Linking Stream Restoration Success with Watershed, Practice and Design Characteristics

Urban S. Withers

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Biological Systems Engineering

Theresa M. Thompson
Eric P. Smith
William C. Hession

September 27, 2019
Blacksburg, VA

Keywords: Stream restoration, Success, Assessment, Design, Chesapeake Bay

Linking Stream Restoration Success with Watershed, Practice and Design Characteristics

Urban S. Withers

Scholarly Abstract

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

To improve stream restoration success rates by advising practitioners and stakeholders in site selection and project assessment, a selection of completed Maryland stream restoration projects were assessed at the watershed and project level. Watershed, site, and design characteristics were quantified using ArcGIS, restoration design plans and monitoring reports. Using current literature and expert advice, stream restoration assessment methodologies were developed to assess geomorphic function and design success both in the field and through monitoring reports. Multiple linear regression analysis and related methods were then used to identify correlations and relationships between watershed- and project-level characteristics and stream restoration success. At the watershed scale, land use was most strongly related to functional success, with projects in more natural watersheds exhibiting higher geomorphic function. Design scores correlated negatively with watershed area. At the project level, projects with higher width to depth ratios scored higher on the functional assessment, while particle size was negatively correlated with geomorphic function. Study results suggest stream restoration designs are improving over time, but the ability to determine project success from monitoring remains limited.

Linking Stream Restoration Success with Watershed, Practice and Design Characteristics

Urban S. Withers

General Abstract

In the United States, stream restoration is currently a multi-billion-dollar industry. Though it is commonly used as a method for water quality improvement, stormwater management, and habitat restoration after human disturbance, there is little scientific knowledge defending stream restoration as an effective tool for addressing these issues. In particular, few studies have been conducted with the goal of providing recommendations for future design improvements.

To improve stream restoration success rates by advising practitioners and stakeholders in site selection and project assessment, a selection of completed Maryland stream restoration projects were assessed at the watershed and project level. Watershed, site, and design characteristics were quantified using spatial data analysis software along with restoration design plans and monitoring reports. Using current literature and expert advice, stream restoration assessment methodologies were developed to assess stream ability to transport water and sediment, as well as design resilience using monitoring reports, and during field visits. Data analysis showed projects built in more rural, natural watersheds were more similar to undisturbed streams. Projects constructed in large watersheds were less likely to remain stable after repeated storm events. At the project level, projects that were wider rather than deep were more functional, while those with significant amounts of large rock were less successful. Stream restoration designs seem to be improving with time, but the ability to determine project success from monitoring remains limited.

To Mom and Dad

“Eventually, all things merge into one, and a river runs through it” –Norman Maclean

Acknowledgments

First, I must preface these acknowledgements with a summary of the chaotic year I have had: halfway through my thesis study, in November 2018, I suffered a stroke which placed me in the ICU of Roanoke Memorial Hospital and afterwards in an inpatient rehabilitation facility. As a result of the stroke, I was forced to take the first half of the 2019 spring semester off of school to recover and continue therapy. I cannot express enough the gratitude I have for everyone who helped me through this difficult time. I may not be writing these words without Kate Mott, who jumped to action, called the ambulance, and stayed with me for weeks in the hospital room, or the staff of Roanoke Memorial Hospital. In particular, thanks to my neurosurgeon, Dr. John Entwhistle, and the nurses of the vascular ICU (Shanika, Ben, Christine, Jessica, Emily, Greg, Marilee) for keeping me alive. A huge thanks to my Therapists, Hannah, Lauren, Janet, Sarah, Warren, Jen, Lindsay, Mary, Kellyn, Cheryl, and Caley, without whom the return to daily life would have been much more difficult.

This thesis would not have been possible without the support of many individuals and organizations. First, I would like to thank the Chesapeake Bay Trust and the Maryland State Highways Association for providing funding for this research, and the counties of Anne Arundel, Baltimore, Frederick, Harford, Howard and Montgomery for providing information and files with which I could collect data. In addition, I have the utmost gratitude for my advisor Dr. Tess Thompson, and my committee members, Dr. Cully Hession and Dr. Eric Smith for guiding me on this path. Also, I owe a great deal of thanks to the Biological Systems Engineering Department for providing me with an incredible education from 2014 until now. In particular, I must thank Ms. Priscilla Baker for always permitting me to distract her with conversation, Dumitru Branisteanu for continual encouragement and friendship, and Denton Yoder for computer help and many mugs

of Kombucha. A huge thanks to my undergraduate assistant Ben Smith for spending tedious hours reading monitoring reports and patiently helping me flip through plan sets with my lame hand while waist deep in streams, and to Rex Gamble and Billy Paraszczuk for helping hands in checking and compiling data. My friends have been incredible during this time, so I must give thanks to the Squad, the WSSI engineers, the BSE graduate students, the VT soil Judging Team, and my fellow dancers. I have also been very fortunate to have two families open their homes to me as I finished this degree, so thank you to Joe Baker and Janet Yoder for the roofs, beds and meals.

Finally, I would not be where I am without my family. Thanks to Dad for inspiring me from an early age to love streams and wetlands, to Mom for being my rock, and to Wylie and Elliot for unfailing brotherly love.

Table of Contents

1 Introduction

1.1 Background and research objectives

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) reminds 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 Literature Review

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. Riparian 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 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).

2.2 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 his 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 is 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. Select examples of data sheets used to accomplish these assessments are in Appendix A.

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. 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.

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.

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. 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.

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 (Rosgen, 2006).

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:

$$R_v = \frac{V_{98} - V_{02}}{V_{50}} \tag{1}$$

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.

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-foot 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 the appendix.

Riparian, Channel, and Environmental Inventory

The Riparian, Channel, and Environmental Inventory (RCE) was developed to assess the physical and biological condition of small streams (<3 m 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. 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 10 m of the channel, retention devices, channel structure, channel sediments, streambank structure, bank undercutting, and stony substrate feel and appearance.

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.

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. 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. Again, he RBPs were too lengthy to include in the appendix.

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 the appendix.

Stream assessment method summary

Table 2-1 Summary of parameters included in the aforementioned assessment methods*.**

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	✓

✓ - Protocol has one or more measures of assessment group

X - Protocol has no measure of assessment group.

[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

***Adapted from Akinola, A., unpublished material

2.2.1 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 NY 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. This signified that the same channel was stabilizing.

Improvement with time was also shown by Purcell et al. (2002) by indicating progressively improved biological and habitat quality in 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 discussed 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 were listed as either impaired or failed.

Dave (2018) and Endreny and Soulman (2011) also discussed structure failures. Dave assessed the effectiveness of streambank stabilization structures by quantifying stream bank retreat using aerial imagery before and after 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 efficient at controlling erosion than control sites, she observed multiple failures of rock vanes and jetties. Rock vanes in particular exhibited poor performance, as both failed during the flood. Jetties proved to be the most effective stabilization measure, as a 70% success rate was observed. Endreny and Soulman assessed a New York project designed according to 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 Pacific Northwest restored 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 claim that these results signify the adequacy of stable stream design and construction by practitioners.

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.

3 Methods

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 4-1. Documents such as design plans, design reports, 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.

3.1 Project assessment

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?

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.

3.1.1 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, a diversity of flow 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, 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 taken. 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 3-1.

Table 3-1 Geomorphic function assessment to be used during field visits

	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

3.1.2 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 count 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.

3.1.3 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 3-2.

Table 3-2 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

In accordance with the assumption that three years gives a high probability of sufficient time for a restoration project to establish vegetation and 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 score an assessment category was not provided in the monitoring report text, photographs were used to estimate a score.

3.2 Explanatory variables

As mentioned 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 3-1, table 3-3 and table 3-4.

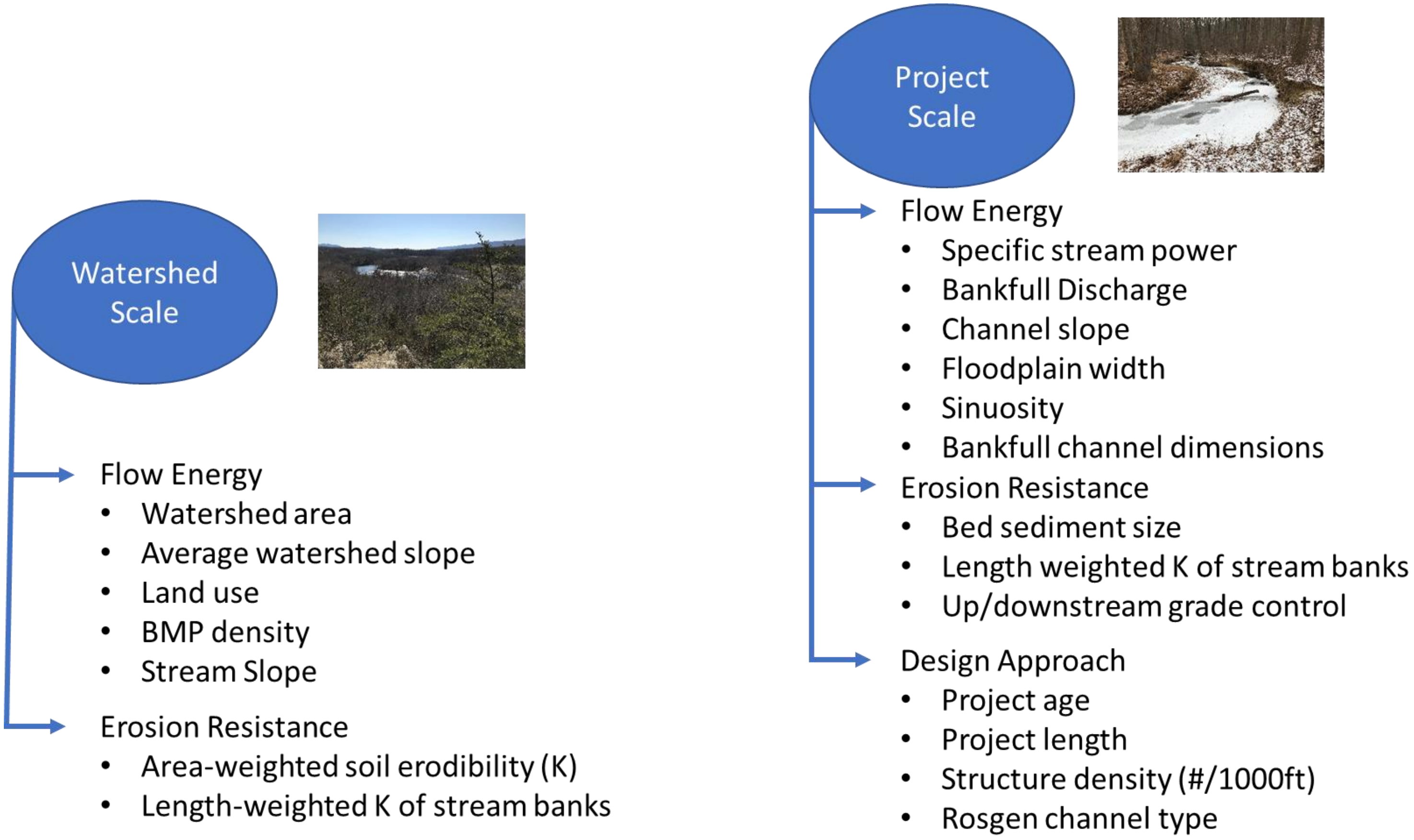


Figure 3-1 Schematic of explanatory variables included in analysis

Table 3-3 Watershed-level variables included in analysis.

Explanatory variable	Scale	Units	Category	Data Source
Watershed area	watershed	$length^2$	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	$\#/length^2$	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	length/length	flow energy	GIS slope analysis

Table 3-4 Project-level variables included in analysis.

Explanatory variable	Scale	Units	Category	Data Source
Year completed	project	year	design approach	Monitoring reports
Project length	project	length	design approach	Design plans
Project slope	project	length/length	flow energy	Design plans
Flood prone width	project	length	flow energy	GIS terrain analysis
Bankfull width	project	length	flow energy	Design plans
Entrenchment ratio	project	unitless	flow energy	Design plans
Design discharge	project	$\text{length}^3/\text{time}$	flow energy	Design reports
Ratio of discharge to watershed area	project	$(\text{length}^3/\text{time})/\text{length}^2$	flow energy	Design reports
Bankfull depth	project	length	flow energy	Design plans
Width to depth ratio	project	unitless	flow energy	
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	#/length	design approach	Design plans
Design approach	project	N/A	design approach	Design plans
Distance from upstream end of project to upstream grade control	project	length	erosion resistance	Google Maps
Distance from downstream end of project to downstream grade control	project	length	erosion resistance	Google Maps

3.2.1 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 3-5.

Table 3-5 DEM specifications.

County	Horizontal Accuracy (cm)	Vertical Accuracy (cm)	Year Collected	resolution (m)
Anne Arundel	N/A	8.1	2017	0.3
Baltimore	27	6.79	2015	0.7
Frederick	N/A	10	2012	1
Harford	N/A	6.8	2013	1.5
Howard	N/A	18.5	2011	2
Montgomery	N/A	8.8	2013	1
Calvert	3	12.3	2017	2
Prince Georges	N/A	10	2018	0.7

To ensure consistency in watershed analysis between counties, each DEM was resampled to 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 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.

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 use 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 far more precipitation and result in a less flashy hydrograph. These hydrologic characteristics are important indicators of stream geomorphology and stability. Land cover data (2010) were also found in the Maryland iMap database. This data file was in the form of a shapefile derived using the National Agriculture Imagery Program (NAIP) high resolution aerial imagery in conjunction with parcel-level information and tax maps from 2008. Land use categories considered were high density development, medium density development, low density development, agriculture, and forest. Descriptions of each land use category are provided in Table 3-6. Percent of watershed covered by each of these land uses was collected.

Table 3-6 Maryland 2008 Land use category descriptions (Maryland Department of Planning, 2010)

High density development	Areas of more than 90 percent% 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 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 found 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 is 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 personal experience 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 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 could result in higher 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.

3.2.2 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 and 3, respectively. The regional curve Discharge output in ft^3/s was converted to m^3/s for this study.

$$Q_{bf} = 53.1(DA)^{0.842} \tag{2}$$

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

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 4.

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

where: ω = specific stream power (N/m/s);
γ = specific weight of water (9810 N/m^3);
Q = stream discharge (m^3/s);

S = stream slope; and,
w = stream bankfull width (m).

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 second revised universal soil loss equation (RUSLE2; USDA-NRCS, Washington, D.C.), was used to indicate the erosion resistance of the project streambanks. 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 particle 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 meters 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.

3.3 Data analysis

All project data were stored in a Microsoft Access (Microsoft, Redmond, WA) database. To normalize the project-scale variables to account for the size of each stream reach, ratios were developed. These ratios and included variable are described in Table 3-77.

Table 3-7 Ratios developed to normalize 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 3-88 to visually evaluate relationships between measures of project success and the explanatory variables. Based on this visual observation, 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 summarized using adjusted R^2, tests and standardized regression coefficients to evaluate the size of possible relationships both individually and in multiple regression models. Null hypotheses for variable significance were tested at $\alpha<0.05$.

Table 3-8 Regression summary.

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 included summarizing and comparing the variables and general trends shown in each model (i.e. positive or negative effect), to identify potential problems, such as multicollinearity, in the regressions. 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 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 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.

