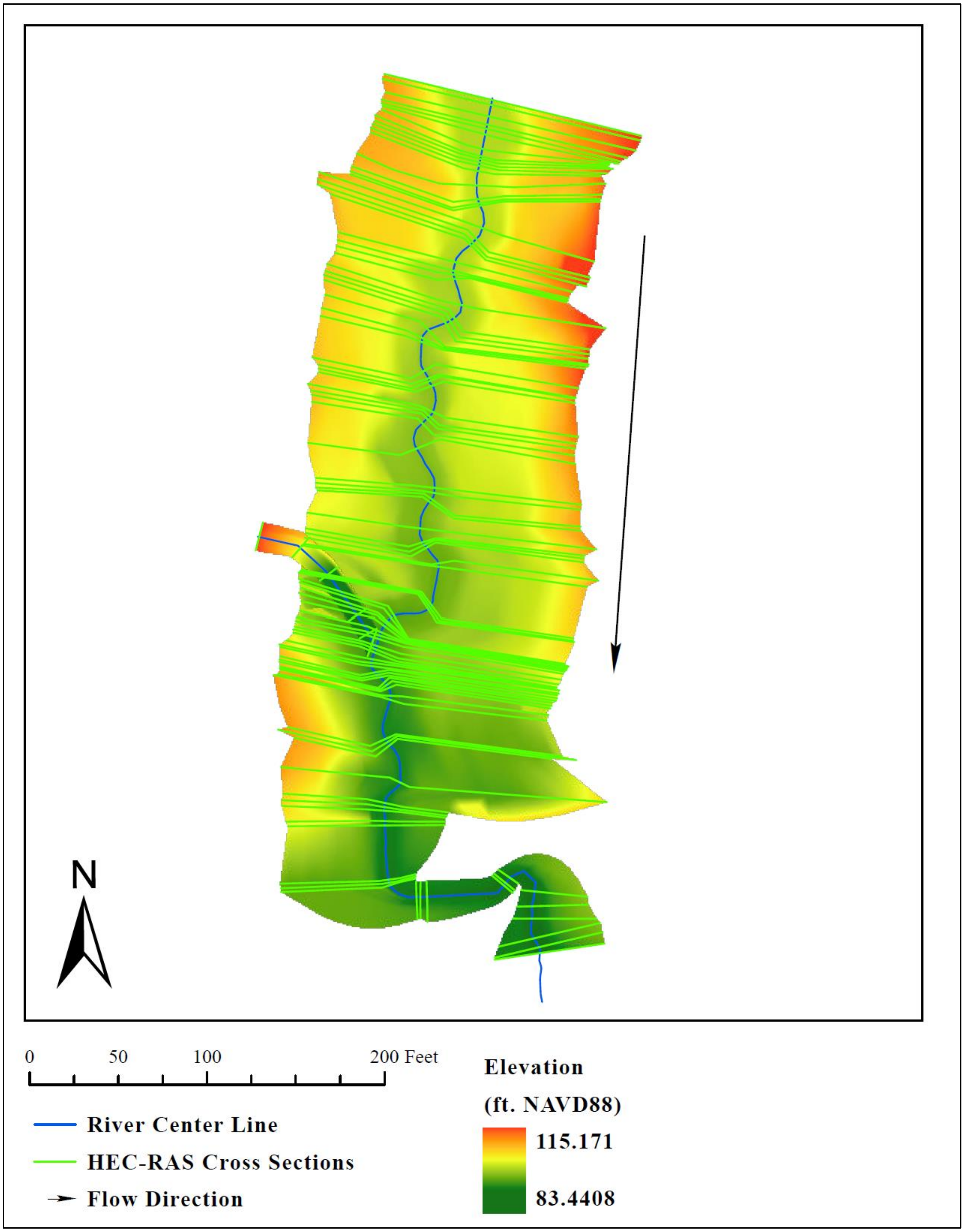

Figure C.9 Cross sections developed for 1D HEC-RAS model for Project 25.

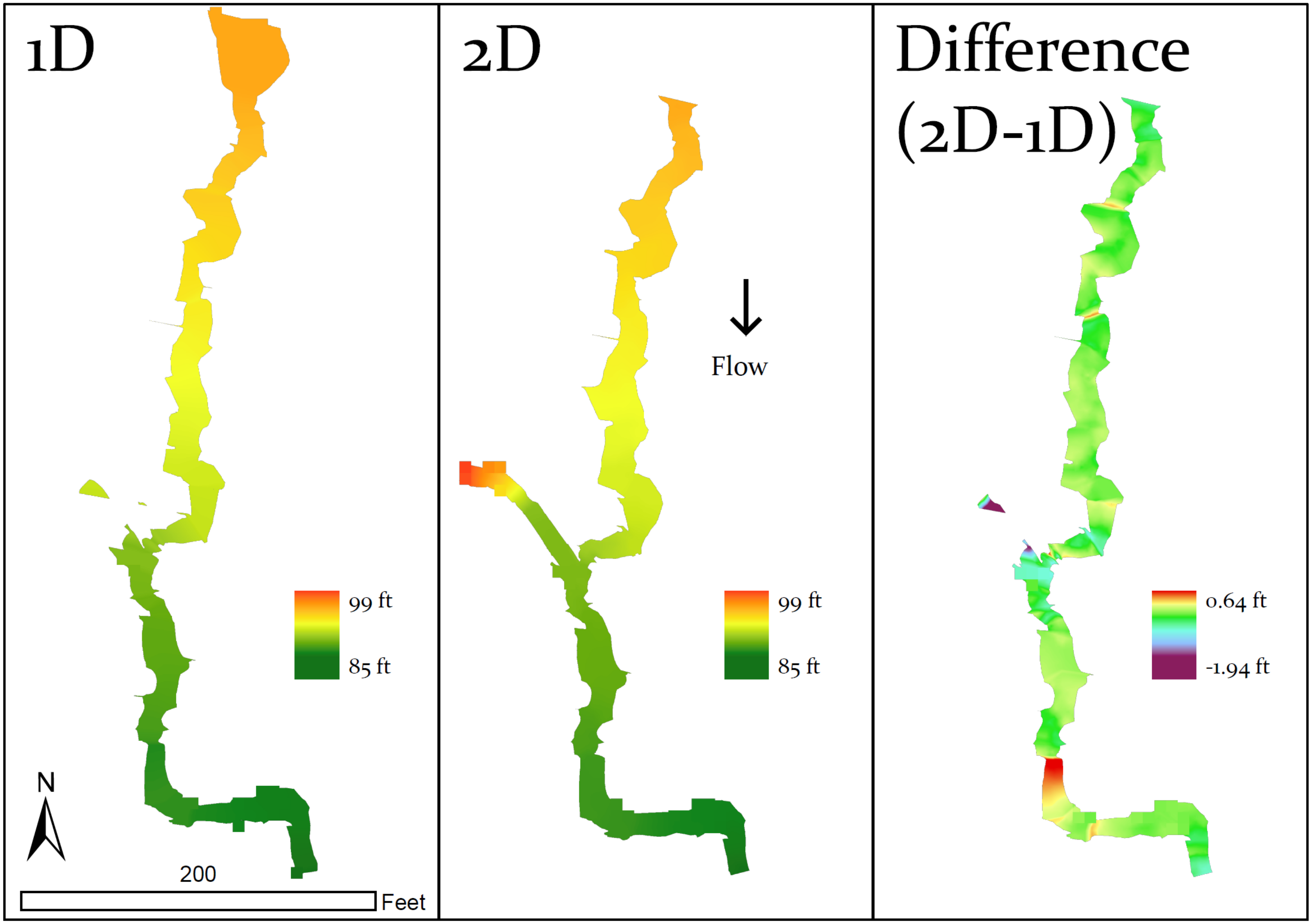

Figure C.10 Water surface elevations for 1D and 2D models for Project 25.

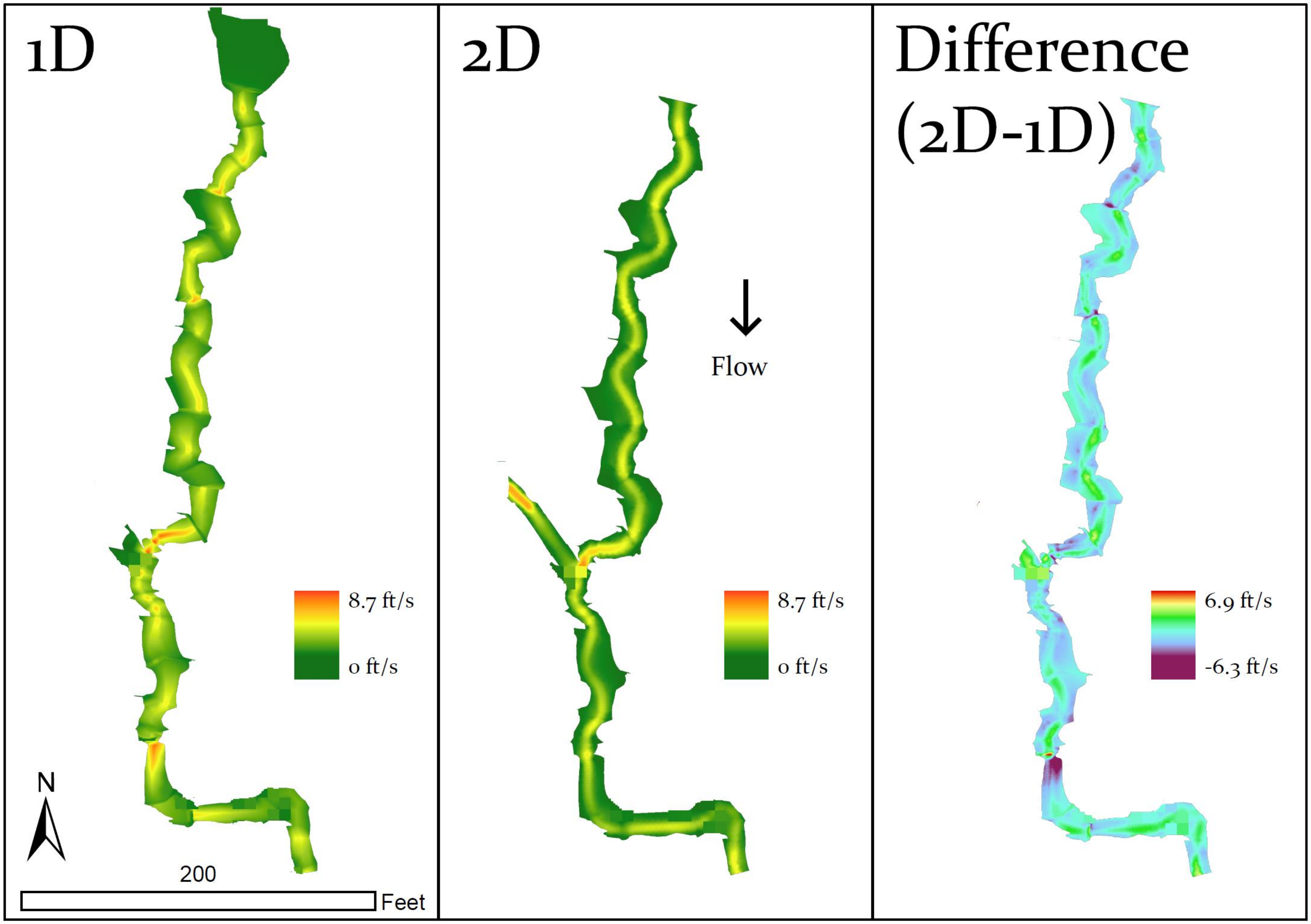

Figure C.11 Velocity for 1D and 2D models for Project 25.