4 Results and Discussion

Information was obtained for 65 projects in this study. Of these projects, the number per county is shown in

Table 4-1. Additionally, the availability of project files is summarized in Table 4-2.

Table 4-1 Project breakdown by county.

County	Number of projects
Anne Arundel	13
Baltimore	11
Calvert	1
Frederick	6
Harford	10
Howard	10
Montgomery	12
Prince Georges	2

Table 4-2 Information availability.

Material Provided	**Number of Projects**
Design Report	16
Design Plan	52
Year 3 Monitoring Report	27

Since a complete collection of project information was not provided for every project, not all were able to be assessed. In particular, monitoring reports that met the requirements for the monitoring assessment (at least Year 2 and containing enough information to complete the assessment) were only available for 33 projects. As such, 33 projects were assessed using monitoring reports, and field assessments were completed for 24 projects. Of these projects, 14 were assessed both in the field and using monitoring reports. A map showing the locations of all assessment locations can be seen in Figure 4-1

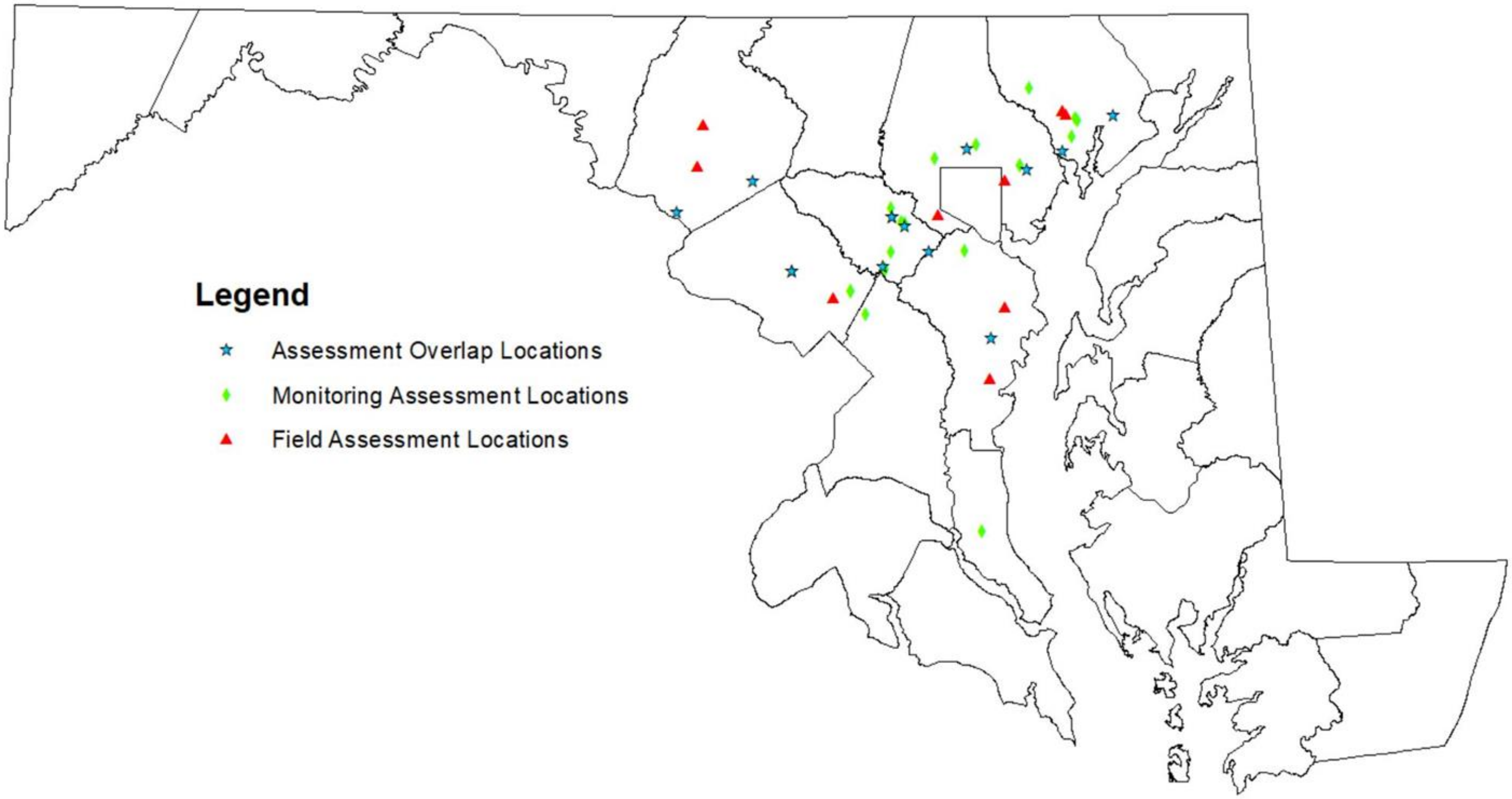


Figure 4-1 Project assessment locations

Distributions of the scores developed in each assessment are in Figure 4-2. Further, plots comparing the scores between each assessment are shown in Appendix D. No significant relationships between the different assessment scores were found.

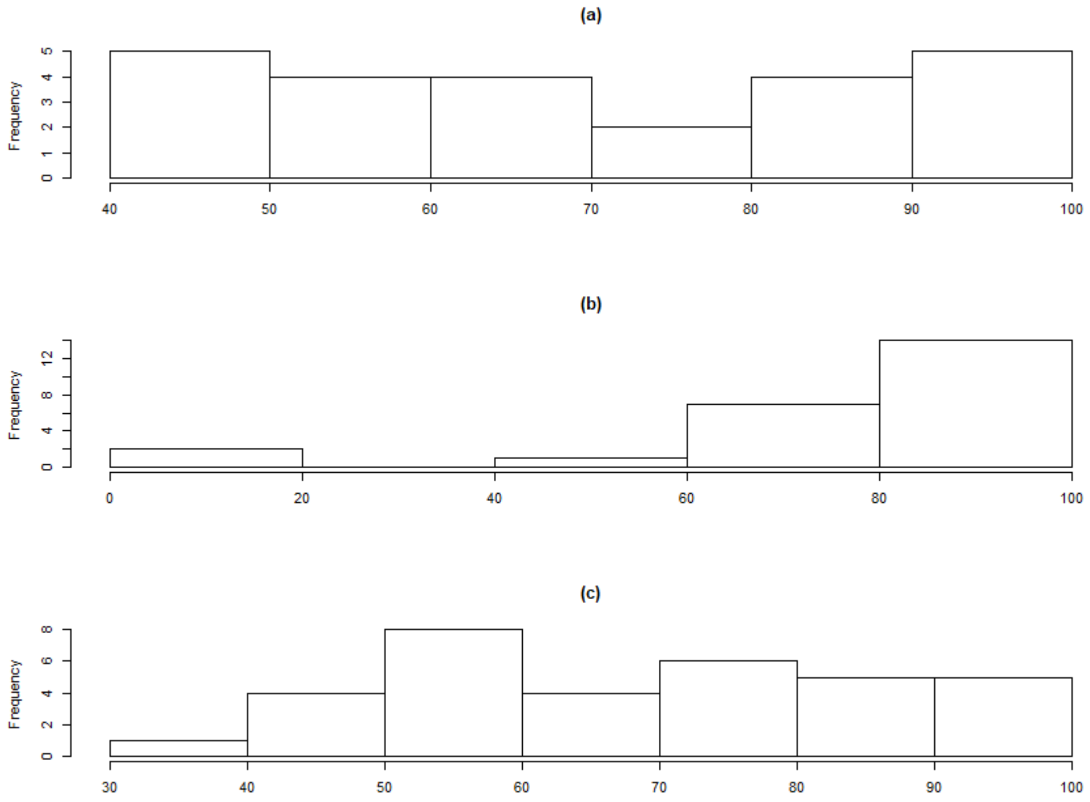


Figure 4-2 Score distributions from assessments; (a) function score from field assessment, (b) design score from field assessment, (c) monitoring assessment score

At the watershed scale, among the projects assessed in the field, watershed area varied from 0.21 to 46.83 km^2 with an average of 6.21 km^2. Of those projects assessed using monitoring reports, watershed area varied from 0.1 to 139 km^2 with an average of 12.42 km^2. Landuse also varied largely between watersheds, with percent high density development ranging from 0-72%, percent forested from 0-49% and percent agriculture from 0-63%.

Of the projects assessed in the field, project length ranged from 30 m to 1370 m, while channel slopes ranged from 0.3% to 5%. Average length and slope were 409 m and 2%, respectively. Of the monitoring-assessed projects, lengths ranged from 30 to 1372 m, and slopes ranged from 0.02% to 5%. Stream width to depth ratio varied widely as well, ranging from 3.4-32. Full summaries of the variables and transformations used in the watershed- and project-scale analyses are given in Appendix A.

4.1 Geomorphic function assessment

Overall, function assessment scores determined from field visits ranged from 42% to 100%. Lower function scores were commonly a result of 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 stability (i.e. 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 both exhibit the aforementioned attributes of a functionally successful stream restoration project. Photographs shown in Figure 4-3 and Figure 4-4 highlight these characteristics.

Figure 4-3 Representative photograph of project 7

03.11.2019

Figure 4-4 Representative photograph of project 28

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.

4.1.1 Watershed scale

Spearman correlation between watershed-scale variables and assessment scores was weak, with only percent medium density development, percent forest, log of percent agriculture, log of watershed area being significantly correlated with geomorphic function score. None of the watershed variables were significantly correlated with the monitoring score. All correlation coefficients between watershed-scale variables and geomorphic function score are outlined in table 4-3.

Table 4-3 Spearman correlation coefficients between watershed-scale variables and geomorphic function assessment scores.

Variable	Function Score
HighP**	-0.13 (0.53)*
MedP	-0.41 (0.04)
ForP	0.50 (0.01)
StrmK	-0.35 (0.10)
Strmslp	-0.13 (0.54)
logA	0.44 (0.03)
Loglow	0.19 (0.39)
logAg	0.55 (0.005)
logBMP	-0.26 (0.22)
K^2	0.31 (0.13)

*values in parenthesis denote the p-value of the correlation Coefficient

**HighP is percent high density development, MedP is percent medium density development, ForP is percent forested, StrmK is length-weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, and K^2 is the square of area-averaged soil erodibility of the watershed.

The far-left columns of tables 4-4, 4-6, 4-8, and 4-10 denote the assessment score against which watershed-scale regressions were run, and groups all the models developed in that regression analysis, while the second columns reports the number of observations utilized in the regression. The remaining columns describe the results from the stepwise regression model development. Each row represents an individual model, increasing in number of variables as the table progresses down the rows. Column three displays the correlation coefficient (the amount of variability in assessment score explained by each model), and column four displays the p-value (a measure of statistical significance). The columns labeled by a variable name contain the coefficient corresponding to that variable in the linear model, and the associated p-value. Please note that intercepts were not reported in this table though they were developed in each model. Models of the function and design scores contained one to three explanatory variables. All models at the watershed-scale reflected relationships between assessment score and watershed land cover.

In regressions of function score, log of percent agricultural area (logAg) showed up in the one-, two- and three-variable models. In each, the coefficient corresponding to logAg was positive and exhibited a p-value less than 0.05, suggesting that projects constructed in rural watersheds scored higher in the function assessment. Percent forested area also appeared in the two- and three-variable models with positive coefficients and significance at $\alpha<0.05$ in each. Log of low-density development also appeared in the three-variable model but was not significant ($\alpha>0.10$). Adjusted R^2 was also minimally increased by the addition of this variable, so this model was likely over-fit, and does not offer substantial insight into stream restoration function success. The one- and two-variable models, however, explain 24% and 37%, respectively, of the variability in function score, and provide some insight into the characteristics of watersheds where stream restoration projects achieve high geomorphic function.

Table 4-4 Summary of watershed-scale statistical models for function score.

Assessment Type	**n**	**Adjusted R^2**	**Model p-value**	**HighP****	**logAg**	**logA**	**ForP**	**loglow**
Function coefficient (p-value)	24	0.24	0.0086		6.86 (0.0086)			
		0.37	0.0033		5.92 (0.0141)		0.55 (0.0319)	
		0.41	0.0035		4.92 (0.0392)		0.63 (0.0149)	4.09 (0.1294)

**HighP is percent high density development, ForP is percent forested, logA is log of watershed area, loglow is log of percent low density development, logAg is log of percent agricultural land.

In the watershed-scale analysis, the regression models developed for function score resulted in positive coefficients for percent agriculture, percent forest, and percent low density development. Since these three land uses are not urban, a watershed containing higher percentages of them will be more natural and more space will be available for channel adjustment, energy dissipation, and riparian buffer development. Additionally, watershed land cover 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 a streams capacity to move sediment and the amount of sediment delivered from its watershed, and summarized potential geomorphic responses to include 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).

4.1.2 Project scale

Correlations between project-scale variables and assessment scores were also weak. Coefficients with a p-value<0.05 were only found between D_{50}, log of construction year, and log of bankfull discharge and function score; between width to depth ratio and log of structure density and design score; and, between entrenchment ratio and log of construction year and monitoring score. Of these correlation coefficients, only the relationship between width to depth ratio and function score had a magnitude greater than 0.5 (0.52). A full list of correlation coefficients between project-scale variables and assessment scores is shown in table 4-5.

Table 4-5 Spearman correlation coefficients between project-scale variables and geomorphic function score.

Variable	Function Score
Slope**	-0.47 (0.02)*
ER	0.01 (0.96)
WD	0.52 (0.009)
Power	-0.04 (0.86)
Sin	0.44 (0.03)
K	-0.27 (0.21)
D_{50}	-0.28 (0.22)
log_year	-0.09 (0.68)
log_length	-0.22 (0.30)
log_Q	0.37 (0.07)
logstrucd	-0.47 (0.022)
logugrade	0.34 (0.11)
logdgrade	0.28 (0.18)

*values in parenthesis denote the p-value of the correlation coefficient

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control +1.

The results of the stepwise regression between function score and project-scale variables are shown in table 4-6. Regressions were run on two datasets. Because D_{50} information was not available for projects 3, 22 and 19, these projects were excluded from the field assessment analyses in which D_{50} was considered.

Table 4-6 Summary of project-scale statistical models for function score

Assessment Type	n	Adjusted R^2	Model p-value	WD*	Log year	ER	Log length	Logdgrade	Log_Q	Slope	Power	D_{50}
Function coefficient (p-value)	24	0.25	0.0078	1.94 (0.0078)								
		0.49	0.0009	1.76 (0.0146)			-9.76 (0.045)					
Function including D50 coefficient (p-value)	21	0.27	0.0086	2.14 (0.0086)								
		0.51	0.0007	2.6 (0.0005)								-0.07 (0.0055)
		0.58	0.0004	3.05 (0.0001)		0.83 (0.05)						-0.08 (0.0017)

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control +1.

Regressions against function score were overwhelmingly dominated by width to depth ratio, as it appeared in every regression regardless of the number of variables included in the model and D_{50} inclusion. The consistency of the appearance of width to depth ratio in the linear models and the high Spearman correlation coefficient between width to depth ratio and function score provide strong evidence that channels with a high width:depth ratio have higher geomorphic function. Log of project length appeared in the two-variable regression against function score, but the relationship was not highly significant (p-value>0.05), and the increase in adjusted R^2 was negligible, so compared to width to depth ratio, project length was not a good predictor of function success. This three-variable model, however was the best in terms of adjusted R^2, as it explained 49 percent of the variance in function score. When D_{50} was included in the explanatory variables, it was a significant predictor of function score in the two- and three-variable models ($p<0.01$). The third variable that appeared was entrenchment ratio. The relationship between D_{50} and function score was negative, while the relationship with entrenchment ratio was positive. The three-variable model relating function score to width to depth ratio, entrenchment ratio, and D_{50} exhibited an adjusted R^2 of 0.58, so it explained 58% of the variability in function score.

At the project scale, projects that tended to score higher for function had low bank heights, and well-established, native vegetation (see Figures 4-6 and 4-7). The quantitative results of this study further support this observation, as every regression model developed for the function score at the project level resulted in a positive coefficient for width to depth ratio. This result shows that projects with higher width to depth ratios (i.e., wider than deep) tended to score higher in the function assessment. The relationship between stream flow and flow area is described by the continuity equation:

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

where: Q = stream flow (m^3/s);

V = flow velocity (m/s)

A = flow area (m^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):

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

Where:

V = flow velocity (m/s)

R = hydraulic radius (flow area divided by wetted perimeter) (m)

S = energy slope

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 cross section. This behavior is well-illustrated in figure 4-5. As can be seen in the rating curve (stage-discharge relationship), larger increases in discharge result in smaller increases in stage when the flow has reached the floodplain.

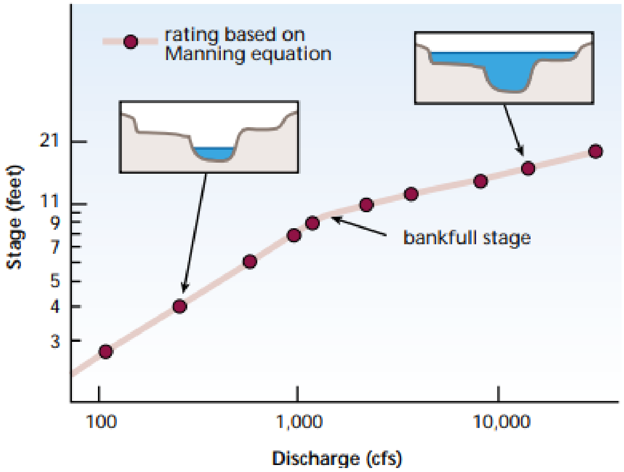


Figure 4-5 Determining bankfull stage from a rating curve (from FISRWG, 1998)

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 width to depth ratio 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 width to depth ratio of 15 would result in a function score of 80%.

Other significant variables identified in the models include entrenchment ratio, project length and D_{50}. The coefficient for entrenchment ratio was positive, further showing that better access to the adjacent floodplain is positively correlated with improved geomorphic function. Coefficients for project length and D_{50}, however, were negative, indicating higher values of these two parameters were negatively correlated with geomorphic function. Upon further study of the function assessment and D_{50} data, it became apparent that projects with substrate D_{50} greater than six inches had significantly lower average scores in the bedforms and substrate categories in the function assessment ($p<0.05$). Because projects with larger bed sediment sizes tended to be armored with rip rap, and were intended to be immobile, it makes sense that these components of stream function would decrease with increasing D_{50}.

4.2 Design assessment

4.2.1 Watershed scale

In the regression using design score, only a single, one-variable model was developed. This regression indicated a statistically significant, negative relationship between design score and log of watershed area (logA). When 0% design scores were removed, however, one-, two- and three-variable models were developed. Each of these regressions had a significant positive relationship between percent high density development and design score ($\alpha<0.05$). However, as with the three-variable model for project function score, the addition of variables to the models resulted in negligible increases in adjusted R^2, and significance was lost. The variability explained by each of these models was also very low, with a maximum of 34% by the three-variable model which included percent high density development, percent forest, and log of watershed area. Consistency in the negative relationship between design score and logA both with and without outliers, and agreement with the correlation coefficient between these two variables (Table 4-7), strongly supports that watershed area and stream restoration design success are negatively correlated.

Design assessment scores from the field ranged from 0% to 100%. At the watershed scale, log of watershed area was the only variable significantly correlated with design score.

Table 4-7 Spearman correlation coefficients between watershed-scale variables and design score.

Variable	Design Score
HighP**	0.31 (0.14)
MedP	-0.31 (0.14)
ForP	0.09 (0.67)
StrmK	0.25 (0.25)
Strmslp	0.21 (0.33)
logA	-0.52 (0.009)
Loglow	-0.26 (0.23)
logAg	-0.18 (0.40)
logBMP	-0.03 (0.87)
K^2	-0.09 (0.68)

*values in parenthesis denote the p-value of the correlation coefficient

**HighP is percent High density development, MedP is percent medium density development, ForP is percent forested, StrmK is length-weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, and K^2 is the square of area-averaged soil erodibility of the watershed.

Table 4-8 Summary of watershed-scale statistical models for design score.

Assessment Type	n	Adjusted R^2	Model p-value	HighP**	logAg	logA	ForP	loglow
Design coefficient (p-value)	24	0.21	0.014			-8.25 (0.014)		
Design>0 coefficient (p-value)	22	0.23	0.013	0.27 (0.013)				
		0.29	0.016	0.28 (0.0082)			0.27 (0.13)	
		0.34	0.014	0.22 (0.043)		-2.63 (0.12)	0.27 (0.11)	

**HighP is percent High density development, ForP is percent forested, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land.

4.2.2 Project scale

In the Spearman correlation analysis, D_{50}, log of construction year and log of bankfull discharge exhibited significant correlation coefficients with design score. In addition, particularly high correlation coefficients were found with log of construction year and design score (0.64), and log of bankfull discharge (-0.58).

Table 4-9 Spearman correlation coefficients between project-scale variables and design score.

Variable	Design Score
Slope**	0.27 (0.20) *
ER	0.03 (0.90)
WD	0.02 (0.93)
Power	-0.27 (0.20)
Sin	-0.30 (0.15)
K	0.14 (0.52)
D_{50}	0.46 (0.04)
log_year	0.64 (0.0007)
log_length	0.15 (0.49)
log_Q	-0.58 (0.003)
logstrucd	0.001 (0.996)
logugrade	-0.15 (0.49)
logdgrade	-0.26 (0.22)

*values in parenthesis denote the p-value of the correlation coefficient

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control +1.

Interesting relationships with log of project construction year were illuminated by regressions of project variables against design score. Highly significant ($p<0.0001$) one-, two-, and three-variable models were developed in the regression between design score and the project-level dataset, regardless of D_{50} inclusion. Log of construction year was included in each model and the adjusted correlation coefficient for the one-variable model for design score was relatively high (adjusted $R^2 = 0.69$), indicating the year the project was constructed was strongly correlated with design success. The high Spearman correlation coefficient between log of construction year and design score further supports this relationship. Log of distance to downstream grade control, and log of project length were the other two variables that appeared in the two- and three-variable models, respectively. Distance to downstream grade control exhibited a negative relationship with design score showing that projects with a farther distance to grade control downstream of the restoration extent were less likely to maintain stable designs. Longer projects, however, were more successful, as evidenced by the positive relationship between project length and design score. Downstream grade control most likely effects design stability by resisting knickpoint formation and migration that could compromise the integrity of restoration project design. Longer projects could have scored better for design, because they include larger extents of floodplain and riparian restoration, which allows more opportunity for flow energy reduction and assists in lowering in-channel stress.

Because projects 3 and 22 received design scores of zero, which strongly influenced the regression equations, they were removed as outliers, and the regressions were rerun. In the regression where projects 3 and 22 were removed (labeled as "Design > 0 " in table 4-10), log of construction year did not appear as a significant predictor of design score. This observation suggests that projects 3 and 22 are major drivers of the relationship between construction year and design score. As projects 3 and 22 were the two oldest projects assessed in this study (constructed in 1995 and 1999, respectively), it is reasonable to conclude that these projects exerted a large amount of leverage on the design score regression. Figure 4-6 further illustrates this point.

Table 4-10 Summary of project-scale statistical models for design score.

Assessment Type	n	Adjusted R^2	Model p-value	WD*	Log year	ER	Log length	Logdgrade	Log_Q	Slope	Power	D_{50}
Design coefficient (p-value)	24	0.69	<0.0001		8570 (<0.0001)							
Design >0 Coefficient (p-value)	22	0.32	0.0036						-5.37 (0.0036)			
		0.45	0.0013						-8.07 (0.0003)	-498.1 (0.026)		
		0.5190	0.0010			0.63 (0.07)			-9.24 (<0.0001)	-516.6 (0.016)		
Design Including D50 coefficient (p-value)	21	0.69	<0.0001		9927.86 (<0.0001)							
		0.74	<0.0001		10993 (<0.0001)			-1.97 (0.0547)				
		0.79	<0.0001		11145 (<0.0001)		7.34 (0.034)	-2.67 (0.0094)				
Design >0 Including D50 coefficient (p-value)	20	0.29	0.0079		6126.9 (0.0079)							
		0.49	0.0031		7227.3 (0.0014)			-1.93 (0.033)				
		0.60	0.03		7388.3 (0.0003)		7.32 (0.0121)	-2.63 (0.0027)				

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control+1.

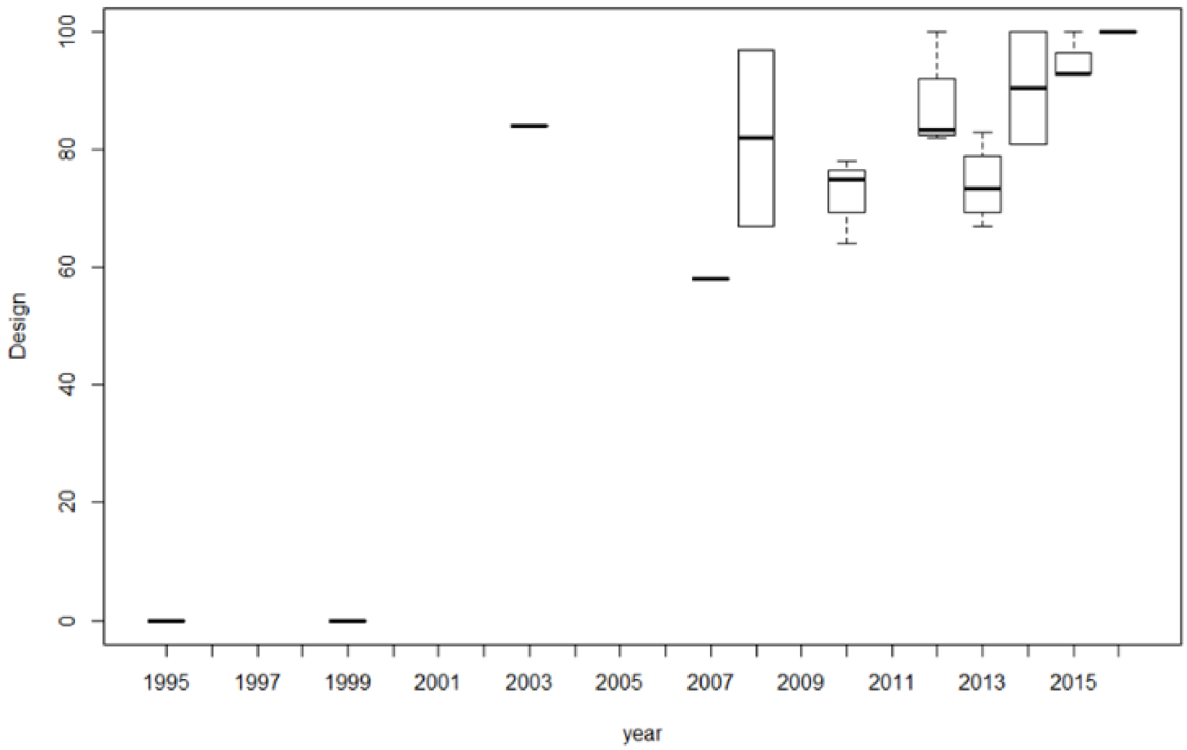


Figure 4-6: Box plot of project design scores for each year: flat lines indicate a single observation for that year.

Interestingly, however, log of construction year reappeared as a significant variable when D_{50} was included as a predictor (i.e., when projects missing D_{50} information were removed). As projects 3 and 22 were two of the three projects removed for missing D_{50}, the only difference between the datasets used in the "Design>0" and "Design>0 including D50" regressions was the removal of project 19 for missing D_{50}. As such, project 19 clearly exerted a large influence on the "Design >0" regression, likely because project 19 was a relatively old project (constructed in the early 2000s) but received a high design score of 84%. Upon further observation of project 19, it became apparent that it was designed conservatively using a large amount of rock that was large relative to the stream size, a technique that was atypical of the older projects assessed in this study. A representative photograph of the design approach used in project 19 is shown in Figure 4-7.

Only one significant single-variable model was developed for the regression between the full project-level dataset and design score (labeled “Design” in table 4-10). Models of up to three variables, however exhibited significant relationships in the “Design > 0”, “Design including D_{50}”, and “Design>0 including D50” regressions. In the regression excluding 0% design scores, and not considering D_{50} as an explanatory variable, log of bankfull discharge appeared in the one-variable model, exhibiting a negative relationship with design score. This result continued to appear in the two- and three-variable models, with the addition of a negative relationship with channel slope in the two-variable model. The three-variable design score>0 model continued the trend with log of bankfull discharge, and slope, but an additional positive relationship with entrenchment ratio appeared.

Figure 4-7 Conservative design of project 19

Multiple projects had perfect scores in the design assessment, indicating 100% of the design components were still in place and functioning as intended. Of these projects, most were designed as threshold channels and contained a large amount of rock or contained few in-stream structures. Upon further investigation of the data, it became apparent that of the projects scoring greater than 80% on the design assessment, the majority were designed as threshold channels. In addition, most were located in watersheds dominated by medium- and high-density development. The statistical models support this observation, as the coefficient for percent high density development was positive for all the design score models. This finding suggests stream restoration designs in urban areas are typically conservative and focused primarily on channel stabilization. On the other hand, the regression models also contained positive coefficients for percent forested area; however, coefficient p-values for the percent forested area were greater than 0.10, suggesting the coefficients were not statistically different from zero.

Project design score was negatively related to watershed area, indicating stream restoration projects with large watersheds, and thus larger discharges, are less resilient. Regression results further supported that the design success was related to flow energy, as both log of bankfull discharge and channel slope were inversely related to the design scores. As discharge and slope are the two parameters utilized in the calculation of stream power, the existence of these two relationships shows that increased flow energy increases the risk that design elements will fail.

The regression analysis also suggested a positive relationship between construction year and design score, but when outliers (design score = 0) were removed, construction year did not appear. This suggests that the two projects with zero percent design success exerted a strong influence on the relationship between design score and construction year. Upon further exploration and the creation of Figure 4-6, it became apparent that the two projects with low design scores were also the oldest projects. With the absence of a complete timeline of projects, it is difficult to determine a strong relationship between construction year and design success, but Figure 4-6 suggests stream restoration design and construction techniques may be improving with time as a result of greater experience of restoration professionals, project repairs were made between construction and site assessment, and/or the newer projects have experienced fewer large storms. As only one of the fourteen projects assessed both in the field and using monitoring reports was repaired, project repairs are likely not the reason for the improved design performance of the more recent projects. Additionally, the fact that 2018 was Maryland's wettest year on record [annual total rainfall of over 2 m compared to the 30-year average of 1.2 m (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.