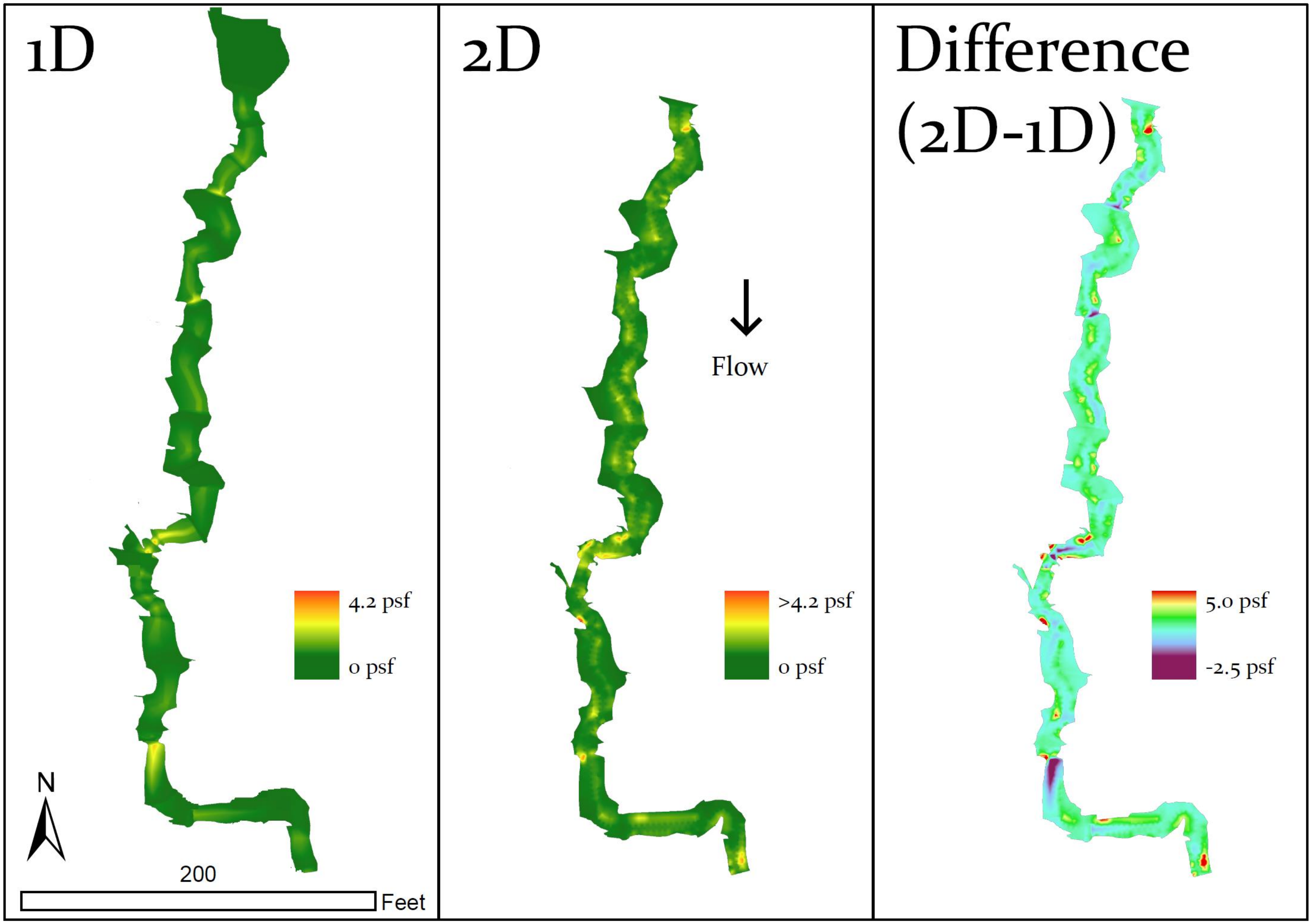

Figure C.12 Maximum boundary shear stress for 1D and 2D models for Project 25.

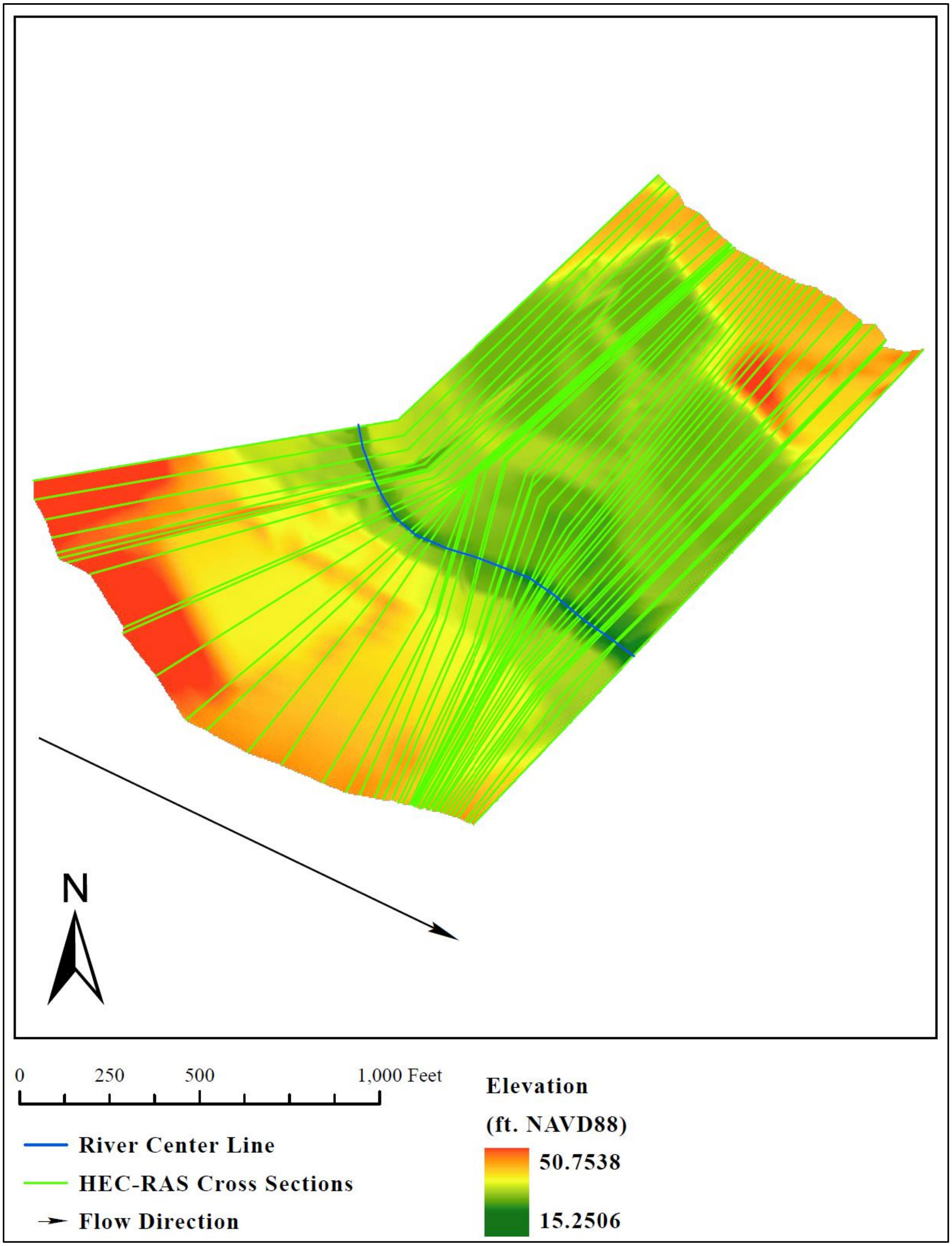

Figure C.13 Cross sections developed for 1D HEC-RAS model for Project 41.

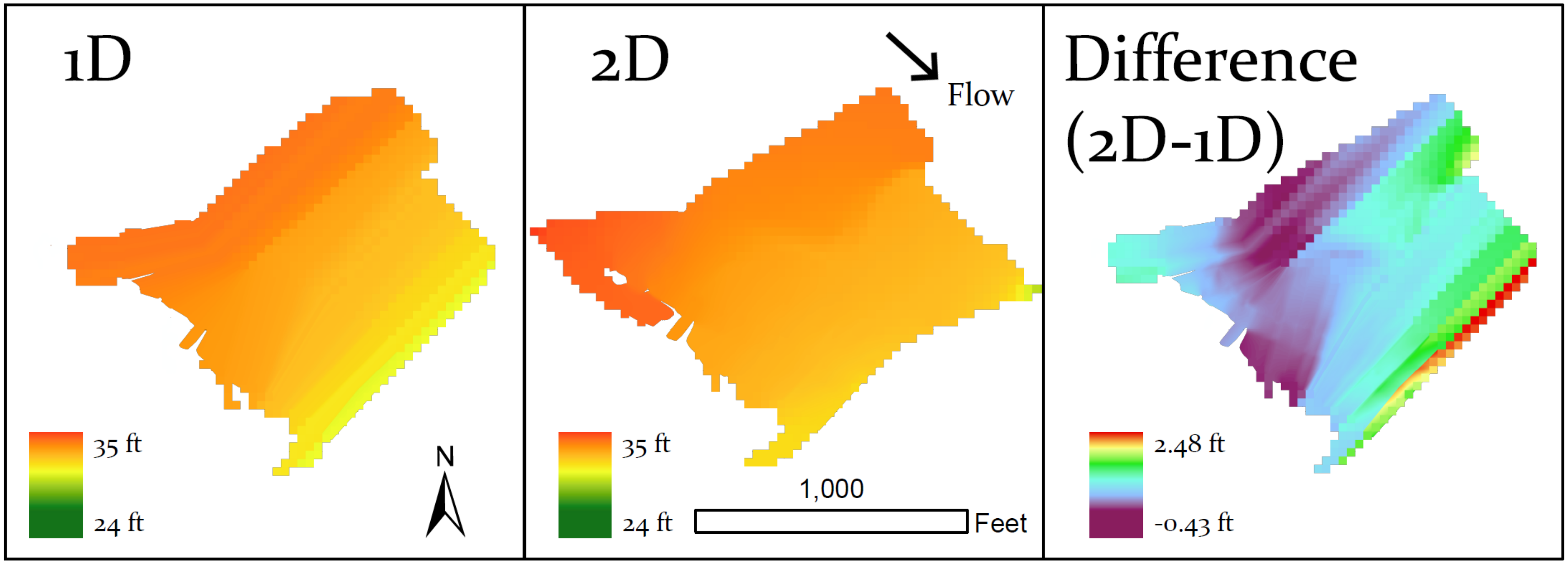

Figure C.14 Water surface elevations for 1D and 2D models for Project 41.