4.3 Score Discrepancies

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 completely fail according to another. For instance, in this study, a given project may have had very different levels of "success" depending on the evaluation tool. These assessment discrepancies are illustrated in Figure 4-8.

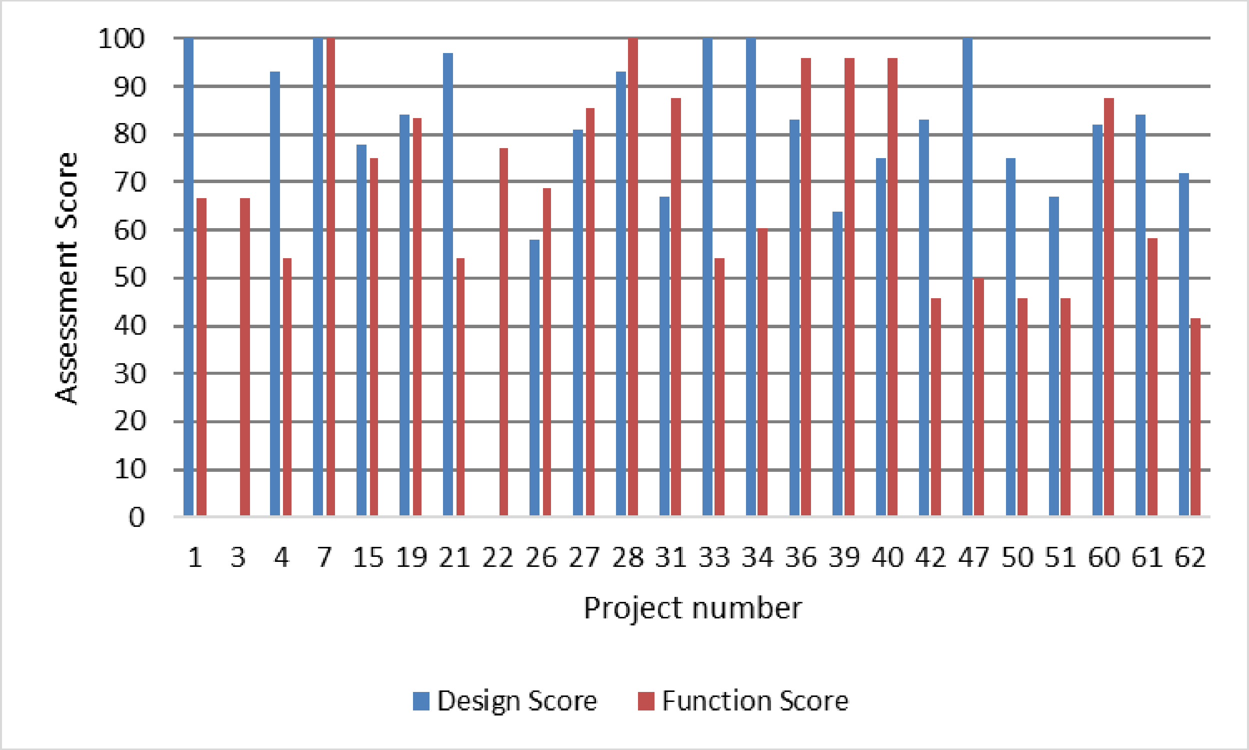


Figure 4-8 Comparison of design and function scores from field assessments

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 constructed in areas confined by development and included a lot of large rock in their designs. 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. The remaining categories are indicators of sediment transport function, which was not apparent during the field assessment. As can be seen in Figure 4-9, project 47 consisted of a majority of 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.

03.12.2

Figure 4-9 Representative photograph of project 47

In contrast, projects 3 and 22 scored zero in the design assessment but exhibited many 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 projects' lifetime. Since they were minimally invasive to the stream channel; however, their failure did not have large effects on stream function. Both projects received high scores for bedforms, substrate, and cover, but exhibited poor floodplain connectivity. Photographs of these two projects are shown in Figures 4-4 and 4-5. Note that both projects appear to be functioning as natural streams, but no intact structural design components are apparent.

Figure 4-10 Representative photograph of project 3

Figure 4-11 Representative photograph of project 22

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.

4.4 Monitoring assessment

Because the objectives on which this study focused tended toward geomorphic function and design success, certain elements were sought when studying monitoring reports. These elements, and a summary of their inclusion in the monitoring reports utilized in this study are shown in table 4-11. If not 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.

Table 4-11 Elements included in 33 assessed monitoring reports.

Monitoring Element Included	Number of Projects
Clearly stated project goals	12
Pre-construction monitoring	17
Baseline monitoring	22
Bank stability inspection	28
Planting inspection	26
Cross section survey	24
Longitudinal profile survey	20
Bed sediment survey	13
In-stream structure inspection	28
Photographic documentation	23

4.4.1 Watershed scale

At the watershed scale, no significant relationships were found with monitoring score. None of the spearman correlation coefficients had a p-value less than 0.05, and no significant models were developed from step-wise regression analysis. Spearman correlation coefficients from the watershed-scale monitoring assessment analysis are shown in Table 4-12.

Table 4-12 Spearman correlation coefficients between watershed-scale variables and monitoring score

Variables	Monitoring Score
HighP**	-0.04 (0.80)
MedP	-0.27 (0.12)
ForP	-0.007 (0.97)
StrmK	0.20 (0.26)
Strmslp	-0.03 (0.89)
logA	-0.11 (0.54)
Loglow	0.22 (0.21)
logAg	-0.002 (0.99)
logBMP	0.09 (0.62)
K2	-0.13 (0.48)

**HighP is percent High density development, MedP is percent medium density development, ForP is percent forested, StrmK is length-weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, and K^2 is the square of area-averaged soil erodibility of the watershed.

4.4.2 Project scale

The significance of log of construction year continued in regressions of project variables against monitoring score. Again, this variable appeared in every regression with a significance of $p>0.05$ and exhibited a significant Spearman correlation coefficient with monitoring score. Entrenchment ratio also exhibited a significant correlation with monitoring score. All project-level Spearman correlation coefficients are shown in table 4-13.

.

Table 4-13 Spearman correlation coefficients between project-scale variables and monitoring score

Variables	Monitoring Score
Slope**	0.19 (0.28)
ER	0.36 (0.04)
WD	-0.04 (0.83)
Power	-0.17 (0.35)
Sin	-0.06 (0.73)
K	0.25 (0.17)
D_{50}	0.21 (0.31)
log_year	0.49 (0.004)
log_length	-0.30 (0.08)
log_Q	-0.17 (0.35)
logstrucd	-0.06 (0.74)
logugrade	0.16 (0.39)
logdgrade	0.12 (0.51)

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control +1.

Only models of up to two variables were developed for the project scores based on the monitoring reports and none explained much of the variability in the monitoring report-based scores (low adjusted R^2). In the regression without D_{50} the second variable that appeared was log of project length, also with a negative relationship to monitoring score. Like the field-assessed projects, not all projects assessed from monitoring reports had D_{50} information available, so projects 38, 49, 3, 12, 31, 45, 48 and 65 were excluded the monitoring assessment analyses in which D_{50} was considered. When D_{50} was considered, the second variable to appear was entrenchment ratio, exhibiting a positive relationship to monitoring score.

Table 4-14 Summary of project-scale statistical models for monitoring score.

Assessment Type	n	Adjusted R^2	Model p-value	WD*	Log year	ER	Log length	Logdgrade	Log_Q	Slope	Power	D_{50}
Monitoring Report coefficient (p-value)	33	0.16	0.0118		2396.5 (0.012)							
		0.27	0.0035		2340.7 (0.0089)		-6.96 (0.026)					
Monitoring Report Including D50 coefficient (p-value)	25	0.29	0.0032		3831.7 (0.0032)							
		0.36	0.0026		4171.21 (0.0011)	0.77 (0.069)						

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control.

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. As the largest differences between high-scoring (>75%) and low-scoring (<50%) projects occurred in the bank stability, riparian vegetation, and structure categories, it can be surmised that problems with bank instability, low riparian plant survival and in-stream structure failure were the most commonly observed difficulties facing projects post-construction.

Both regression and Spearman correlation results show that monitoring scores increase with later construction dates. This relationship could again be explained 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 5-2). As such, these results also suggest stream restoration design and construction are improving with time and experience.

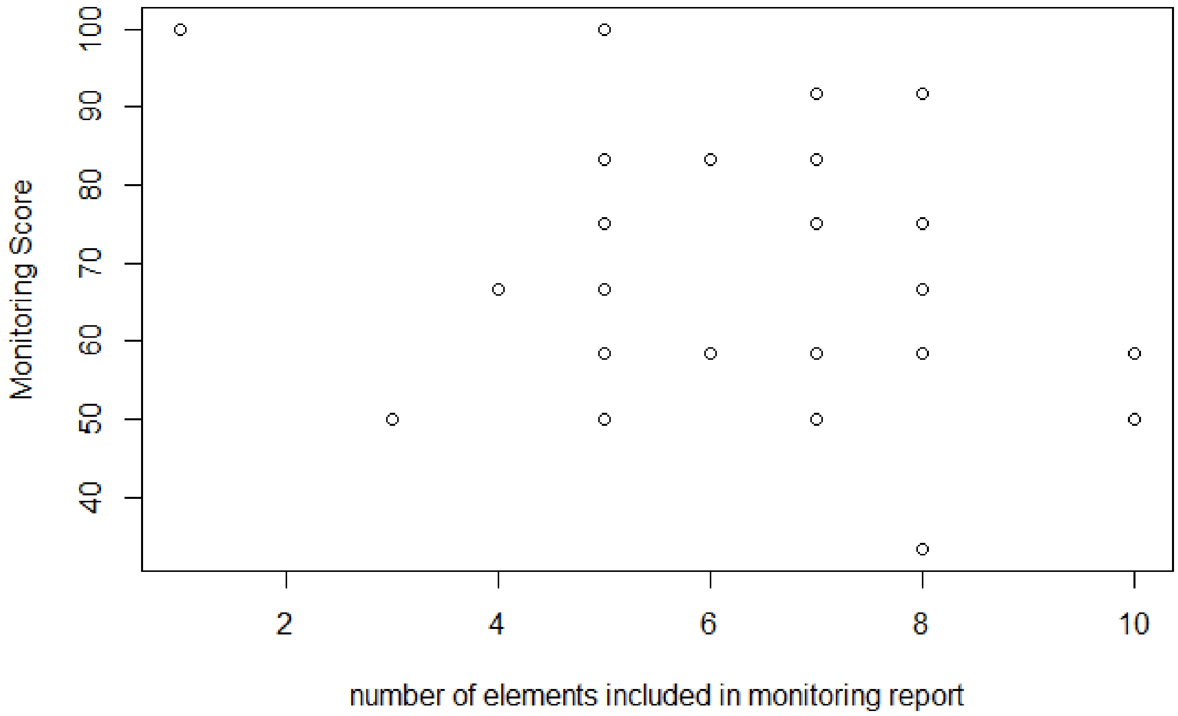


Figure 4-12 Relationship between monitoring report depth and monitoring score

Though 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 a monitoring report, as the Spearman correlation between the two is 0.91. Figure 4-13 illustrates this relationship.

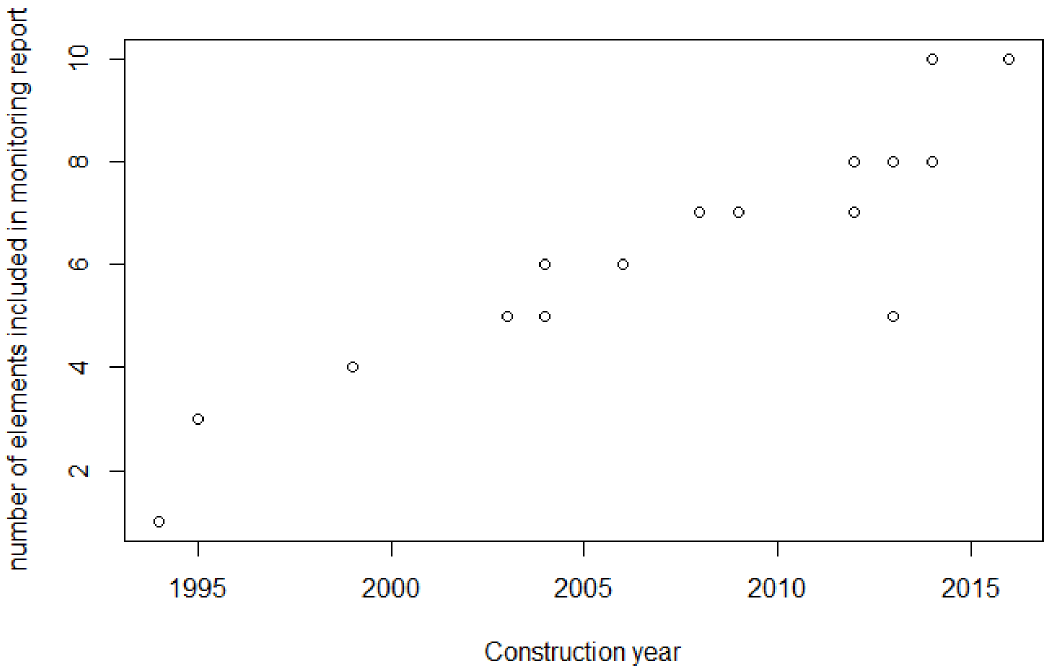


Figure 4-13 Increasing monitoring detail with time.

Monitoring requirements vary largely depending on the individual project and discretion of the MDE permit writer (personal communication), so it is difficult to determine whether this increase in monitoring depth is a result of increased regulatory requirements or consulting experience. It is clear however, that monitoring reports are getting more thorough with 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 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, as mentioned above, the definitions of success emphasized in this study may not perfectly align with those of the assessed projects. Since only half referenced a pre-construction assessment relative to which success could be evaluated, and even less stated clear objectives, however, any definition of success would be difficult.

5 Conclusions

Stream restoration is a complex industry that has rapidly gained in popularity and cost over the past two decades, 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 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 not unsurprising that assessment scores do not always agree. 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 answer to the first question can be yes, stream restoration success increases with decreasing watershed impervious cover when functional lift is a primary restoration goal, but when design stability is a goal, project success can increase with increased impervious area. In the latter case, however, success is more likely a result of conservative design approaches in urban areas rather than stream response. In other words, stream geomorphic function is more likely to be restored in natural watersheds, but urban area has less of an effect on erosion reduction ability as long as projects are designed with extensive use of large rocks. Newer designs with grade controls close to the downstream project limits are also more effective at maintaining stability, so these designs could serve as models for future stability projects. In contrast, the second question can be answered in the same way for both function and stability goals, but for different reasons. Project success is more likely in streams with lower flow energy. For functional lift, this can be achieved in rural watersheds with wide, accessible floodplains, and for design stability, this can be achieved with low-slope channels in small watersheds receiving low flow. The results of this study were insufficient to answer the third question about the effect of watershed sediment supply on restoration success, so this is a possible area of future research.

Because stream restoration success is multi-faceted, and can vary largely based on assessment method, it is important that specific, individual goals are specified for each project, and subsequent evaluation of project success be assessed accordingly. Clarity of goals and strength of monitoring, however, remains low, so further emphasis should be placed on stream restoration study design and reporting in the future.

In addition to further research on sediment supply and stream restoration success, future research should explore the increase in design and monitoring success with time. What have practitioners learned about stream restoration that are making projects more durable?

Along with the conclusions of this study, progress in these areas of research will further the understanding of stream restoration success and will provide practitioners with knowledge to assist in restoration project site selection that will maximize restoration success and optimize limited restoration funding

References

Akinola, A. I., Wynn-Thompson, T. M., Olgun, C. G., Mostaghimi, S., Eick, M.J. (2019). Fluvial Erosion rate of cohesive streambanks is directly related to the difference in soil and water temperatures. *J. Environ. Qual.*

Allen, D. C., Wynn-Thompson, T. M., Kopp, D. A., Cardinale, B. J. (2018). Riparian plant biodiversity reduces stream channel migration rates in three rivers in Michigan, USA. *Ecohydrology* 11. doi:/10.1002/eco.1972

Allmendinger, N. E., Pizzuto, J. E., Moglen, G. E., Lewicki, M., (2007). A sediment budget for an urbanizing watershed, 1951–1996, Montgomery County, Maryland, U.S.A. J. Am. Water Resour. Assoc. 43, 1483–1498.

Bain, D. J., Copeland, E. M., Divers, M. T. Hecht, M. Hopkins, K. G., Hynicka, J., Koryak, M, Kostalos, M., Brown, L., Elliott, E.M. Fedor, J., Gregorich, M., Porter, B., Smith, B., Tracey, C., Zak,M. (2014). Characterizing a Major Urban Stream Restoration Project: Nine Mile Run (Pittsburgh, Pennsylvania, USA). Journal of the American Water Resources Association (JAWRA) 50(6): 1608-1621.

Barbour, M.T., Gerritsen, J., Snyder, B.D. Stribling, J.B. (1999). Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Benke, A. C. (1990). A perspective on America’s vanishing streams. Journal of the North American Benthological Society9:77 – 88

Bennett, S.J., Simon, A., Castro, J. M., Atkinson, J.F. Bronner, C.E., Blersch, S.S. Rabideau, A.J. (2011). The evolving science of stream restoration. In Stream restoration in dynamic fluvial systems: Scientific approaches, analyses and tools (pp. 1- 8). Washington, DC: American Geophysical Union.

Berg, J., Burch, J., Cappuccitti, D., Filoso, S. Fraley-Mcneal, L., Goerman, D., Hardman, N., Kaushal, S., Medina, D., Meyers, M., Kerr, B., Stewart, S., Sullivan, B., Walter, R Winters, J. (2014). Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects. Chesapeake Bay Program.

Bernhardt, E.S. Palmer, M.A., Allen, J.D., Alexander, G, Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J. Galat, D., Gloss, S., Goodwin, P., Hart, D., Hasset, B. Jenkins, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R. Meyer, J.L. O'Donnell, T.K. Pagano, O.L., Powell, B. Suddeth, E. (2005). Synthesizing U.S. River Restoration Efforts. Science, 308, 636-637.

Bernhardt, E.S. and Palmer, M.A. (2007). Restoring streams in an urbanizing world. Freshwater Biology 52 pp. 738-751.

Bledsoe, B.P. (2002) Relationship of stream responses to hydrologic changes. In B. Urbonas (Ed.), Linking Stormwater BMP Designs and Performance to Receiving Water Impact Mitigation. Reston, VA. American Society of Civil Engineers.

Brookes A., and Shields, F.D. (1996). River Channel Restoration: Guiding Principles for Sustainable Projects. Chichester (United Kingdom): Wiley

Buchanan, B.P., Walter, M.T., Nagle, G.N., Schneider, R.L. (2012). Monitoring and Assessment of a River Restoration Project in Central New York. River Research and Applications 28: 216–233. doi: 10.1002/rra.14533.

Buchanan, B.P., Nagle, G.N., Walter, M.T. (2014). Long-term monitoring and assessment of a stream restoration project in central New York. River Res. Applic. 30: 245–258

Charlton, R. (2008). Fundamentals of Fluvial Geomorphology. Abingdon, UK: Routledge.

Chesapeake Bay Foundation. (2012). The Economic Argument for Cleaning Up the Chesapeake Bay and its Rivers. Annapolis, Maryland.

Chesapeake Bay Foundation. (2019). Economic Benefits of cleaning up the Chesapeake. Retrieved from https://www.cbf.org/news-media/features-publications/reports/economic-benefits-of-cleaning-up-the-chesapeake-bay/

Chesapeake Bay Program. (2019). Fish passage. Chesapeake Progress. Retrieved from https://www.chesapeakeprogress.com/abundant-life/fish-passage

Cinotto, P.J., (2003) Development of Regional Curves of Bankfull Geometry and Discharge for streams in the non-urban, Piedmont Physiographic Province, Pennsylvania and Maryland. Water-Resources Investigations Report 03-4014. U.S. Geological Survey, Denver, CO.

Clean Water Act of 1972, 33 U.S.C. §1251 et seq.

Dave, N.N., (2018) Evaluation of Effectiveness of Streambank Stabilization Practices and Flood Impact on Cedar River, Nebraska. Masters thesis. University of Nebraska, Lincoln

Doll, B.A., (2013). Assessing Eco-geomorphological Condition of Stream Restoration Projects in North Carolina. Ph.D. Dissertation, NC State University, Raleigh, North Carolina.

Doll, B. A., Jennings, G. D., Spooner, J., Penrose, D. L., & Usset, J. L. (2015). Evaluating the eco-geomorphological condition of restored streams using visual assessment and macroinvertebrate metrics. Journal of the American Water Resources Association, 51(1), 68–83. https://doi.org/10.1111/jawr.12233

Donovan, M., Miller, A., Baker, M., Gellis, A. (2015). Sediment contributions from floodplains and legacy sediments to Piedmont streams of Baltimore County, Maryland. Geomorphology 235 pp. 88-105.

Endreny, T.A. and Soulman, M.M. (2011). Hydraulic analysis of river training cross vanes as part of post-restoration monitoring.

EPA. (2010). Chesapeake Bay Total Maximum Daily Load for Nitrogen, Phosphorus and Sediment. U.S. Environmenal Protection Agency. Washington, D.C.

EPA. (2013). Streams. Retrieved from https://archive.epa.gov/water/archive/web/html/streams.html

EPA. (n.d.). Indicators: Streambed Sediments. Retrieved from https://www.epa.gov/national-aquatic-resource-surveys/indicators-streambed-sediments

Fischenich, J.C. (2006). Functional Objectives for Stream Restoration, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-52), US Army Engineer Research and Development Center, Vicksburg, Mississippi. http://el.erdc.usace.army.mil/elpubs/pdf/sr52.pdf

FISRWG. (1998). Analysis of Corridor Condition in Stream Corridor Restoration: Principles, Processes, and Practices. By the Federal Interagency Stream Restoration Working Group (FISRWG) (15 Federal agencies of the US gov't). GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653. ISBN-0-934213-59-3.

Galli Sr., J. (1996). Appendix A Final Technical Memorandum: Rapid Stream Assessment Technique (RSAT) Field Methods. Metropolitan Washington Council of Governments, Washington, D.C.

Harman, W. A., Jennings, G. D., Tweedy, K. R., Buck, J. A., Taylor, D.L. (2001) Lessons Learned from Designing and Constructing In-Stream Structures. In D. F. Hays (Ed.) Wetlands Engineering & River Restoration. American Society of Civil Engineers.

Harman, W., Starr, R., Carter, M., Tweedy, K., Clemmons, M., Suggs, K., Miller, C. (2012). A Function-Based Framework for Stream Assessment and Restoration Projects. US

Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC EPA 843-K-12-006.

Harman, W.A. and Jones, C.J. (2017). North Carolina Stream Quantification Tool: Spreadsheet User Manual, NC SQT v3.0. Environmental Defense Fund, Raleigh, NC.

Hill, T., E. Kulz, B. Munoz and J. Dorney. (2011). Compensatory stream and wetland mitigation in North Carolina: an evaluation of regulatory success. North Carolina Dept. of Environment and Natural Resources. Raleigh, NC.

Hoomehr, S., A.I. Akinola, T. Wynn-Thompson, W. Garnand, and M. Eick. (2018). Water temperature, pH, and road salt impacts on the fluvial erosion of cohesive streambanks. *Water* 10(3): 302. doi:10.3390/w10030302

Hupp, C. R., Pierce, A.R., Noe, G. B. (2009). Floodplain geomorphic processes and environmental impacts of human alteration along Coastal Plain rivers, USA. *Wetlands* 29(2) pp. 413-429.

Karr, J. R. and Chu, E.W. (1999). Restoring life in Running Waters: Better Biological Monitoring. Island, Washington D.C.

Kondolf, G.M. (1995). Five elements for effective evaluation of stream restoration. Restoration Ecol. 3(2). 133-136

Kondolf, G.M and Micheli, E.R. (1995). Evaluating stream restoration projects/. Env. Manag. 19(1). 1-15.

Kristolic, J.L. and Chaplin, J.J. (2007). Bankfull Regional Curves for Streams in the Non-Urban, Non-Tidal Coastal Plain, Virginia and Maryland. Scientific Investigations report 2007-5162. U.S. Geological Survey. Reston, VA.

Lake County Stormwater Management Commission Lake County Planning (2002) streambank and shoreline protection manual. Building and Development Department U.S.D.A. - Natural Resources Conservation Service.

Law, N., Stack, B. Starr, R.,. Yagow, E. (2015). Designing sustainable stream restoration projects within the Chesapeake Bay watershed. STAC Publication Number 15-003, Edgewater, MD. 50

Leo, S., Piatt-Kemper, J., Brown, S., Hoskins, J., Meyer, S., Tam, W., Neprash, R., Walch, T. (2018). MS4 Stormwater Permitting Guide. National Association of Clean Water agencies. Washington, D.C.

Loos, J., and Shader, E. (2016). Reconnecting rivers to floodplains: Returning natural functions to restore rivers and benefit communities. River Restoration Program. American Rivers.

Manning, R. (1891). On the flow of water in open channels and pipes. In Transactions of the Institution of Civil Engineers of Ireland, Vol. XX, pp. 161-207.

Maryland Department of Environment. (2012). Maryland’s Phase II Watershed Implementation Plan for the Chesapeake Bay TMDL. Annapolis, MD.

Maryland Department of Natural Resources. (2015). Policy number 2015:01: Principles and Protocols to guide the Department of Natural Resources’ Actions Regarding Stream Restoration Projects. Annapolis, MD.

Maryland Department of Planning. (2010). Land Use/ Land Cover for Maryland. Retrieved from https://planning.maryland.gov/Documents/OurProducts/landuse/metadata.pdf

Miller, J.R., and Kochel, R.C. (2009). Assessment of channel dynamics, in-stream structures, and pot-project channel adjustments in North Carolina and its implications to effective steam restoration. Environ. Earth Sci. 59; 1681-1692

Miller, S.W., Budy, P. Schmidt., J.C. (2010). Quantifying Macroinvertebrate Responses to In-Stream Habitat Restoration: Applications of Meta-Analysis to River Restoration. Restoration Ecology 18(1) pp. 8-19.

Montgomery, D.R., Buffington, J.M. (1997). *Geological Society of America Bulletin*, 109(5)

Morandi B., Piegay H, Lamouroux, N, Vaudor, L. (2014). How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. J. Environ. Manag. 137:178–188

National Research Council. (1992). Restoration of aquatic ecosystems: science, technology, and public policy. National Academy Press, Washington, D.C

NCSU Water Quality Group. (2006). Stream Restoration Evaluation Assessment. NC State University, Raleigh, NC.

NOAA. (2017). Barriers to Fish Migration. Retrieved from https://www.fisheries.noaa.gov/insight/barriers-fish-migration

NRCS. (2007). Part 654 Stream restoration, Design National Engineering Handbook. 210-VI-NEH. USDA. Washington D.C.

NRCS. (1996). Riparian Areas Environmental Uniqueness, Functions, and Values. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/?cid=nrcs143_014199#what

Palmer, M.A and Bernhardt., E.S. (2006). Hydroecology and river restoration: Ripe for research and Synthesis.Water Resour. Res.,42, XXXXXX, doi:10.1029/2005WR004354

Palmer, M.A, Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, N., Follstad Shah, J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hasset, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L, O'Donnell, T.K, Pagano, L., Sudduth, E. (2005). Standards for ecologically successful river restoration. J. of Applied Ecology, 42, pp. 208-217.

Petersen, R.C. (1992). The RCE: a Riparian, Channel, and Environmental Inventory for small streams in the agricultural landscape. Freshwater Biology (27) pp. 295-306.

Pfankuch, D.J. (1975). Stream reach inventory and channel stability evaluation. U.S.D.A. Forest Service, Region 1, Missoula, Montana, U.S.A.

Pluhowski, E.J. (1970). Urbanization and its effect on the temperature of the streams on Long Island, New York. Geological Survey Professional Paper 627-D. USGS, Washington, D.C.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004.

Purcell, A.H., Friedrich, C., Resh., V.H. (2002). An assessment of a small Urban Stream Restoration Project in Northern California. Restoration Ecology 10(4); 685-694.

Rice, J.S., Anderson Jr., W.P., Thaxton, C.S. (2011). Urbanization influences on stream temperature behavior within low-discharge headwater streams. *Hydrological Research Letters* 5, 27-31.

Roni, P, Hanson, K. Beechie,, T. (2008) Global Review of the Physical and Biological Effectiveness of Stream Habitat Rehabilitation Techniques, North American Journal of Fisheries Management, 28:3, 856-890, DOI: 10.1577/M06-169.1

Roper, B.B., Konnoff, D.,Heller, D., Wieman, K. (1998). Durability of Pacific Northwest instream structures following floods. North American Journal of Fisheries Management (18) pp. 686-693.

Rosgen, D. L. (1994). A Classification of Natural Rivers. *Catena* 22. pp.169-199.

Rosgen, D. L. (2006). *Watershed assessment of river stability and sediment supply (WARSSS).* Fort Collins, CO: Wildland Hydrology.

SAS Institute. (2017). *Base SAS 9.4 procedures guide: Statistical procedures*. SAS Institute.

Shields, F.D, Cooper, D.M., Knight, S.S., Moore, M.T. (2003). Stream corridor restoration research: a long and winding road. *Ecological Engineering* 20(5). pp. 441-454.

Skinner, K.S., Downs, P.W. Brooks., A. (1998). Geo-Hydraulic Diversity Index (GDI) - A method for assessing the sustainability of rivers. In S. Abt, J. Young-Pezeshk, C. watson (ed.) Proc. Int. Water Resources Engineering Conf. 1, pp. 666-671. Reston, VA: ASCE.