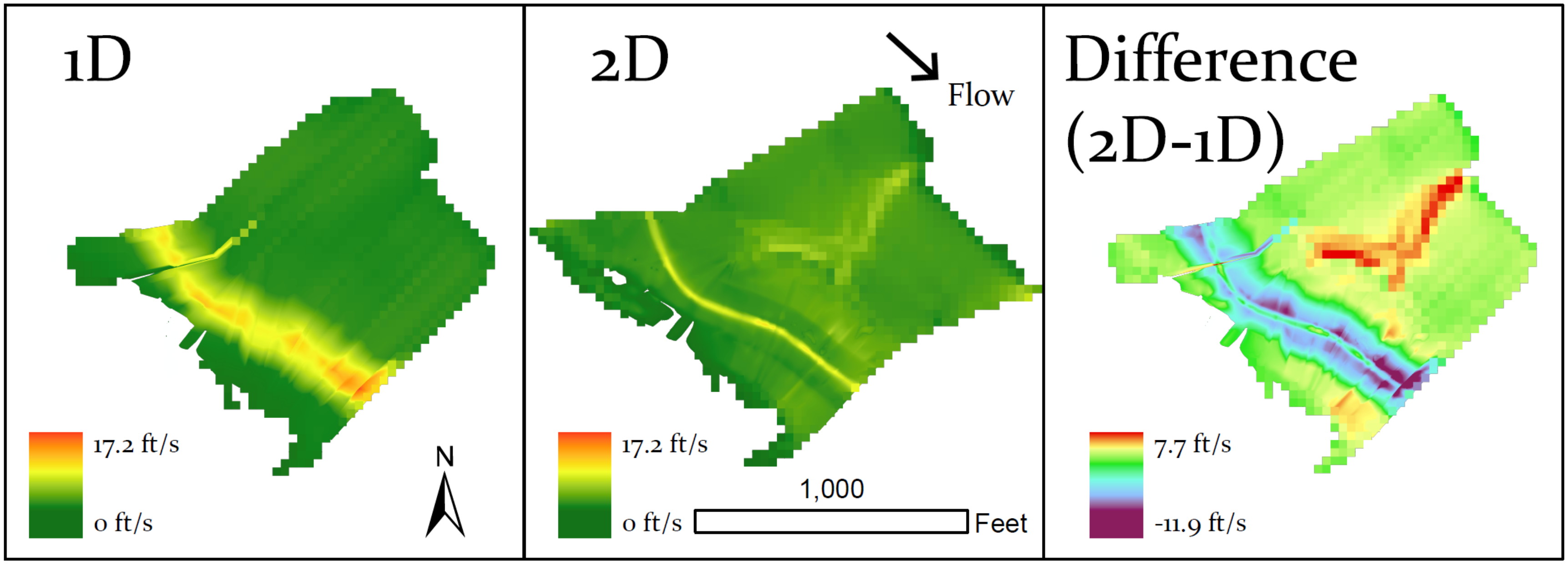

Figure C.15 Velocity for 1D and 2D models for Project 41.

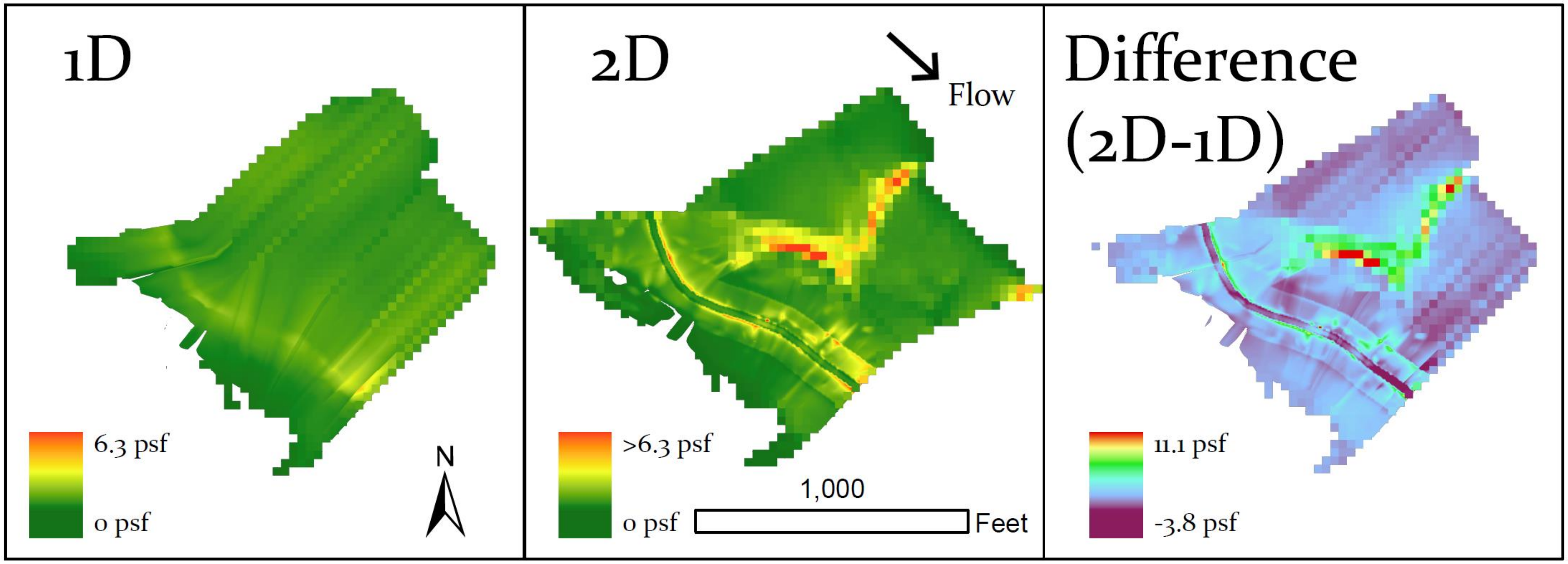

Figure C.16   Maximum boundary shear stress for 1D and 2D models for Project 41.

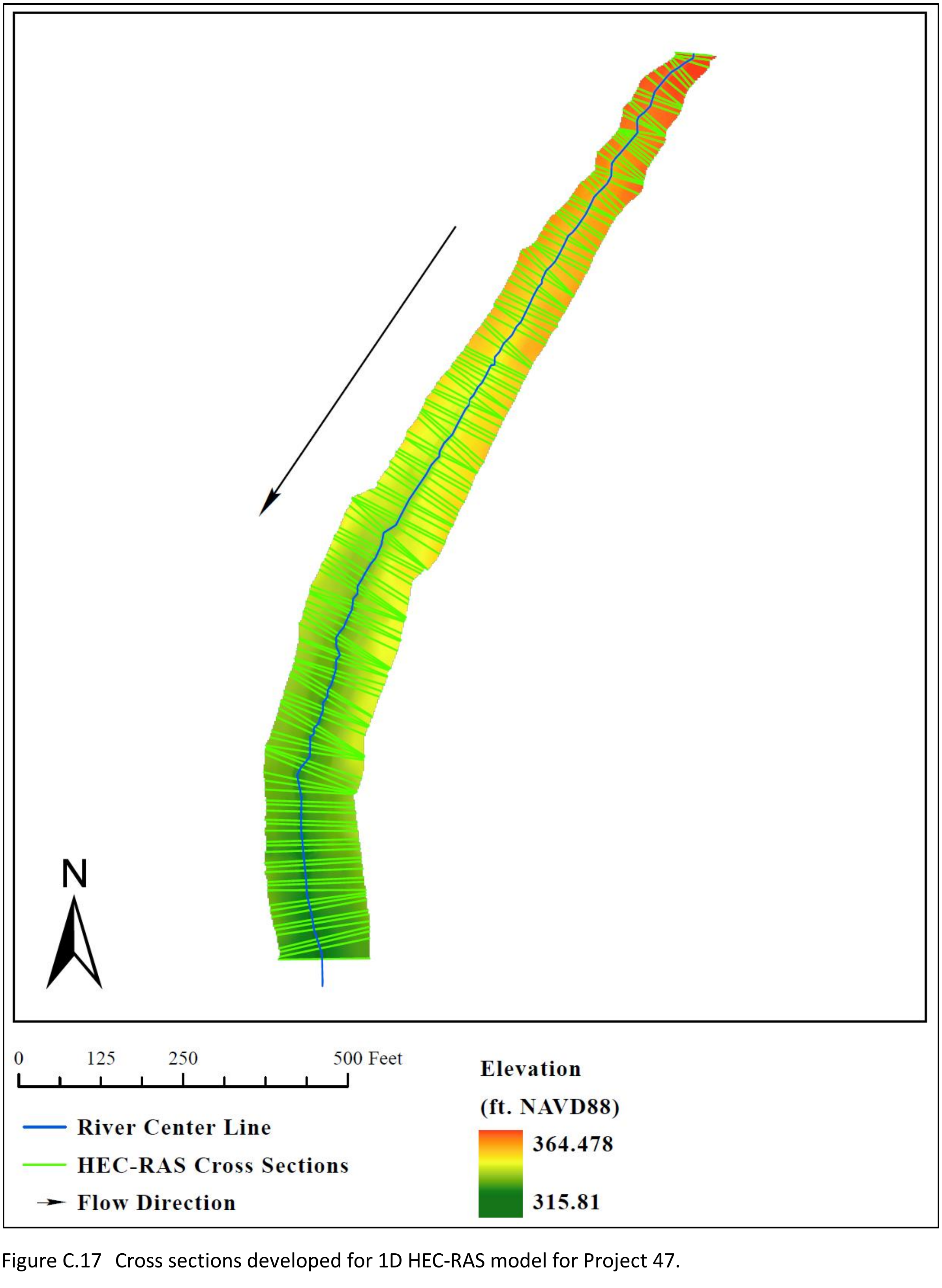

Figure C.17 Cross sections developed for 1D HEC-RAS model for Project 47.