Society for Ecological Restoration Science and Policy Working Group. (2004). The SER Primer on Ecological Restoration. www.ser.org/

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at the following link: https://websoilsurvey.sc.egov.usda.gov/. Accessed [2018]

Thompson, D. M. & Stull, G. N. (2002). The Development and Historic Use of Habitat Structures in Channel Restoration in the United States: The Grand Experiment in Fisheries Management. *Geographie Physique et Quaternaire* 56(1). pp. 45-60.

Thorne, C.R. (1990). "Effects of Vegetation on Riverbank Erosion and Stability." In J. B. Thornes (Ed.), Vegetation and Erosion, John Wiley and Sons, New York.

USDA-NRCS (1998) NWCC Technical Note 99–1, Stream Visual Assessment Protocol. Washington D.C.

U.S. Geological Survey (2016). The StreamStats program, online at **http://streamstats.usgs.gov**, accessed in June 2018.

Vilá, M., Espinar, J.L., Hejda, M., Hulme, P.E., Jarosik, V., Maron, J.L., Pergl, J. Schaffner, U., Pysek, P. (2011) Ecological impacts of invasive alien plant: a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters* 14, 702-708.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *J. N. Am. Benthol. Soc.* 24(3). pp. 706-723.

Wohl, E. (2014). *Rivers in the landscape: Science and management*. Chichester West Sussex, UK. John Wiley and Sons.

Wohl, E., Lane, S.N., Wilcox, A.C. (2015). The science and practice of river restoration. Water Resour. Res. 5974-5997

Wohl, E., Angermeier, P. L. Bledsoe, B. Kondolf, G. M. MacDonnell, L., Merritt, D. MPalmer, ., M. A., Poff, N. L, Tarboton, D. (2005), River restoration, Water Resour. Res.,41, W10301, doi:10.1029/2005WR003985.

Yochum, Steven E. (2018). Guidance for Stream Restoration. U.S. Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center, Technical Note TN-102.4. Fort Collins, CO.

Appendices

Appendix A: Assessment forms from methods summarized in Literature Review

Table 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)	Drop structures, culverts, dams, or diversions

			within 3 miles of the reach.	(>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

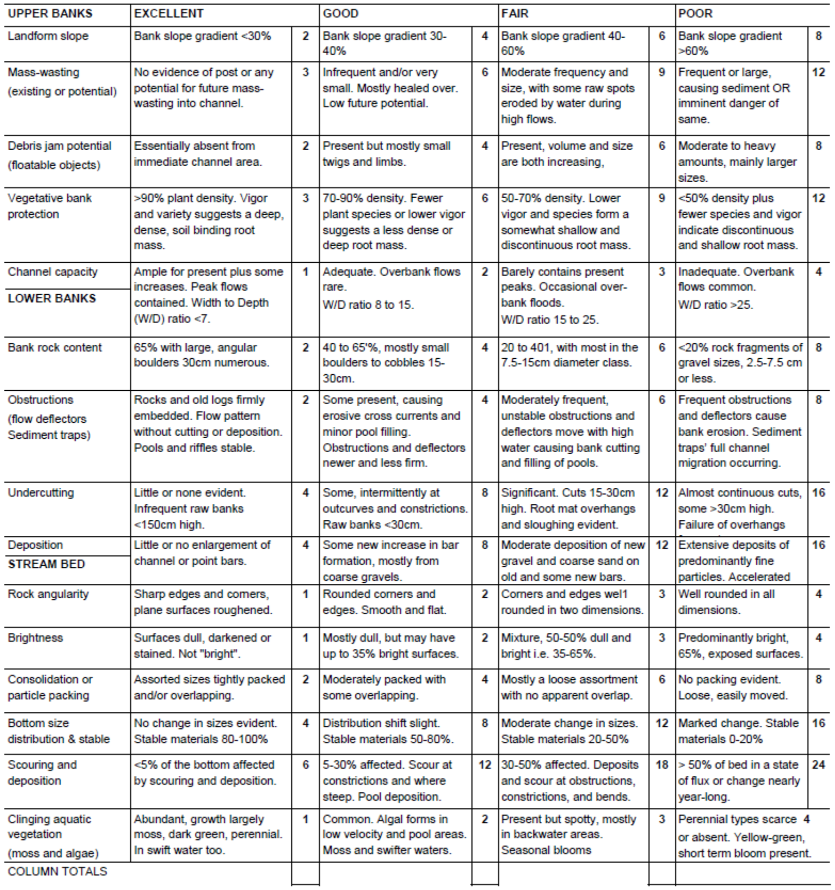
(14) Riffle Embeddedness (if applicable)

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

Table 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 **LOWER BANKS**	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
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 **STREAM BED**	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
Rock angularity	Sharp edges and comers, plane surfaces roughened.	1	Rounded comers and edges. Smooth and flat.	2	Comers 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								

Table 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)

Table A-4 Riparian, Channel, and Environmental Inventory: Land Use

		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 spedes 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

Table A-5 Riparian, Channel, and Environmental Inventory: 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

Table A-5 Riparian, Channel, and Environmental Inventory: Physical stream Structure continued

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
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

Table A-6 Riparian, Channel, and Environmental Inventory: 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 spedes present on all types of substrate	20
	Many species but only in well-aerated habitats	15
	Few spedes present but found in most habitats	5
	Few if any spedes and only in well-aerated habitats	1
	Total Score =	

Table A-7 Riparian, Channel, and Environmental Inventory: 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

Table A-8 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

Table A-9 Stream Performance Assessment: 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

Table A-10 Stream Performance Assessment: 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

Table A-11 Stream Performance Assessment: 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

Table A-12 Stream Performance Assessment: 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

Table A-13 Stream Performance Assessment: 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

Table A-14 Stream Performance Assessment: 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

Appendix B: Data sets utilized in regression analysis and summaries

Table B-1 Watershed-level dataset from field assessment

Project	HighP	MedP	ForP	StrmK	Strmslp	logA	loglow	logAg	logBMP	K2	fxnperc	Design
1	72	8	18	0.35	0.010	13.5	1	0	4	0.03	67	100
3	45	18	20	0.23	0.010	16.3	2	2	4	0.05	67	0
4	36	7	14	0.25	0.011	13.8	4	2	4	0.04	54	93
7	0	0	41	0.29	0.010	14.2	3	3	3	0.05	100	100
15	49	34	13	0.34	0.012	14.2	2	0	2	0.05	75	78
19	24	23	49	0.37	0.007	13.1	2	0	2	0.06	83	84
21	56	43	1	0.37	0.004	13.7	0	0	2	0.03	54	97
22	52	11	24	0.33	0.002	15.8	2	2	3	0.05	75	0
26	10	6	17	0.32	0.012	17.5	3	4	2	0.07	69	58
27	6	2	1	0.21	0.041	12.7	5	0	3	0.05	85	81
28	2	9	25	0.3	0.025	16.5	4	3	1	0.05	100	93
31	7	1	13	0.32	0.005	17.7	3	4	2	0.08	88	67
33	64	0	36	0.44	0.029	12.6	0	0	0	0.15	54	100
34	63	3	0	0.41	0.008	13.5	1	3	0	0.18	60	100
36	13	9	32	0.37	0.007	15.3	4	1	1	0.10	96	83
39	40	32	4	0.36	0.008	15.5	3	2	0	0.11	96	64
40	51	6	20	0.43	0.027	13.1	3	2	0	0.11	96	75
42	14	67	19	0.34	0.033	12.4	0	0	0	0.03	46	83
47	69	4	1	0.43	0.024	12.2	3	0	2	0.02	50	100
50	2	82	0	0.43	0.015	14.2	3	0	5	0.02	46	75
51	0	53	0	0.43	0.002	12.4	4	0	3	0.04	46	67
60	23	49	15	0.37	0.012	15.7	2	2	4	0.14	85	82
61	21	58	8	0.37	0.015	14.3	3	0	4	0.14	58	84
62	4	43	5	0.35	0.018	14.8	4	0	3	0.15	42	72

**HighP is percent High density development, MedP is percent medium density development, ForP is percent forested, StrmK is length weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, K2 is the square of area averaged soil erodibility of the watershed, fxnperc is function score as a percent of perfect, and Design is design score.

Table B-2 Project-level dataset from field assessments

Project	Slope	ER	WD	Sin	K	D50	log_year	log_length	logstrucd	logugrade	logdgrade	Design	fxnperc
1	0.011	0.2	0.2	1.2	0.37	584	7.61	6	0	3	0	100	67
3	0.007	0.4	1.8	2.8	0.32	NA	7.60	6	4	4	7	0	67
4	0.007	1.2	0.3	1.5	0.37	254	7.61	6	3	2	6	93	54
7	0.003	0.9	0.3	1.5	0.37	203	7.61	6	0	2	8	100	100
15	0.029	0.9	1.0	1.2	0.32	15	7.61	6	4	0	3	78	75
19	0.030	0.5	0.5	1.5	0.37	NA	7.60	4	5	3	4	84	83
21	0.014	0.4	0.6	1.1	0.37	406	7.60	6	4	4	0	97	54
22	0.003	1.4	1.2	1.2	0.37	0	7.60	6	0	0	0	0	75
26	0.003	1.3	14.4	1.2	0.37	406	7.60	5	3	7	0	58	69
27	0.033	0.3	0.3	1.4	0.24	203	7.61	5	4	5	4	81	85
28	0.004	0.7	6.3	1.4	0.32	30	7.61	6	4	0	5	93	100
31	0.006	0.6	17.2	1.3	0.32	NA	7.60	5	3	0	8	67	88
33	0.036	2.1	0.2	1.0	0.43	241	7.61	6	4	3	0	100	54
34	0.014	0.2	0.2	1.1	0.4	152	7.61	5	0	4	0	100	60
36	0.005	0.3	0.8	1.4	0.43	38	7.61	6	3	0	6	83	96
39	0.009	0.9	2.8	1.6	0.43	40	7.61	6	4	4	7	64	96
40	0.020	0.6	0.4	1.2	0.43	40	7.61	5	3	5	3	75	96
42	0.026	0.5	0.2	1.1	0.37	196	7.61	6	5	4	4	83	46
47	0.035	0.5	0.2	1.0	0.43	197	7.61	6	6	3	0	100	50
50	0.009	0.9	4.1	1.2	0.43	140	7.61	6	5	3	8	75	46
51	0.047	1.5	0.2	1.0	0.43	140	7.61	3	5	4	1	67	46
60	0.007	0.3	3.3	1.2	0.35	229	7.61	6	3	2	5	82	85
61	0.014	0.3	1.0	1.0	0.35	229	7.61	7	3	0	5	84	58
62	0.012	0.7	1.5	2.3	0.37	152	7.61	7	4	0	7	72	42

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, logdgrade is log of distance to downstream grade control +1, Design is design score, and fxnperc is function score as a percent of perfect.

Table B-3 Watershed-level dataset from monitoring assessment

Project	HighP	MedP	forP	StrmK	Strmslp	logA	loglow	logAg	logBMP	logslp	K2	Monperc
1	72	8	18	0.35	0.010	14	1	0	5	0.174	0.03	92
3	45	18	20	0.23	0.010	16	2	2	4	0.318	0.05	67
12	17	76	7	0.23	0.011	14	0	0	5	0.643	0.00	58
17	37	53	8	0.34	0.004	16	1	0	3	0.806	0.05	58
18	49	40	8	0.35	0.005	14	1	0	3	0.892	0.05	58
21	56	43	1	0.37	0.004	14	0	0	2	1.334	0.03	83
22	52	11	24	0.33	0.002	16	2	2	3	0.278	0.05	50
24	45	2	0	0.35	0.011	13	4	0	2	1.154	0.06	67
25	45	0	29	0.27	0.018	11	1	3	5	1.887	0.01	58
27	6	2	1	0.21	0.041	13	5	0	4	2.449	0.05	67
31	7	1	13	0.32	0.005	18	3	4	1	1.993	0.08	92
32	17	62	0	0.42	0.018	13	3	0	0	2.069	0.11	33
34	63	3	0	0.41	0.008	13	1	3	0	1.188	0.18	75
35	2	0	25	0.36	0.006	17	4	3	0	2.344	0.08	83
36	13	9	32	0.37	0.007	15	4	1	1	2.160	0.10	100
38	15	73	7	0.37	0.020	13	2	0	0	2.277	0.12	58
41	8	7	22	0.32	0.005	19	4	3	0	2.358	0.09	50
42	14	67	19	0.34	0.033	12	0	0	0	2.566	0.03	58
43	0	91	6	0.4	0.021	13	1	0	3	2.224	0.06	58
44	21	30	19	0.33	0.004	18	3	2	4	2.134	0.04	75
45	16	9	15	0.37	0.007	16	3	3	3	2.000	0.07	50
46	24	36	8	0.35	0.009	15	3	2	4	2.140	0.04	75
47	69	4	1	0.43	0.024	12	3	0	3	2.107	0.02	83
48	15	9	15	0.39	0.007	16	3	3	3	1.978	0.07	58
49	27	30	3	0.43	0.020	13	4	2	4	2.059	0.03	100
50	2	82	0	0.43	0.015	14	3	0	4	2.160	0.02	75
51	0	53	0	0.43	0.002	12	4	0	3	2.201	0.04	92
53	0	8	15	0.37	0.033	12	4	0	4	2.026	0.14	83
54	2	44	22	0.36	0.022	14	3	0	4	2.041	0.14	75
55	3	42	23	0.37	0.025	14	3	2	5	1.943	0.14	75
60	23	49	15	0.37	0.012	16	2	2	3	1.984	0.14	67
61	21	58	8	0.37	0.015	14	3	0	4	1.969	0.14	50
65	40	26	21	0.27	0.009	17	0	2	1	2.349	0.07	83

**HighP is percent High density development, MedP is percent medium density development, ForP is percent forested, StrmK is length weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, K2 is the square of area averaged soil erodibility of the watershed, and Monperc is monitoring score as a percent of perfect.

Table B-4 Watershed-level dataset from monitoring assessment

project	Slope	ER	WD	Q	Sin	K	D50	log_year	log_length	log_Q	logugrade	logstrucd	logdgrade	Monperc
21	0.014	22.7	9.6	0.62	1.1	0.37	406	7.60	6.4	-0.47	5	4	0	83
27	0.033	6.1	18.8	0.25	1.4	0.24	203	7.61	5.1	-1.37	4	4	4	67
32	0.020	2.6	15.0	0.45	1.1	0.43	32	7.60	5.8	-0.79	5	4	0	33
36	0.005	11.0	16.4	0.85	1.4	0.43	38	7.61	5.7	-0.16	4	3	6	100
38	0.018	0.0	7.4	0.48	1.4	0.37	NA	7.61	5.7	-0.73	5	5	6	58
41	0.007	2.7	32.0	43.01	1.2	0.35	152	7.60	6.1	3.76	4	3	0	50
42	0.026	6.0	6.4	0.20	1.1	0.37	196	7.61	6.4	-1.62	0	5	4	58
43	0.001	2.0	5.0	0.28	1.2	0.37	71	7.61	5.8	-1.26	3	5	0	58
44	0.000	17.0	16.3	31.26	1.1	0.37	36	7.61	5.3	3.44	4	4	6	75
46	0.005	6.3	8.6	2.58	1.1	0.37	81	7.61	6.0	0.95	2	5	6	75
47	0.035	6.9	5.2	0.17	1.0	0.43	197	7.61	5.9	-1.77	2	6	0	83
49	0.025	8.6	5.4	0.25	1.1	0.43	NA	7.61	5.3	-1.37	2	5	3	100
50	0.009	11.3	7.7	4.11	1.2	0.43	140	7.61	6.1	1.41	1	5	8	75
51	0.047	5.9	4.6	0.20	1.0	0.43	140	7.61	3.4	-1.62	0	5	1	92
3	0.007	2.1	14.4	1.76	2.8	0.32	NA	7.60	6.4	0.56	2	4	7	67
12	0.011	3.6	10.5	0.31	1.0	0.2	NA	7.60	5.8	-1.17	3	5	0	58
25	0.017	1.5	14.3	0.06	1.3	0.27	44	7.61	5.3	-2.87	3	5	6	58
31	0.006	9.4	17.5	17.22	1.3	0.32	NA	7.60	5.0	2.85	4	3	8	92
35	0.005	10.7	10.0	10.62	1.0	0.32	25	7.60	6.3	2.36	3	4	6	83
34	0.014	6.2	8.0	0.23	1.1	0.4	152	7.61	5.3	-1.48	5	0	0	75
45	0.006	8.7	8.3	5.55	1.0	0.37	NA	7.60	6.4	1.71	0	3	7	50
48	0.005	13.1	10.4	5.18	1.1	0.37	NA	7.60	5.6	1.65	3	4	0	58
54	0.023	9.1	6.0	0.93	1.1	0.35	406	7.61	5.8	-0.07	2	4	6	75
53	0.023	7.0	5.6	0.14	1.3	0.37	406	7.61	4.3	-1.95	0	5	0	83
55	0.016	10.4	4.4	0.57	1.1	0.37	406	7.61	5.6	-0.57	6	4	7	75
60	0.007	4.3	20.0	3.31	1.2	0.35	229	7.61	6.5	1.20	1	3	5	67
61	0.014	4.6	10.0	1.02	1.0	0.35	229	7.61	7.2	0.02	4	3	5	50
65	0.020	1.5	25.3	2.86	1.0	0.35	NA	7.60	3.6	1.05	4	6	0	83
1	0.011	4.8	18.0	0.23	1.2	0.37	584	7.61	6.4	-1.48	5	0	0	92
17	0.006	2.4	10.0	2.89	1.4	0.37	381	7.60	7.0	1.06	3	4	0	58
18	0.009	3.7	10.2	1.13	1.2	0.37	381	7.60	4.8	0.12	3	4	6	58
24	0.026	1.9	18.0	0.42	1.0	0.43	89	7.60	6.2	-0.86	3	6	0	67
22	0.003	27.9	4.0	1.19	1.2	0.37	0	7.60	5.6	0.17	8	0	0	50

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, logdgrade is log of distance to downstream grade control +1, and Monperc is monitoring score as a percent of perfect.

Table B-5 summary of watershed-scale variables for field assessment analysis

variable	n	mean	median	min	max
HighP**	24	30.11515	23.7667	0	72.40006
MedP	24	23.69061	10.21565	0	81.8903
ForP	24	15.59903	14.41333	0	49.305
StrmK	24	0.350417	0.355	0.21	0.44
Strmslp	24	0.014346	0.01145	0.0015	0.0414
logA	24	14.36759	14.15222	12.24558	17.66193
loglow	24	2.490217	2.796687	0	4.52251
logAg	24	1.316292	0.706617	0	4.163464
logBMP	24	2.209105	2.398875	0	4.637939
K2	24	0.074754	0.0529	0.0196	0.1849

**HighP is percent High density development, MedP is percent medium density development, ForP is percent forested, StrmK is length weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, K2 is the square of area averaged soil erodibility of the watershed, and Monperc is monitoring score as a percent of perfect.

Table B-6 summary of watershed-scale variables for monitoring assessment analysis

variable	n	mean	median	min	max
HighP	33	25.0882	17.23892	0	72.40006
MedP	33	31.76491	29.7565	0	91.229
ForP	33	12.21238	13.29609	0	31.82182
StrmK	33	0.351818	0.36	0.21	0.43
Strmslp	33	0.013272	0.0103	0.0015	0.0414
logA	33	14.53425	14.15411	11.49577	18.74975
loglow	33	2.477632	2.838575	0	4.52251
logAg	33	1.295545	0.497547	0	4.163464
K2	33	0.070109	0.0576	0.0016	0.1849
logBMP	33	2.676628	2.794798	0	5.755225

**HighP is percent High density development, MedP is percent medium density development, ForP is percent forested, StrmK is length weighted soil erodibility of stream channels in watershed network, Strmslp is slope of longest continual channel in stream network, logA is log of watershed area, Loglow is log of percent low density development, logAg is log of percent agricultural land, logBMP is log of BMP density +1, K2 is the square of area averaged soil erodibility of the watershed, and Monperc is monitoring score as a percent of perfect.

Table B-7 Summary of project-scale variables for field assessment analysis

variable	n	mean	median	min	max
Slope	24	0.016009	0.01135	0.0028	0.0475
ER	24	9.109111	6.076389	1.15	27.88889
WD	24	10.10554	8.611111	3.435897	20
Power	24	26.97262	22.22397	0.607586	90.24213
Sin	24	1.355417	1.2	1	2.85
K	24	0.373333	0.37	0.24	0.43
D_{50}	21	185.5346	195.58	0.375	584.2
log_year	24	7.606198	7.606885	7.598399	7.608871
log_length	24	5.752257	5.85921	3.417071	7.224178
log_Q	24	-0.14301	-0.31818	-1.77254	2.845877
logstrucd	24	3.261558	3.559936	0	5.909259
logugrade	24	3.27686	3.550215	0	7.691551
logdgrade	24	3.711728	4.069218	0	8.022469

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Power is specific stream power, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control +1.

Table B-8 Summary of project-scale variables for monitoring assessment analysis

variable	n	mean	median	min	max
Slope	33	0.014408	0.0111	2.00E-04	0.0475
ER	33	7.332687	6.111111	0.023159	27.88889
WD	33	11.60624	10	4	32
Sin	33	1.202424	1.12	1	2.85
K	33	0.363939	0.37	0.2	0.43
D50	25	201.0408	152.4	0.375	584.2
log_year	33	7.604966	7.606885	7.597898	7.608871
log_length	33	5.706799	5.791976	3.417071	7.224178
log_Q	33	0.021202	-0.1631	-2.87115	3.761509
logugrade	33	3.045825	3.25785	0	7.691551
logstrucd	33	3.946177	4.231313	0	6.213983
logdgrade	33	3.199315	3.593381	0	7.847683

** Slope is reach slope, ER is entrenchment ratio, WD is width to depth ratio, Sin is sinuosity, K is soil erodibility of project stream banks, D_{50} is median particle size, log_year is log of construction year, log_length is log of project construction length, log_Q is log of bankfull discharge, logstrucd is log of structure density +1, logugrade is log of distance to upstream grade control +1, and logdgrade is log of distance to downstream grade control + 1.

Appendix C: Assessment Results

Table C-1 Field assessment scores.

Project	Bedforms	Substrate	Cover	Bank stability	Riparian veg	Floodplain	Design	fxnperc
26	3	4	2	1	3	4	58	69
42	2	1	1	4	3	1	83	46
1	1	2	1	4	4	4	100	67
33	2	2	1	3	3	2	100	54
34	1	1	1	4	4	4	100	60
3	3	4	3	3	2	1	0	67
4	1	1	3	3	4	1	93	54
27	4	4	2	3	4	4	81	85
36	4	4	3	4	4	4	83	96
28	4	4	4	4	4	4	93	100
60	4	2	3	4	4	4	82	88
61	3	2	3	3	3	1	84	58
7	4	4	4	4	4	4	100	100
39	4	4	4	4	4	3	64	96
40	4	4	4	4	4	3	75	96
19	3	3	4	3	4	3	84	83
21	1	2	1	4	4	1	97	54
22	4	4	4	2	3	2	0	77
62	1	1	2	2	4	1	72	42
47	2	2	1	4	3	1	100	50
31	3	4	2	4	4	4	67	88
50	3	2	1	3	2	1	75	46
51	2	3	1	2	2	1	67	46
15	4	3	3	1	4	3	78	75

** Where Design = design score and fxnperc = function score

Table C-2 Monitoring assessment scores.

Project	Bed Aggradation/degredation	Bank Stability	Riparian vegetation cover	Structures	Monperc
21	3	3	1	3	83
27	2	3	2	1	67
64	3	3	3	3	100
32	1	1	1	1	33
36	3	3	3	3	100
38	3	1	2	1	58
41	3	1	1	1	50
42	1	3	1	2	58
43	2	1	2	2	58
44	3	1	2	3	75
46	2	3	2	2	75
47	2	3	2	3	83
49	3	3	3	3	100
50	3	2	3	1	75
51	3	3	3	2	92
3	3	1	2	2	67
12	1	2	3	1	58
25	2	2	2	1	58
31	3	3	2	3	92
35	3	2	3	2	83
34	2	2	2	3	75
45	3	2	1	1	50
48	3	1	2	1	58
54	3	2	2	2	75
53	3	2	2	3	83
55	2	2	2	3	75
60	3	2	1	2	67
61	2	2	1	1	50
65	3	3	3	1	83
1	3	3	2	3	92
17	1	2	2	2	58
18	1	3	2	1	58
24	2	2	2	2	67
22	1	1	3	1	50

**Where Monperc = monitoring score

Appendix D: Plots of Assessment Scores vs Explanatory Variables.

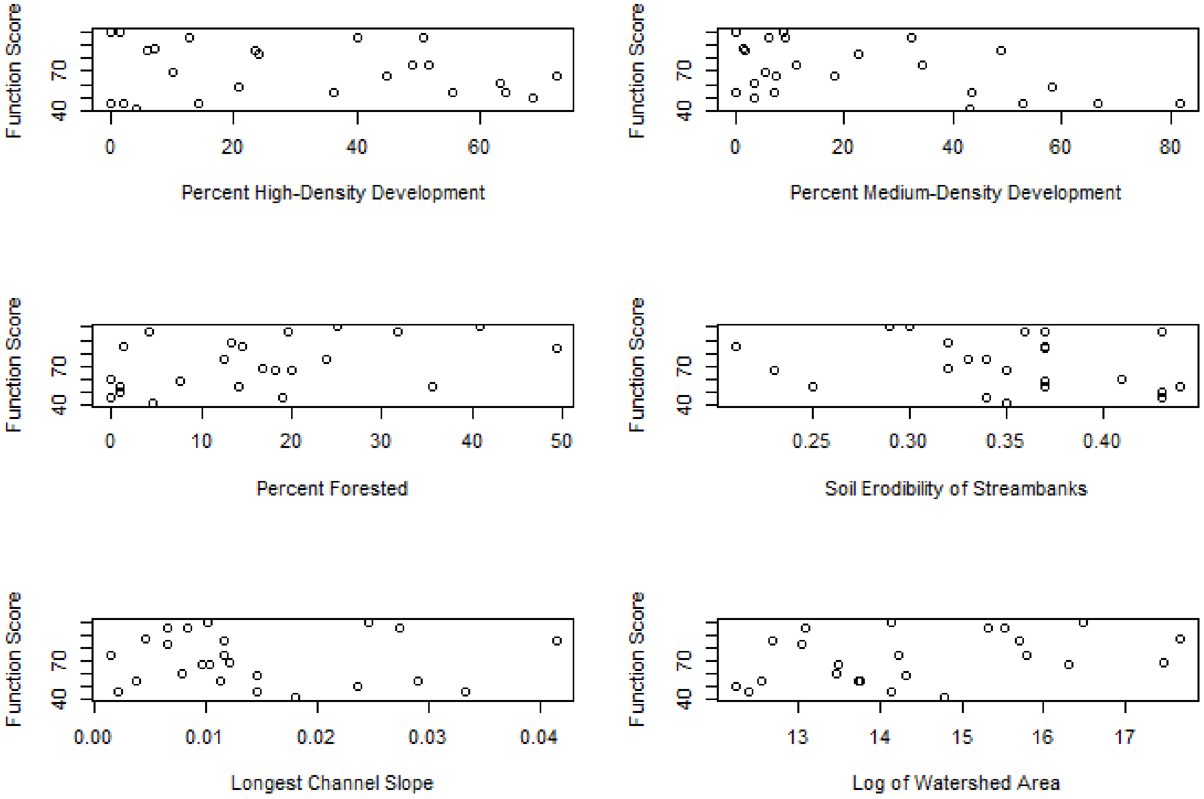


Figure D-1 Function score vs watershed-level variables.

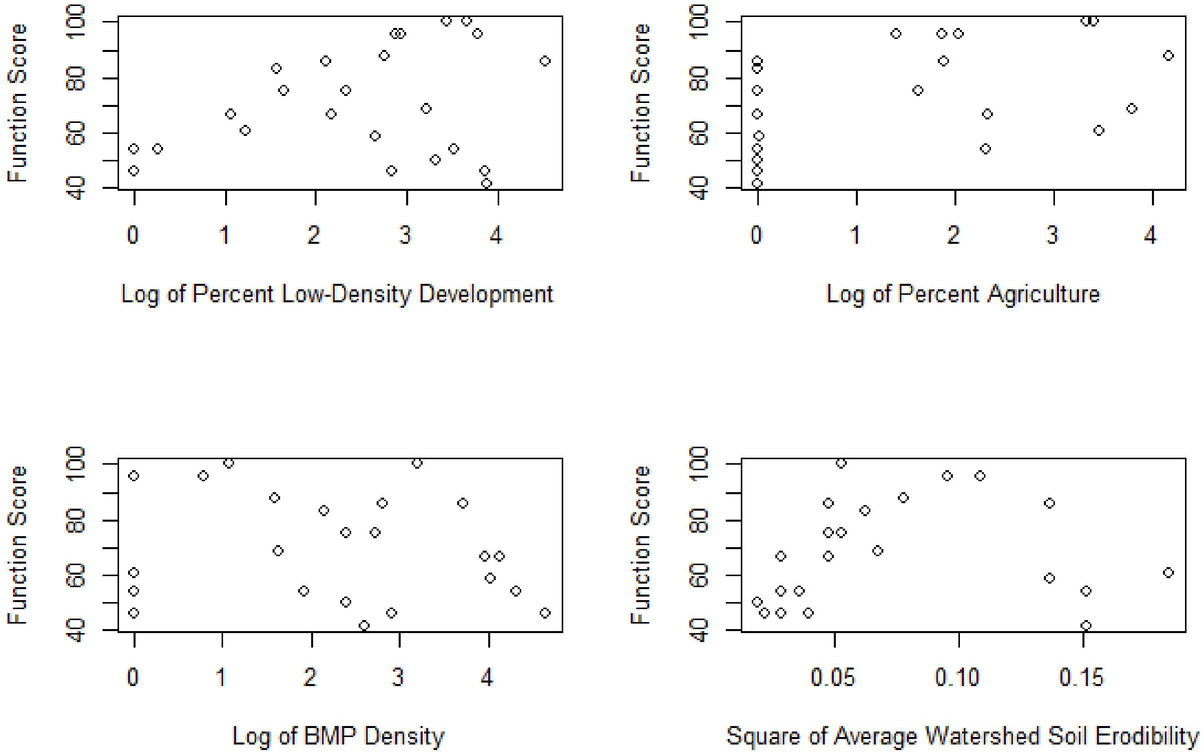


Figure D-1 Function score vs watershed-level variables continued.