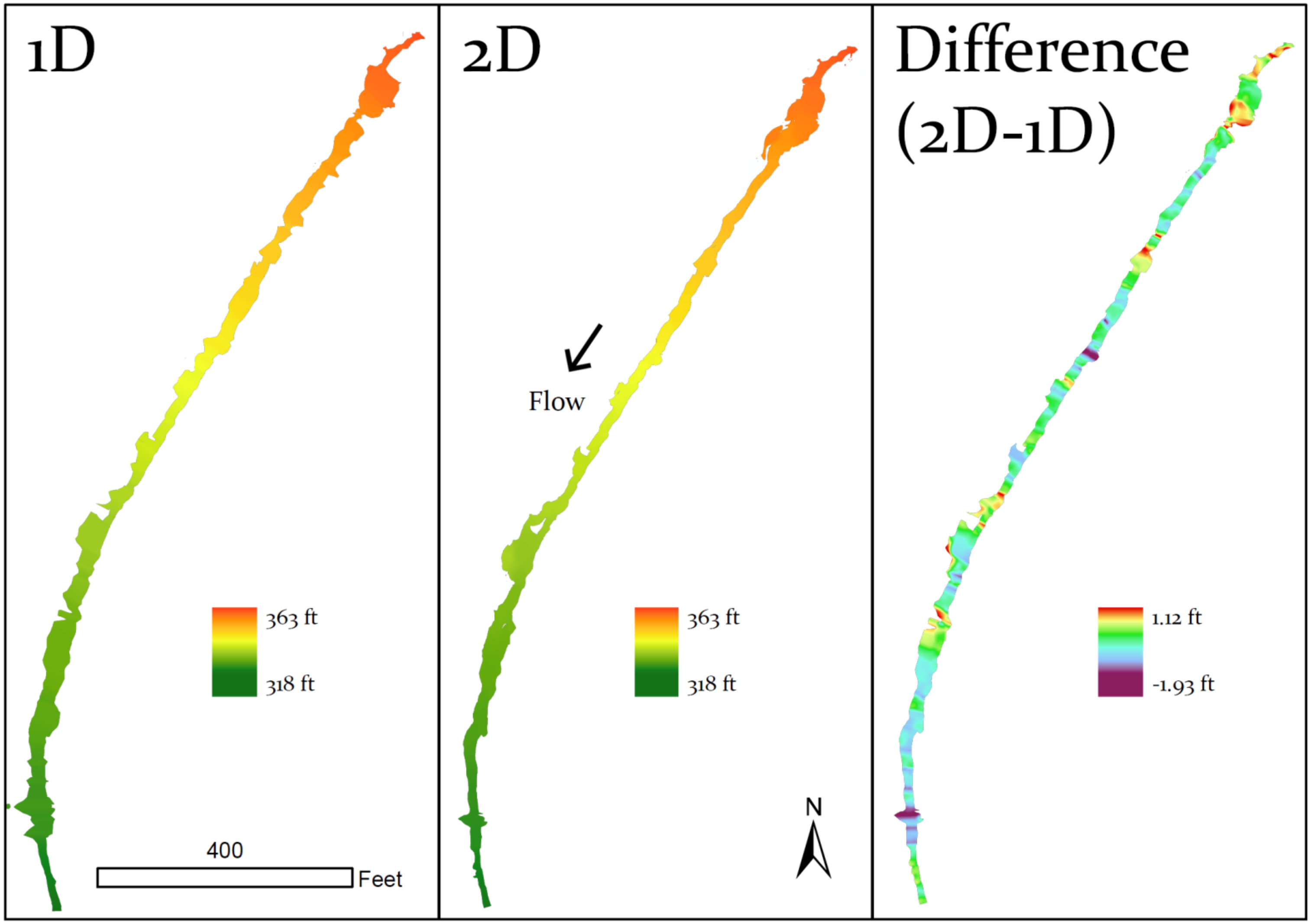

Figure C.18 Water surface elevations for 1D and 2D models for Project 47.

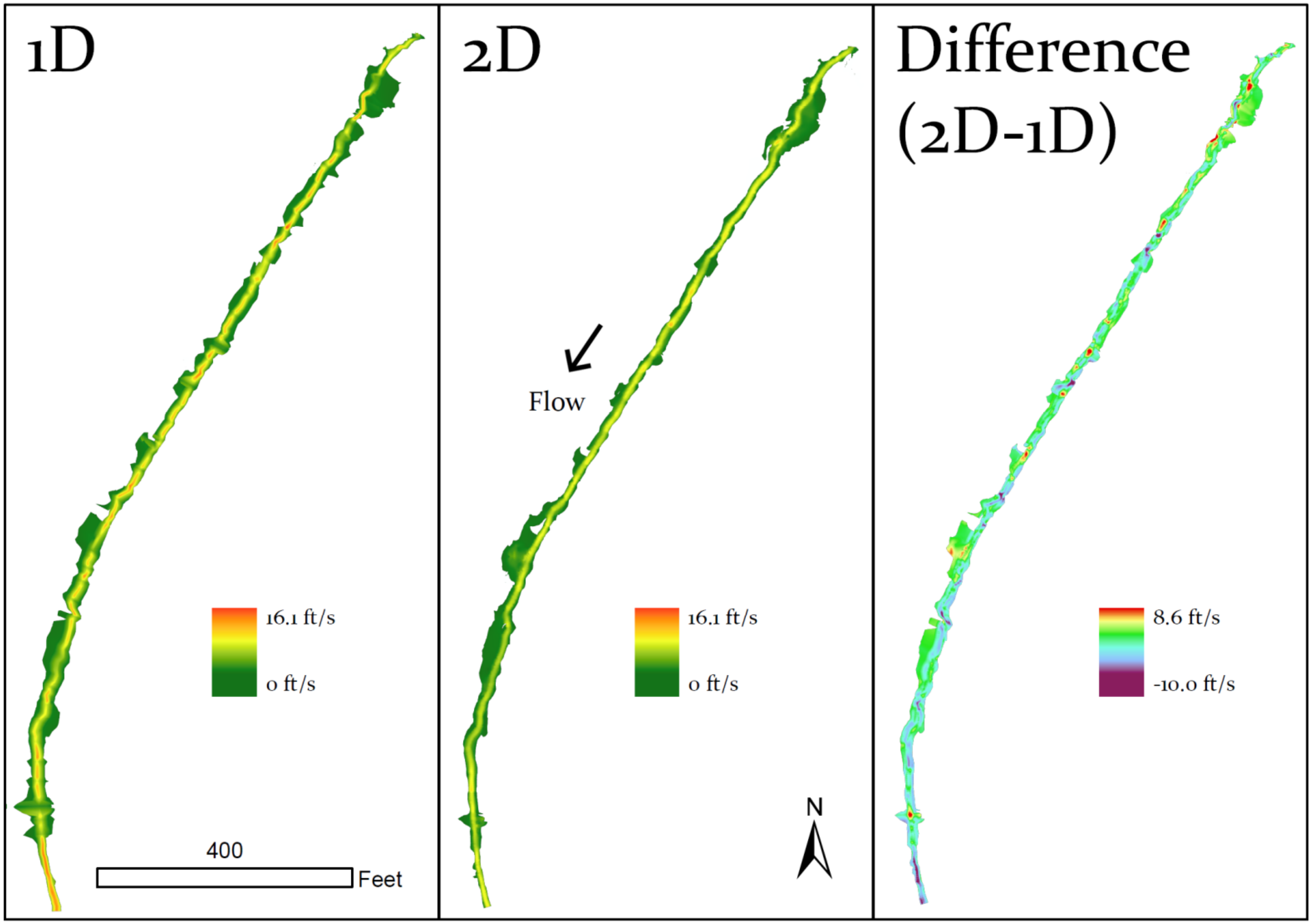

Figure C.19 Velocity for 1D and 2D models for Project 47.

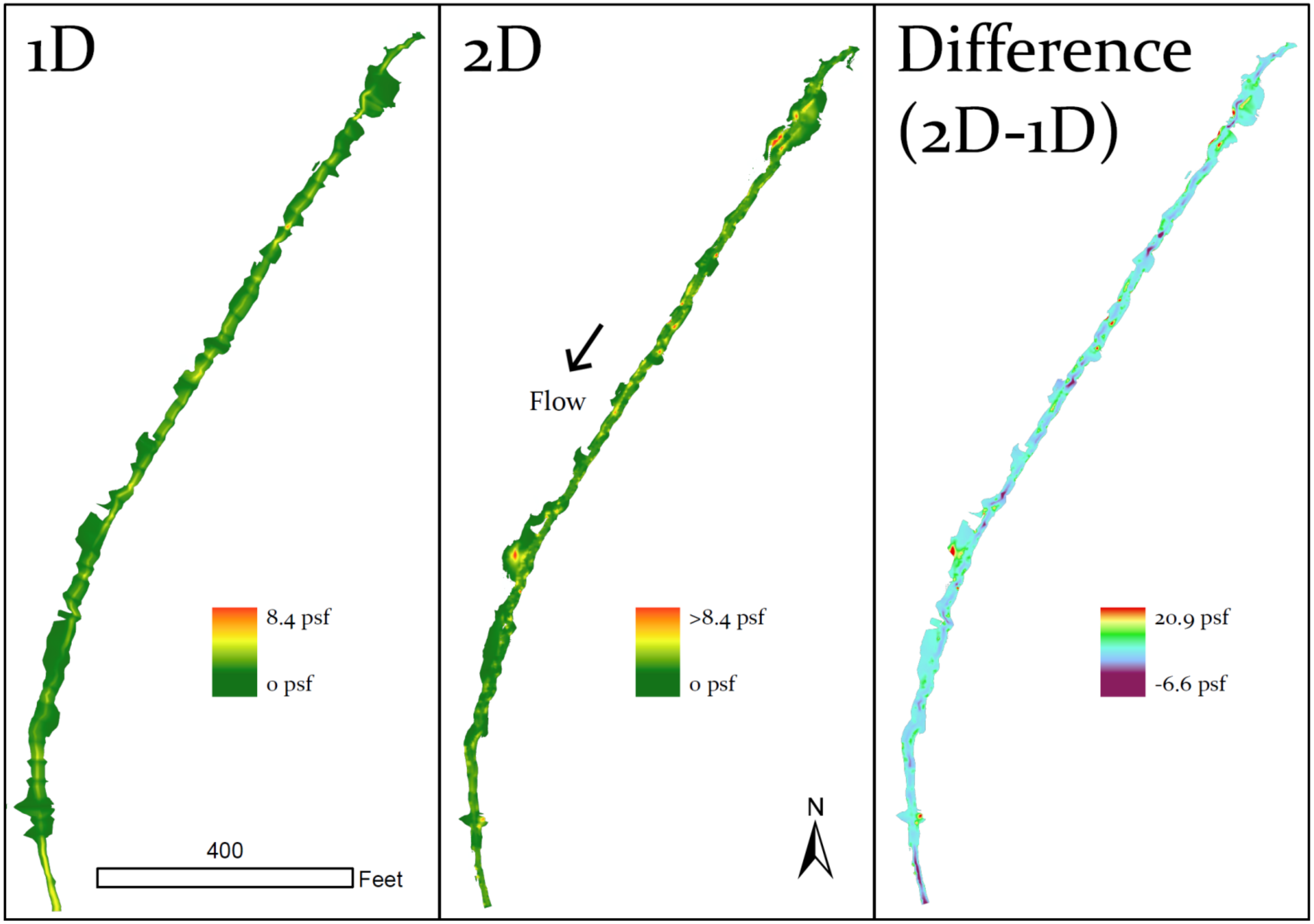

Figure C.20 Maximum boundary shear stress for 1D and 2D models for Project 47.

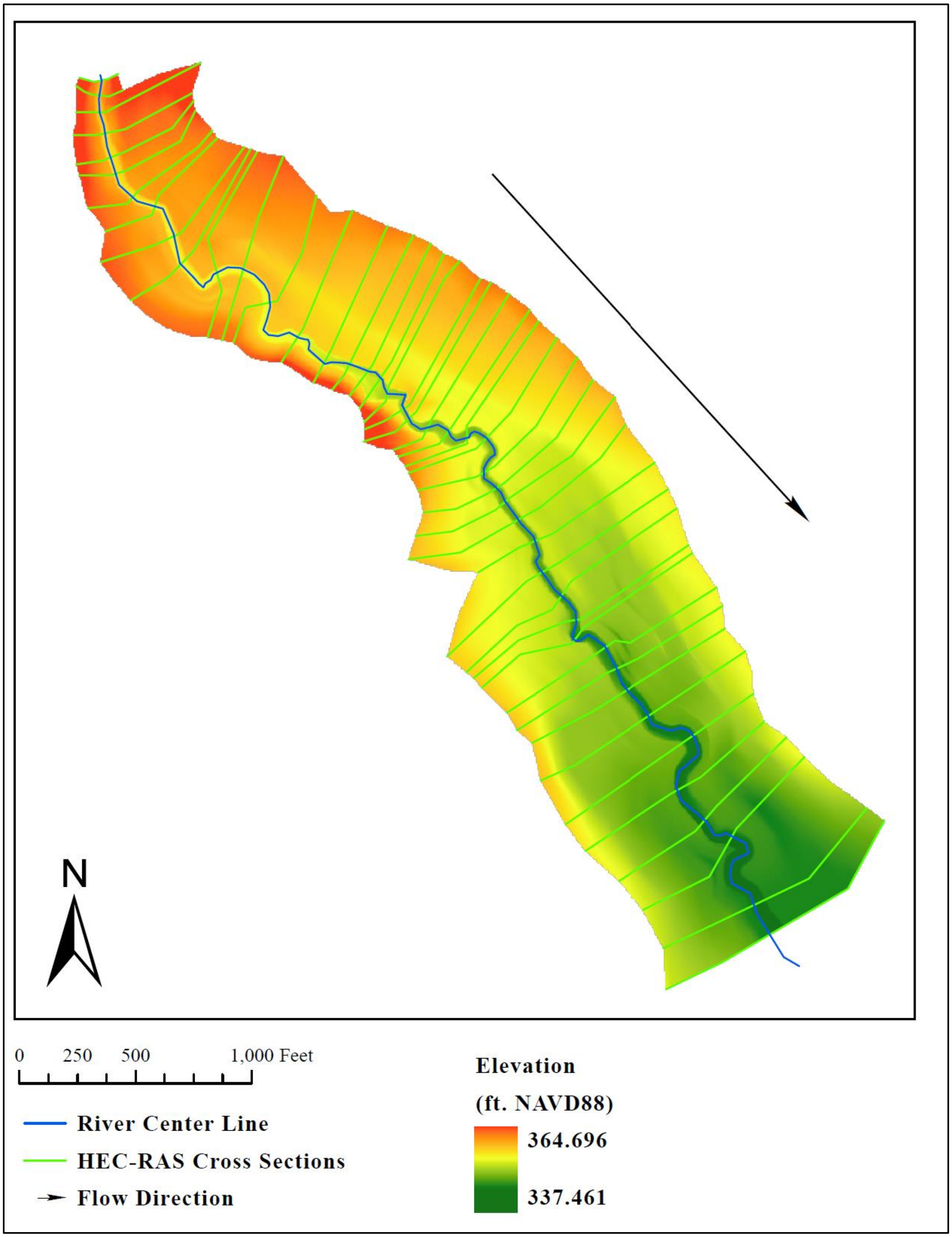

Figure C.21 Cross sections in FEMA 1D model for Project 24, which included structures.

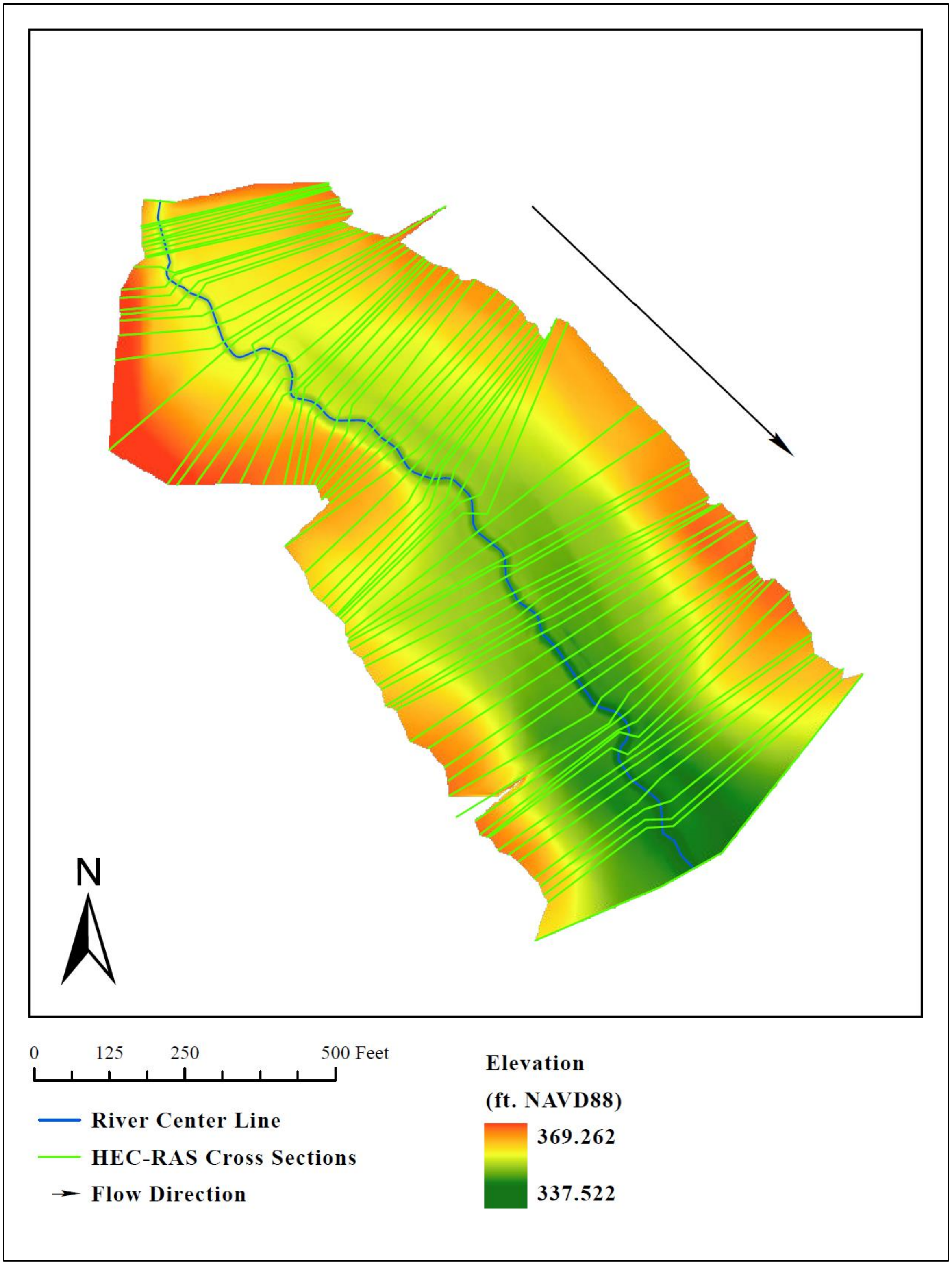

Figure C.22 Cross sections in developed 1D model for Project 24 with 3-4 cross sections per structure.

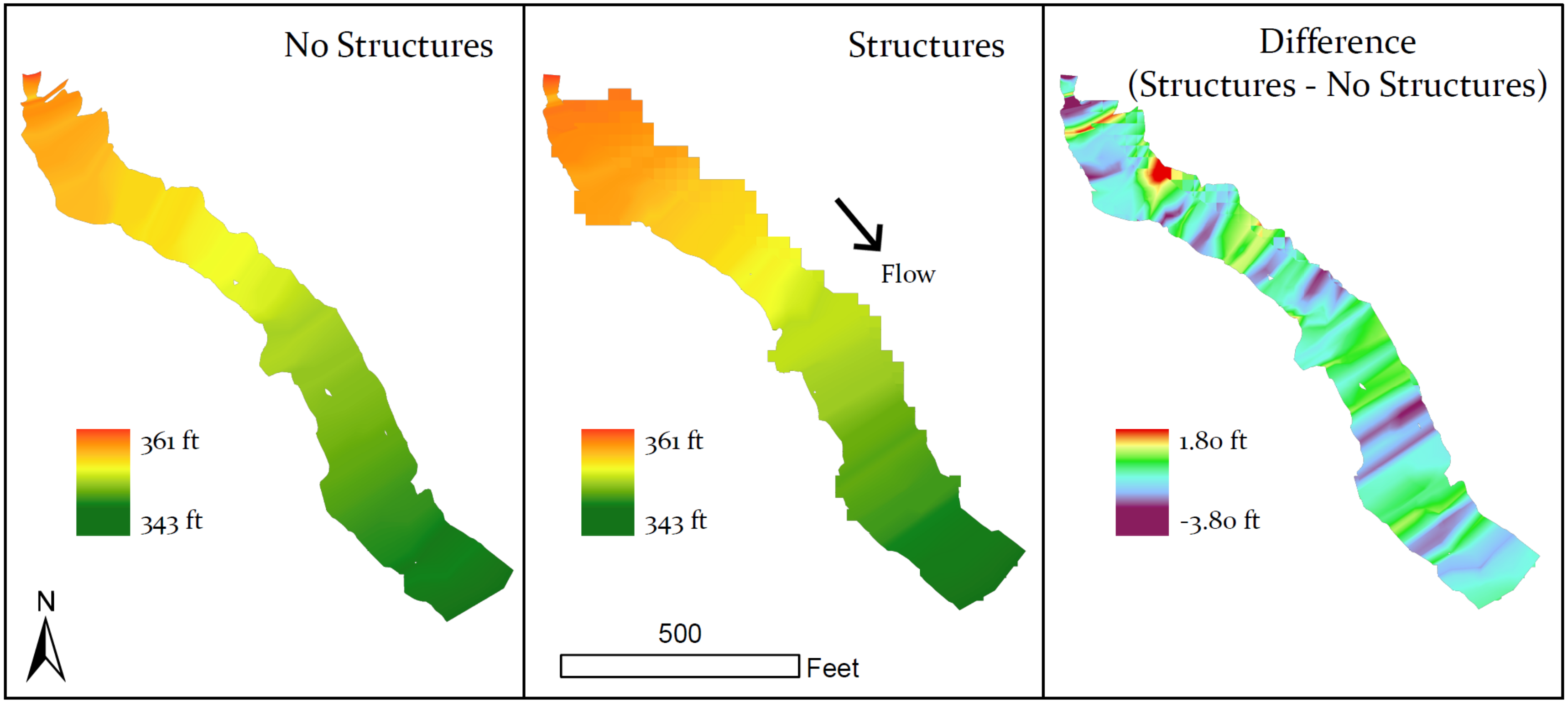

Figure C.23 100-yr water surface elevations for FEMA 1D and 1D model with structures for Project 50.

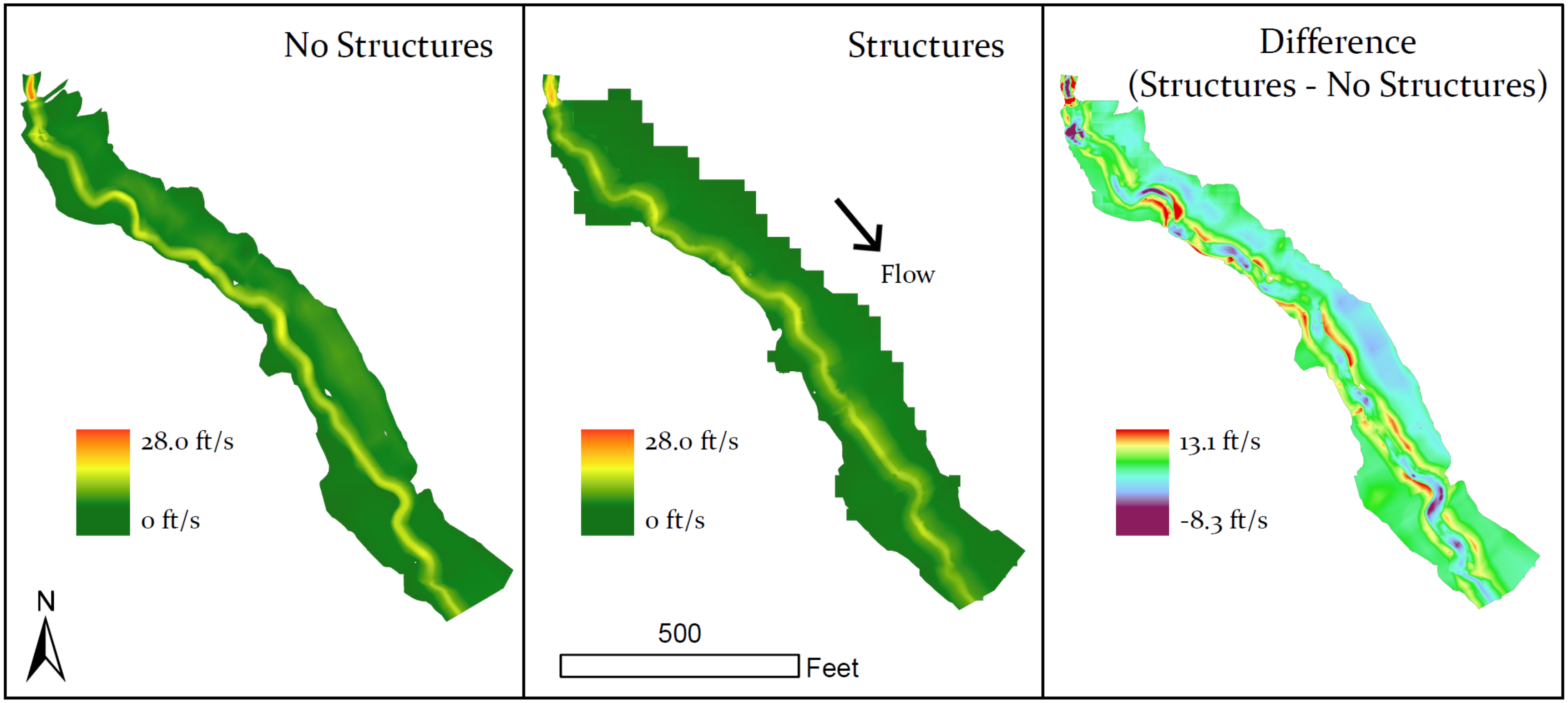

Figure C.24 Velocity for FEMA 1D and created 1D model with structures for Project 50.

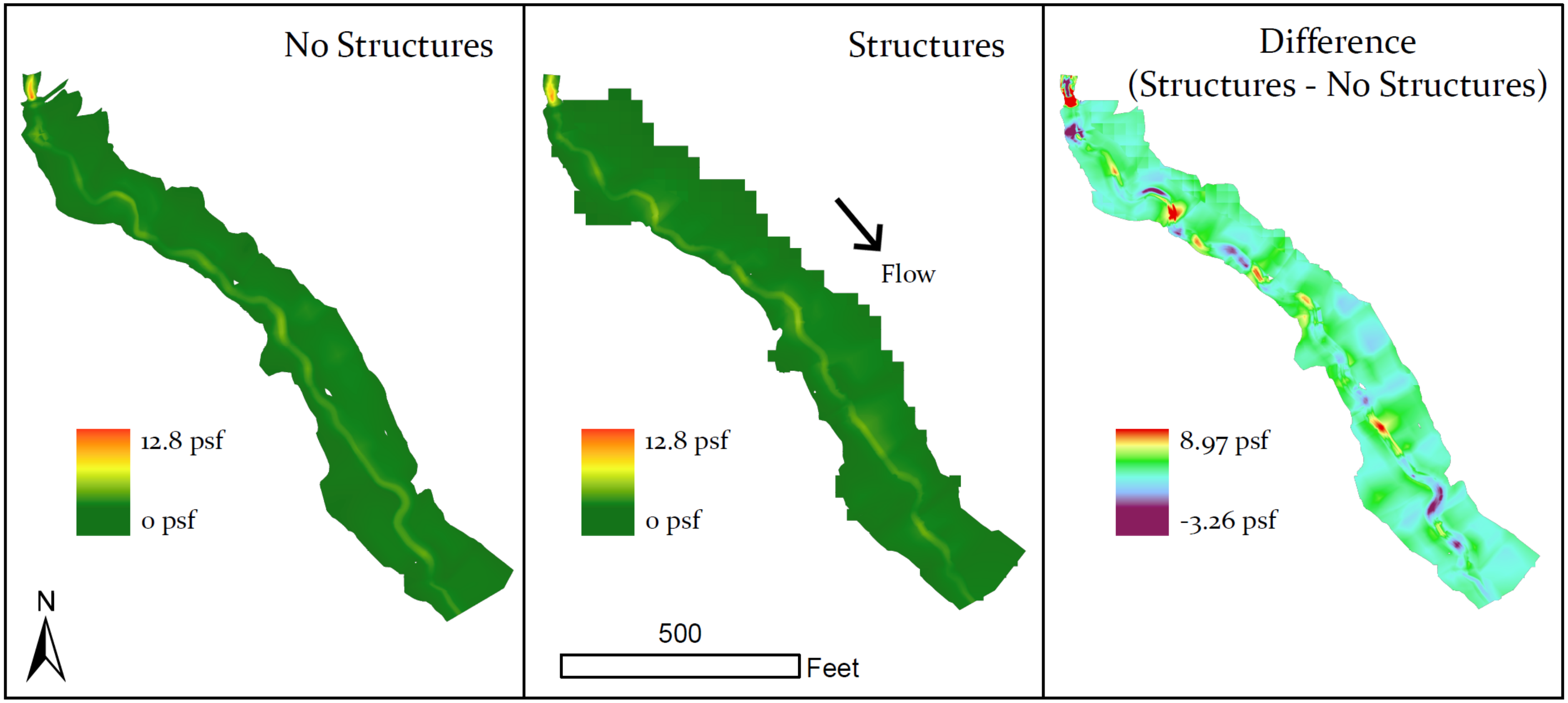

Figure C.25 Maximum boundary shear stress for FEMA 1D and created 1D model with structures for Project 24.

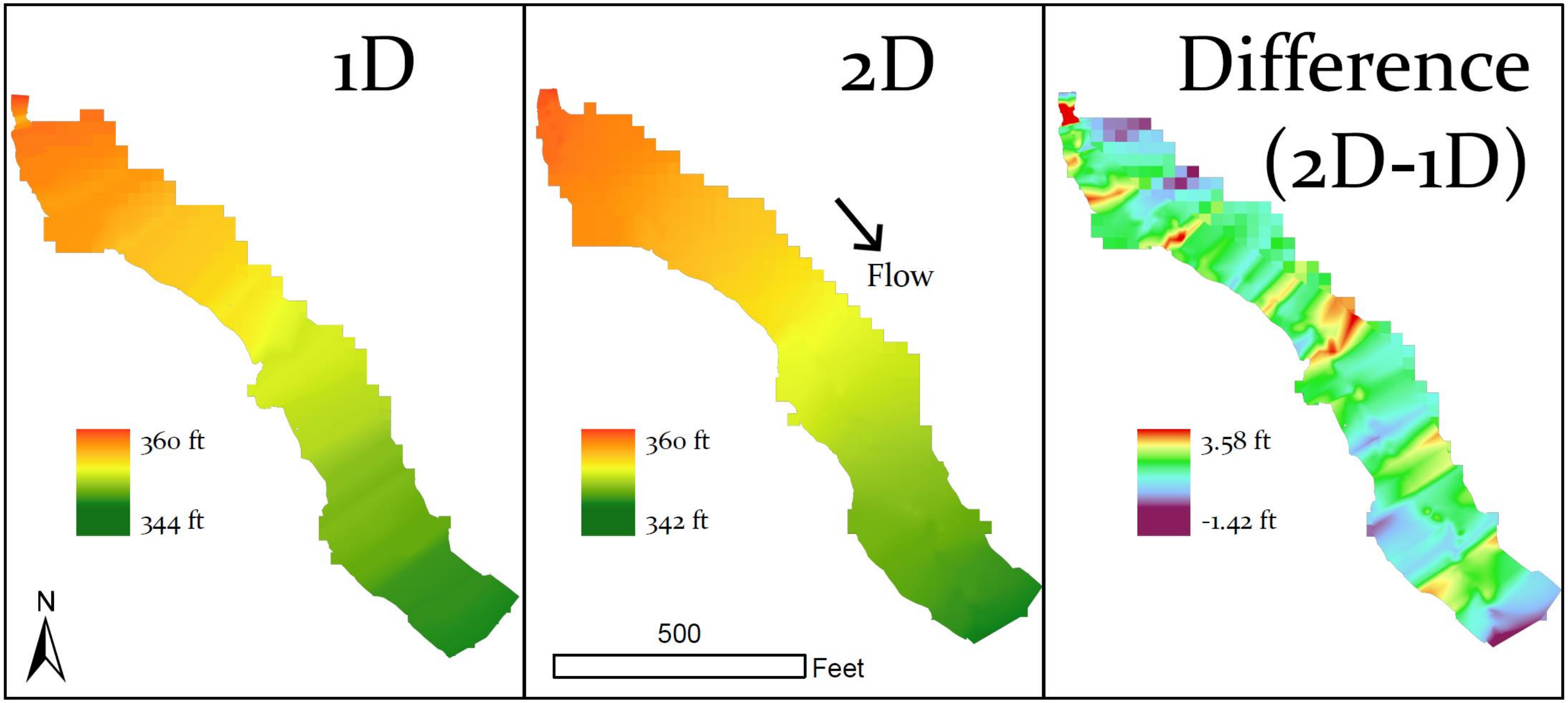

Figure C.26 Water surface elevations for 1D and 2D models for Project 50.

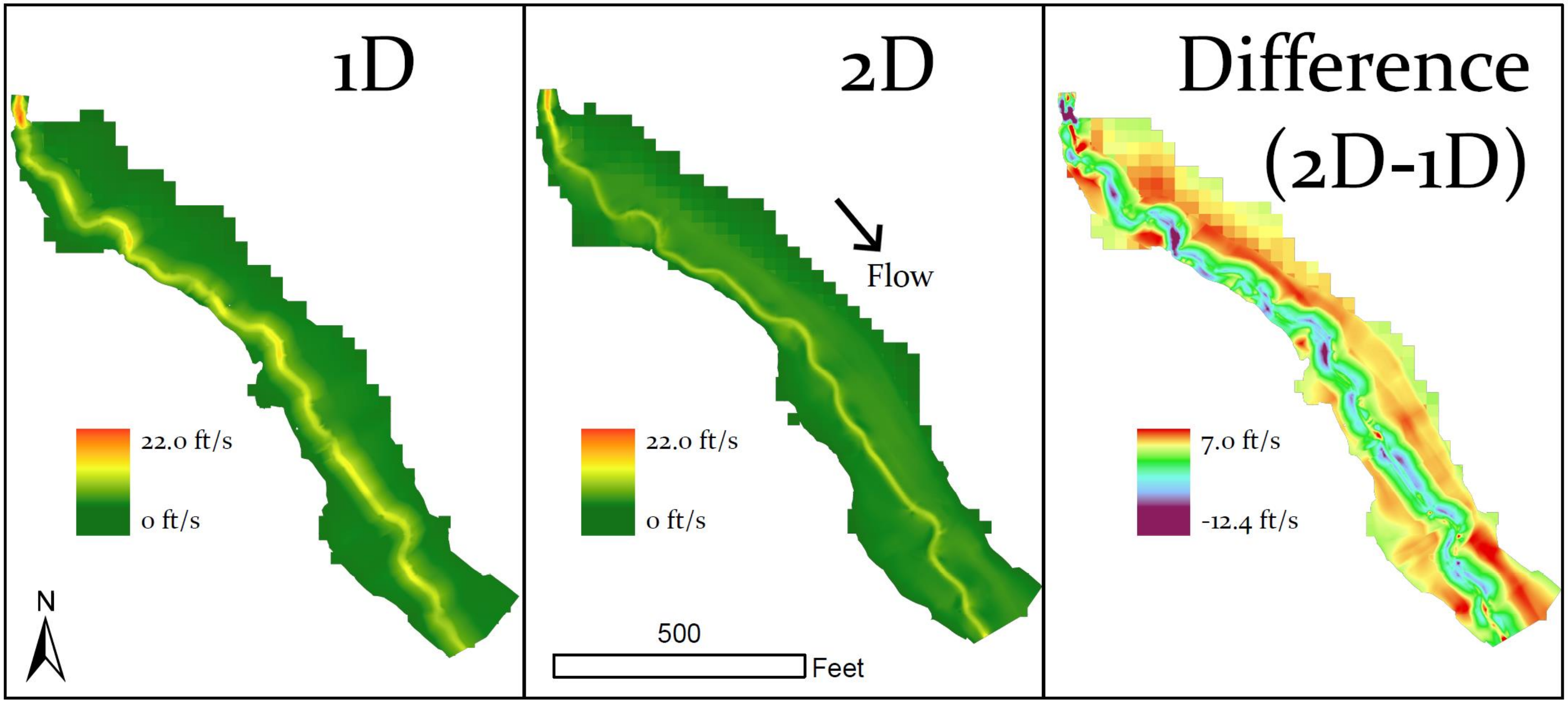

Figure C.27 Velocity for 1D and 2D models for Project 50.

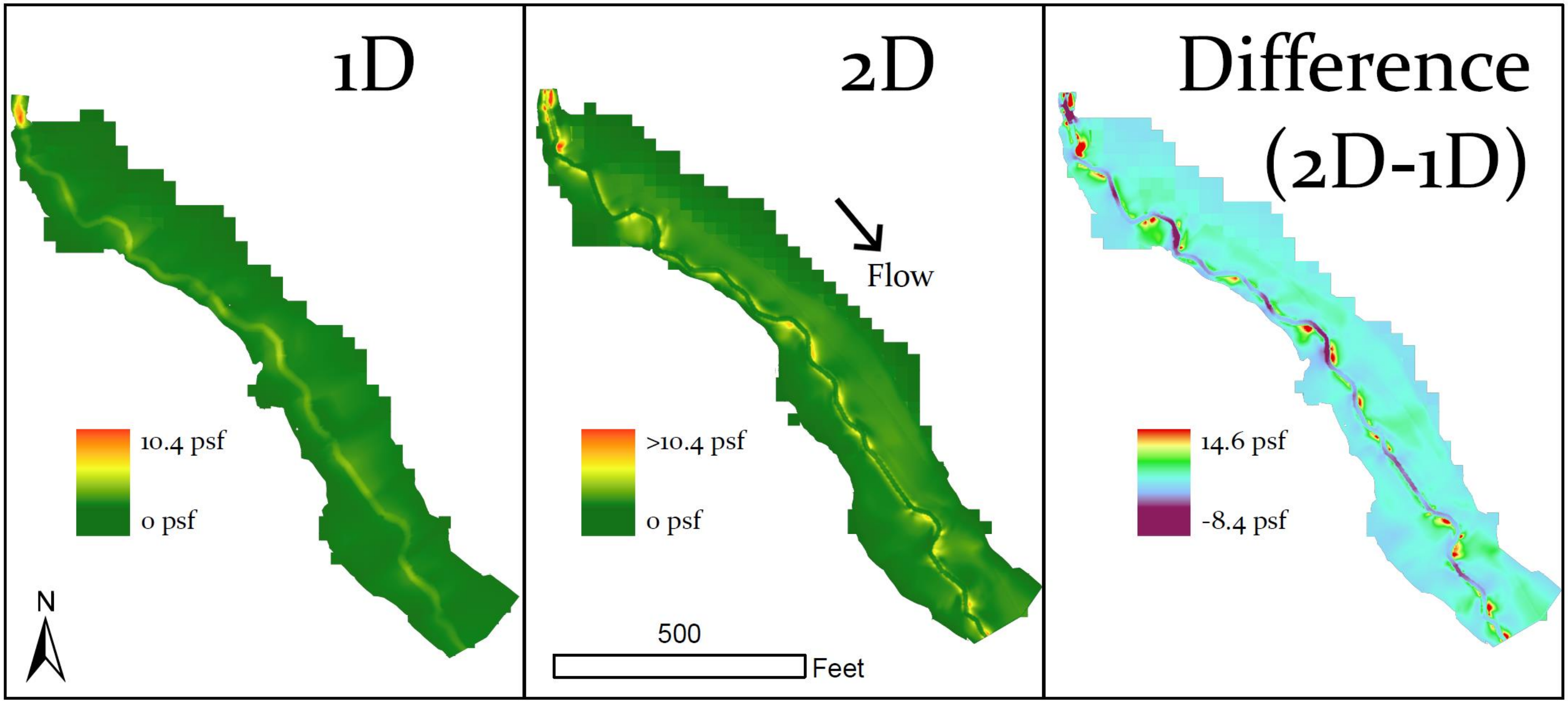

Figure C.28 Maximum boundary shear stress for 1D and 2D models for Project 50.

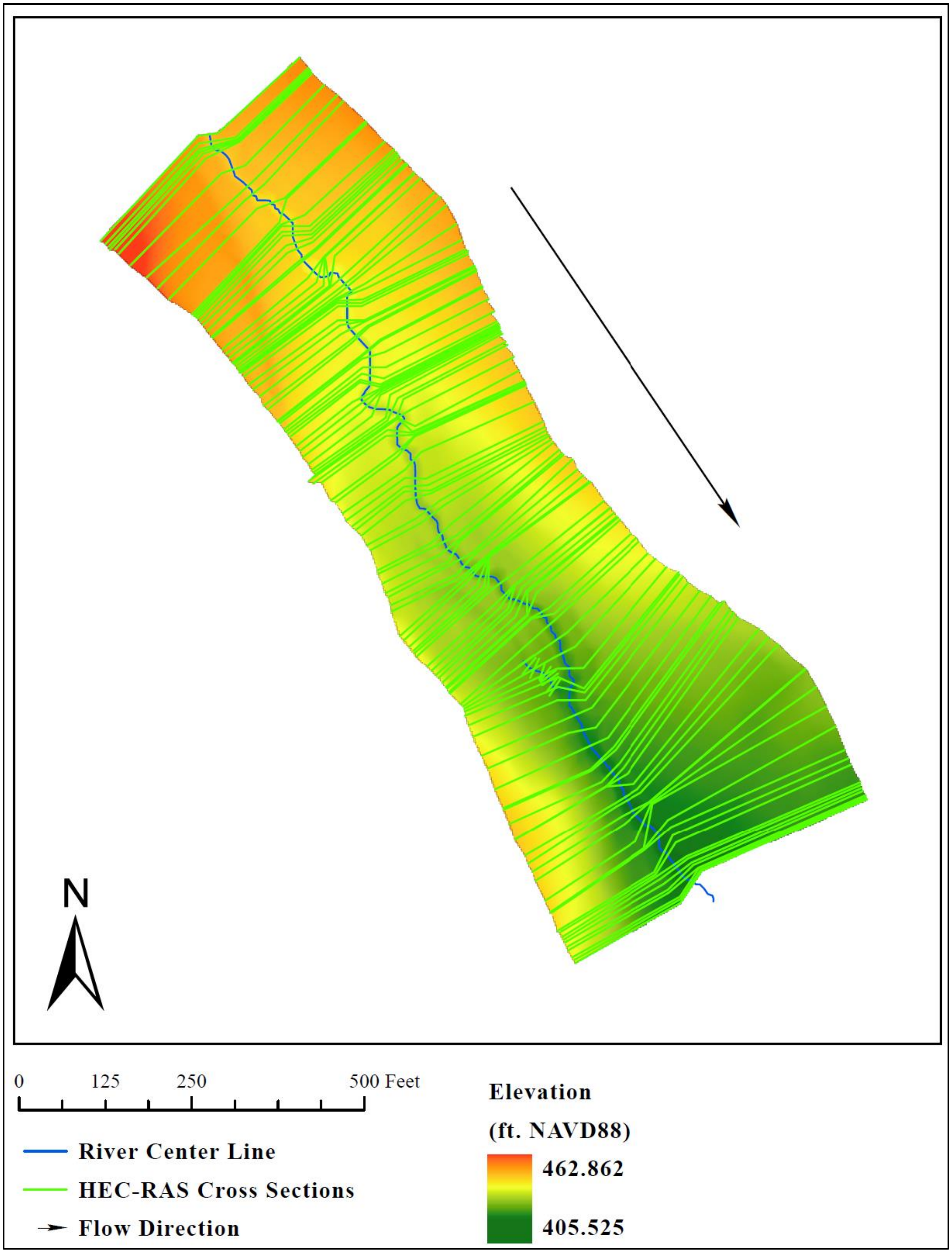

Figure C.29 Cross sections developed for 1D HEC-RAS model for Project 55.

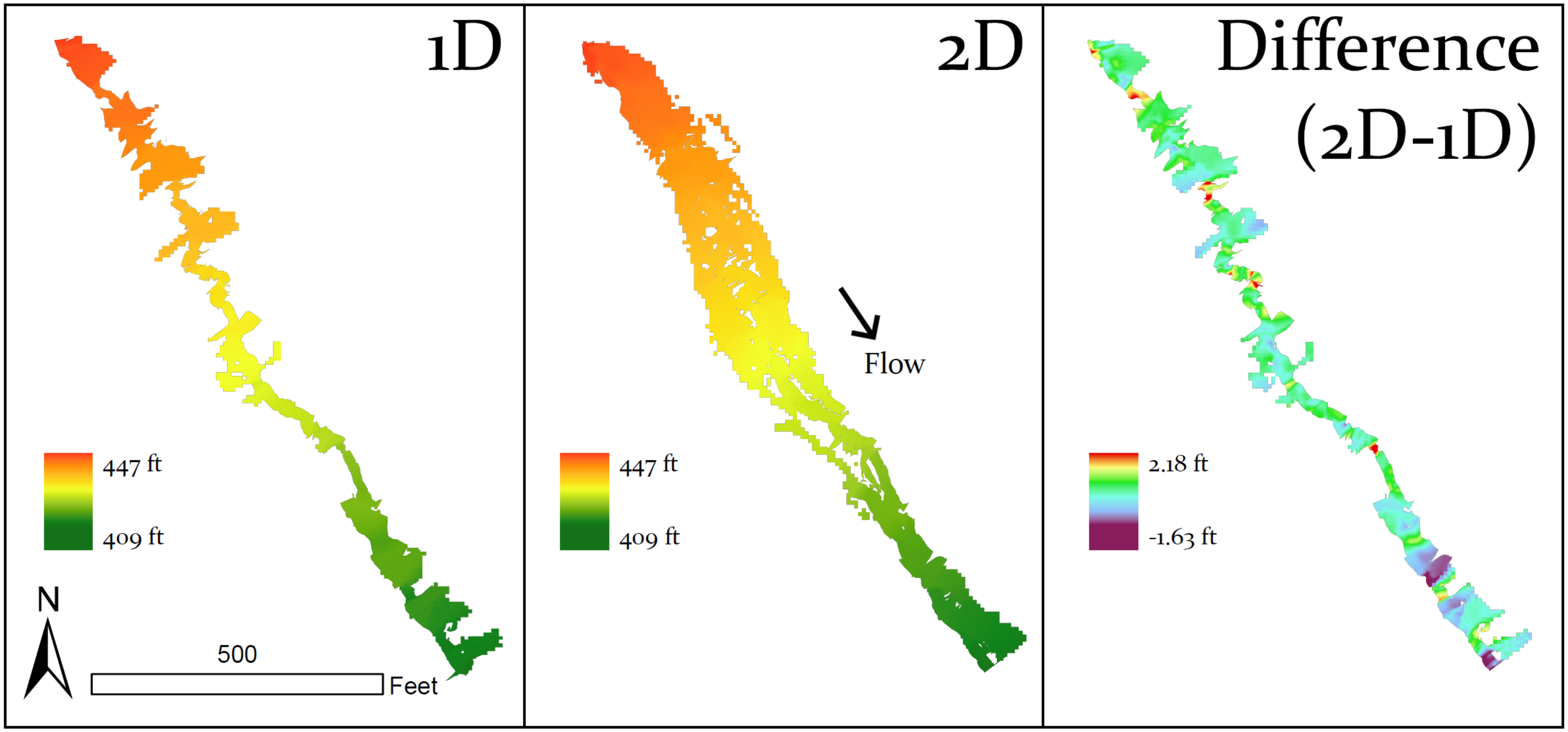

Figure C.30 Water surface elevations for 1D and 2D models for Project 55.

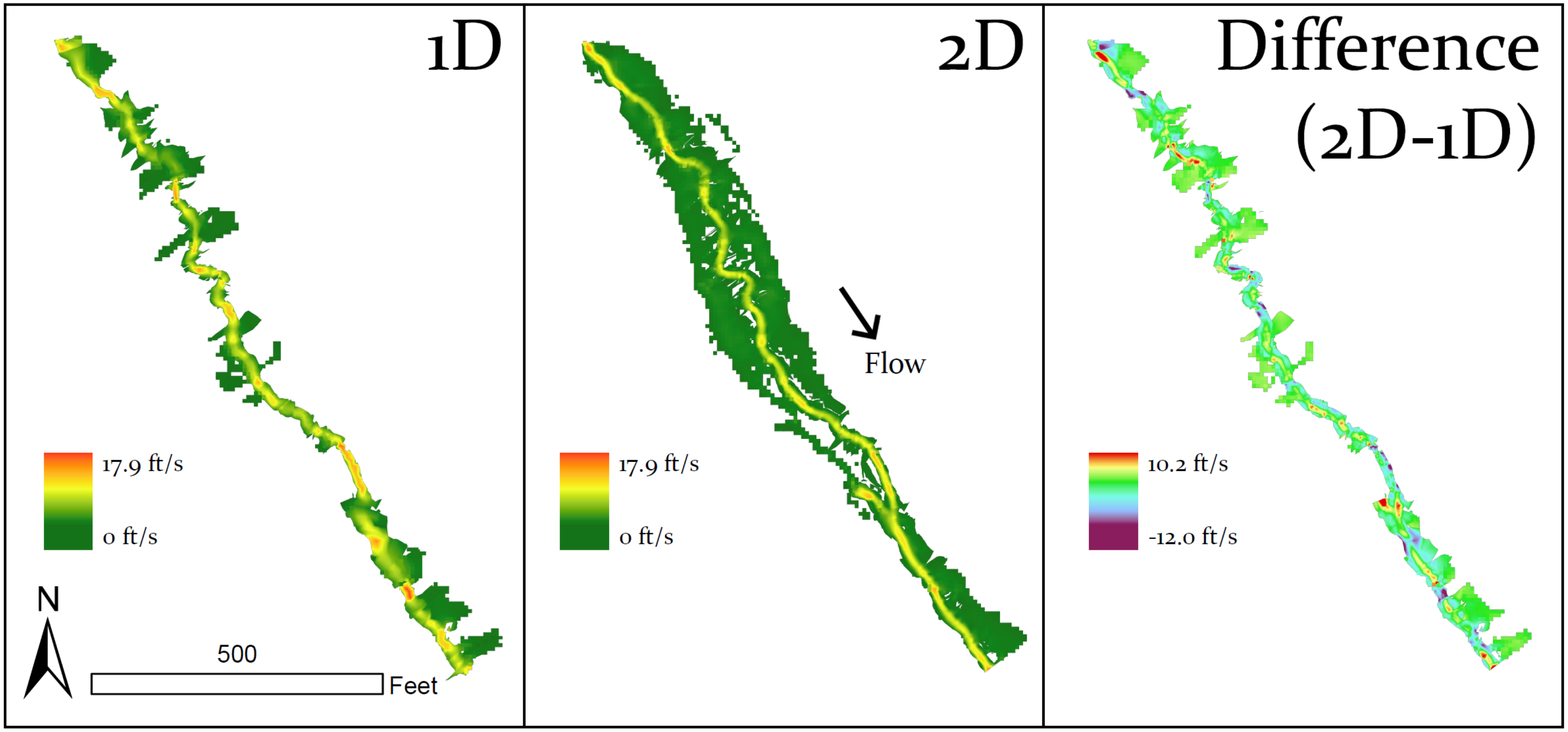

Figure C.31 Velocity for 1D and 2D models for Project 55.

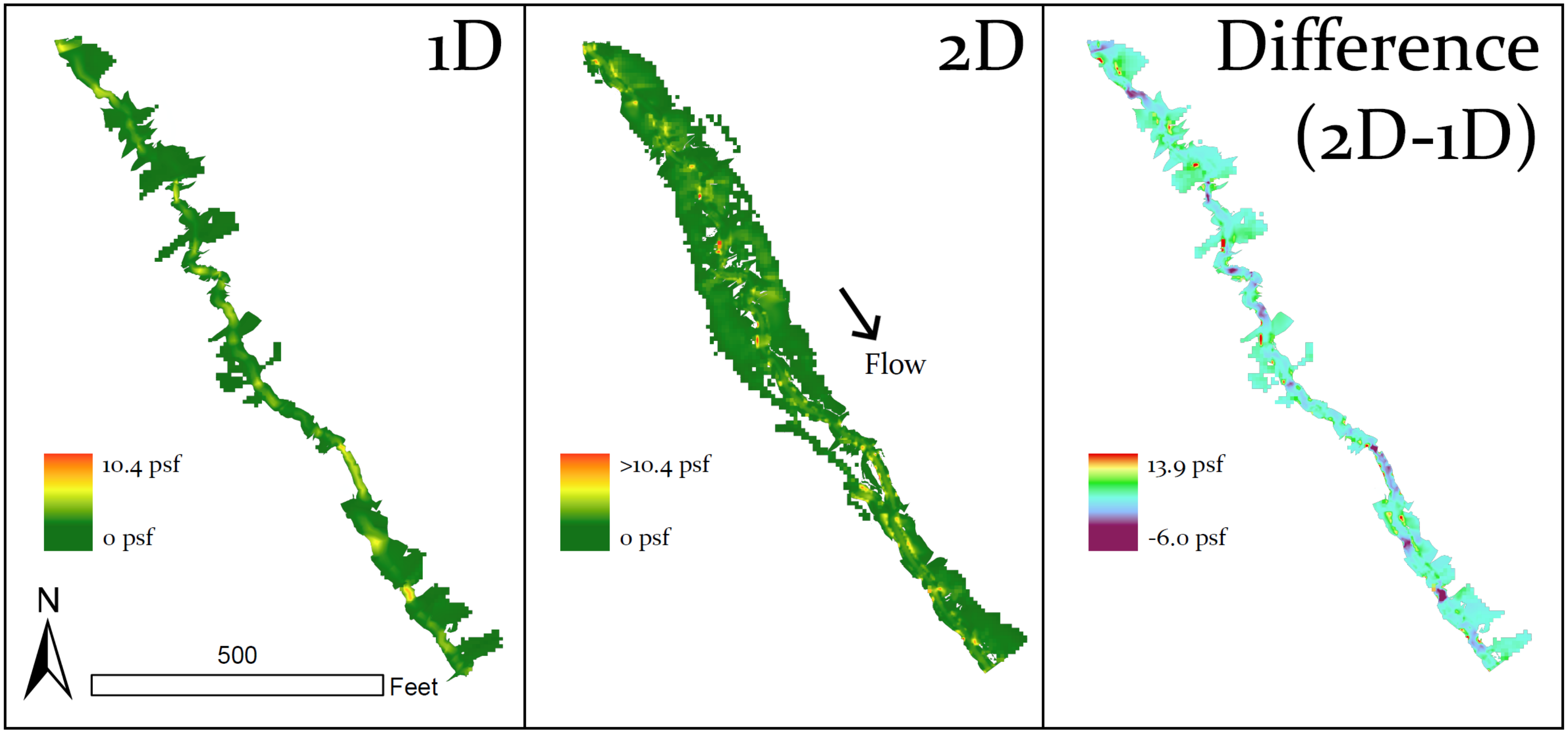

Figure C.32 Maximum boundary shear stress for 1D and 2D models for Project 55.