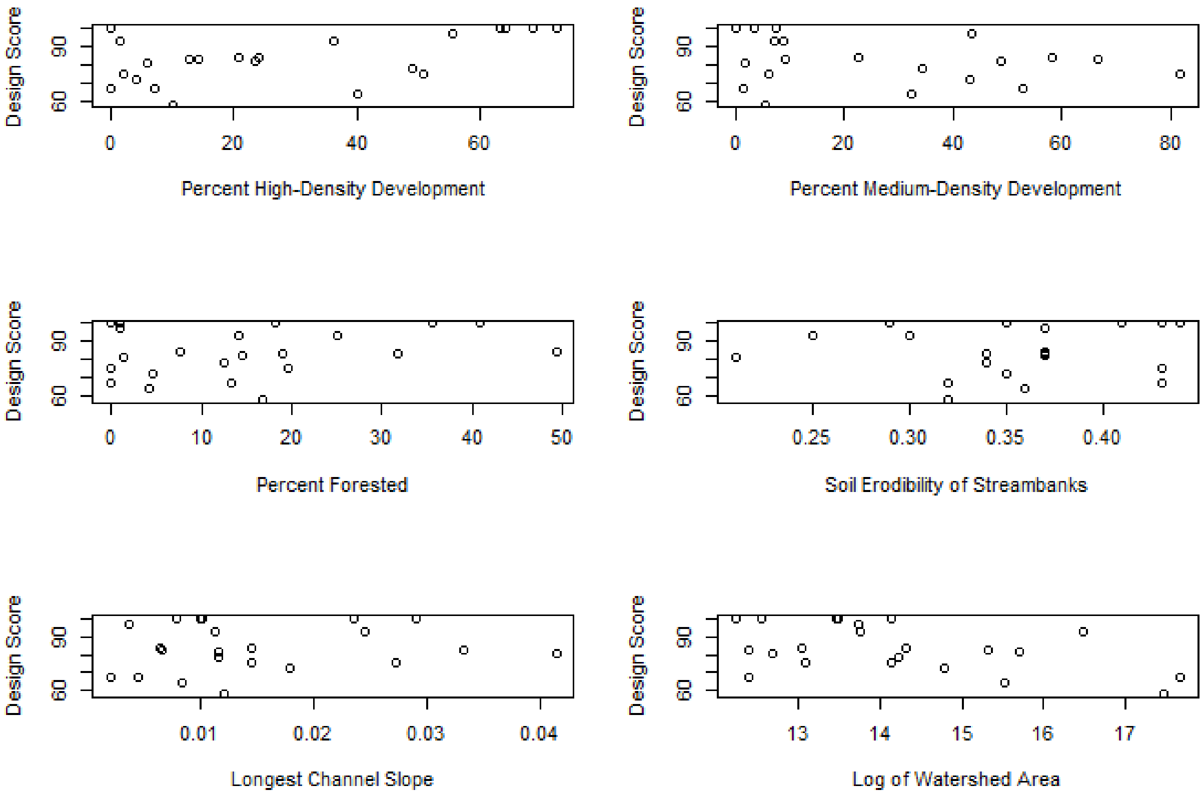


Figure D-2 Design score vs watershed-level variables

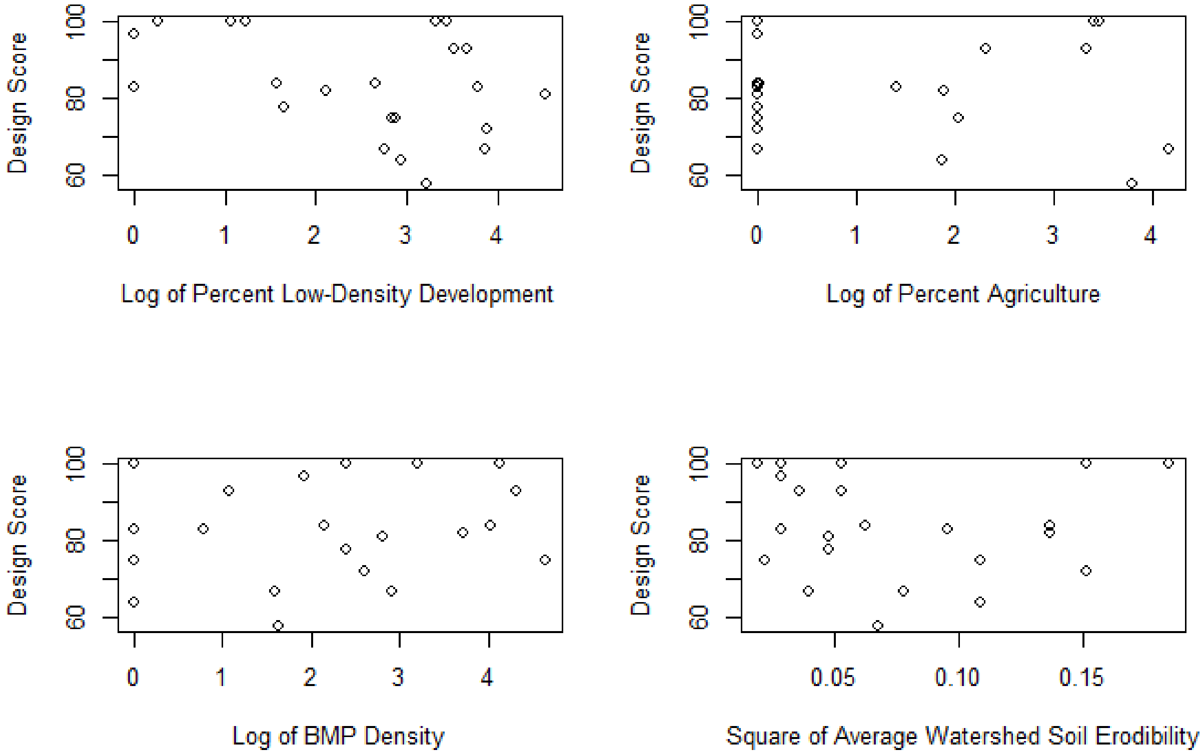


Figure D-2 Design score vs watershed-level variables continued

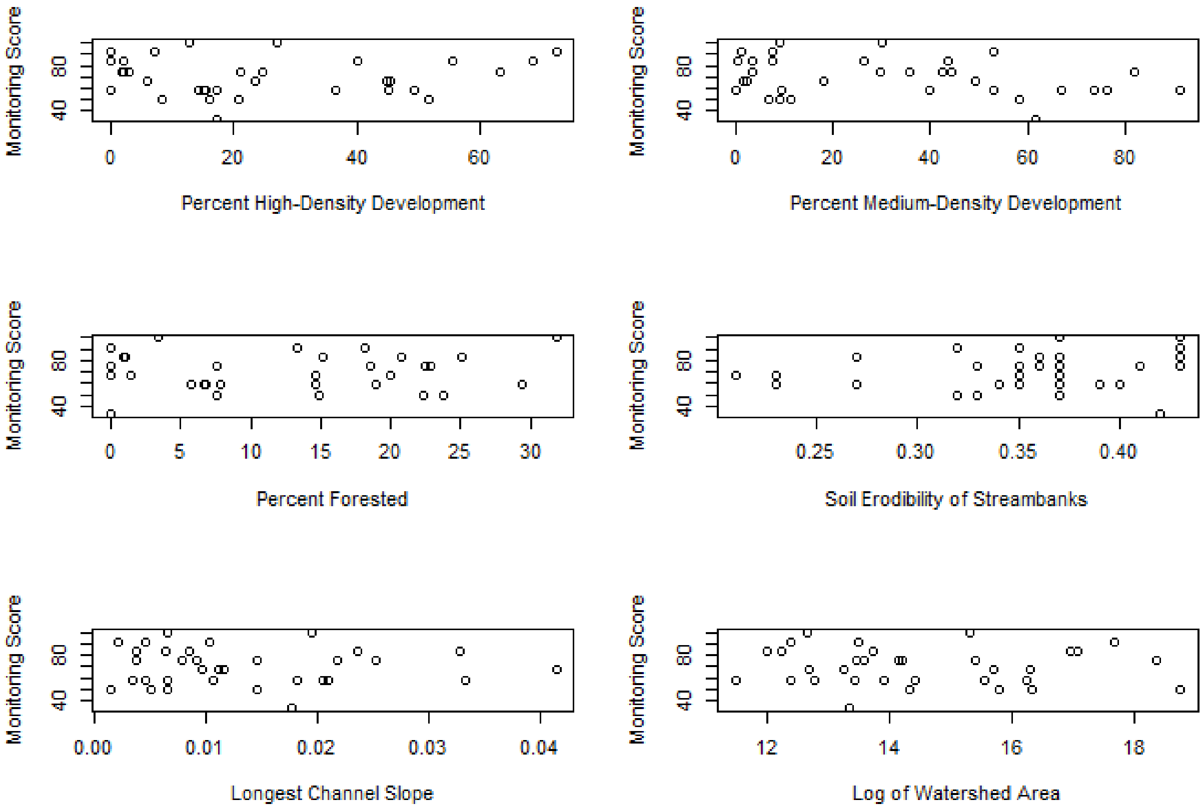


Figure D-3 Monitoring score vs watershed-level variables

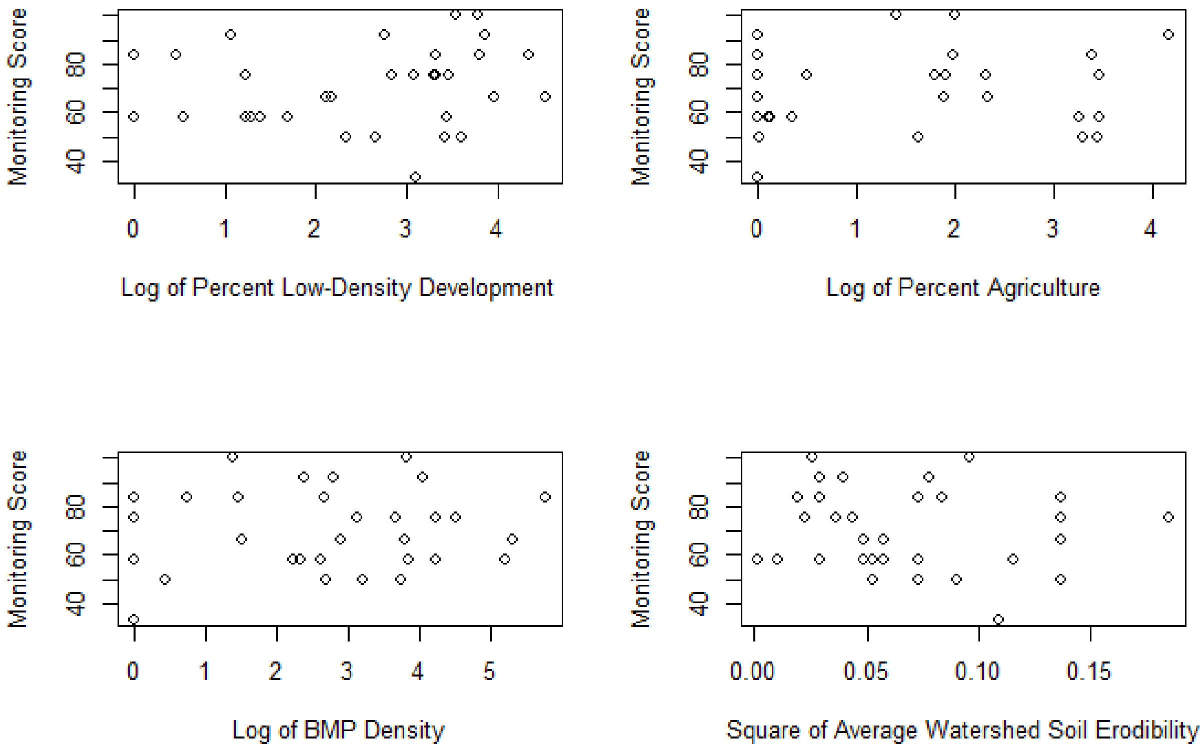


Figure D-3 Monitoring score vs watershed-level variables continued

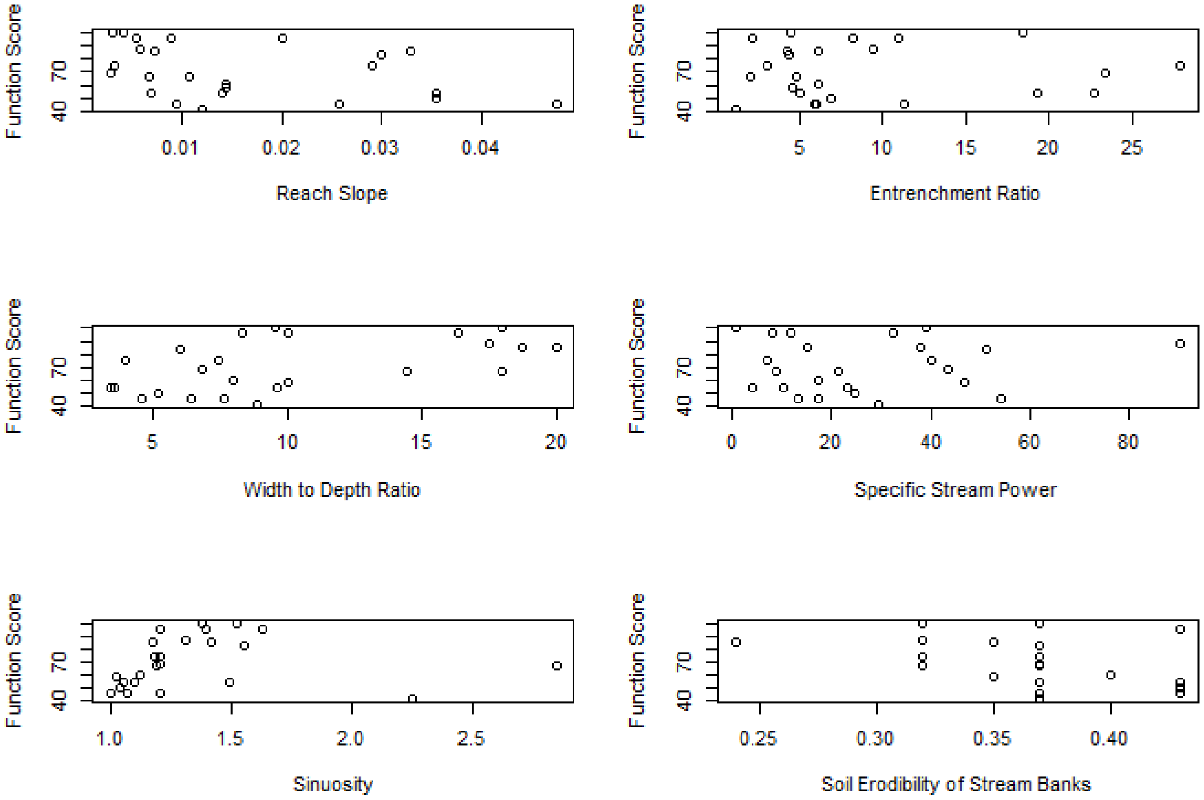


Figure D-4 Function score vs project-level variables

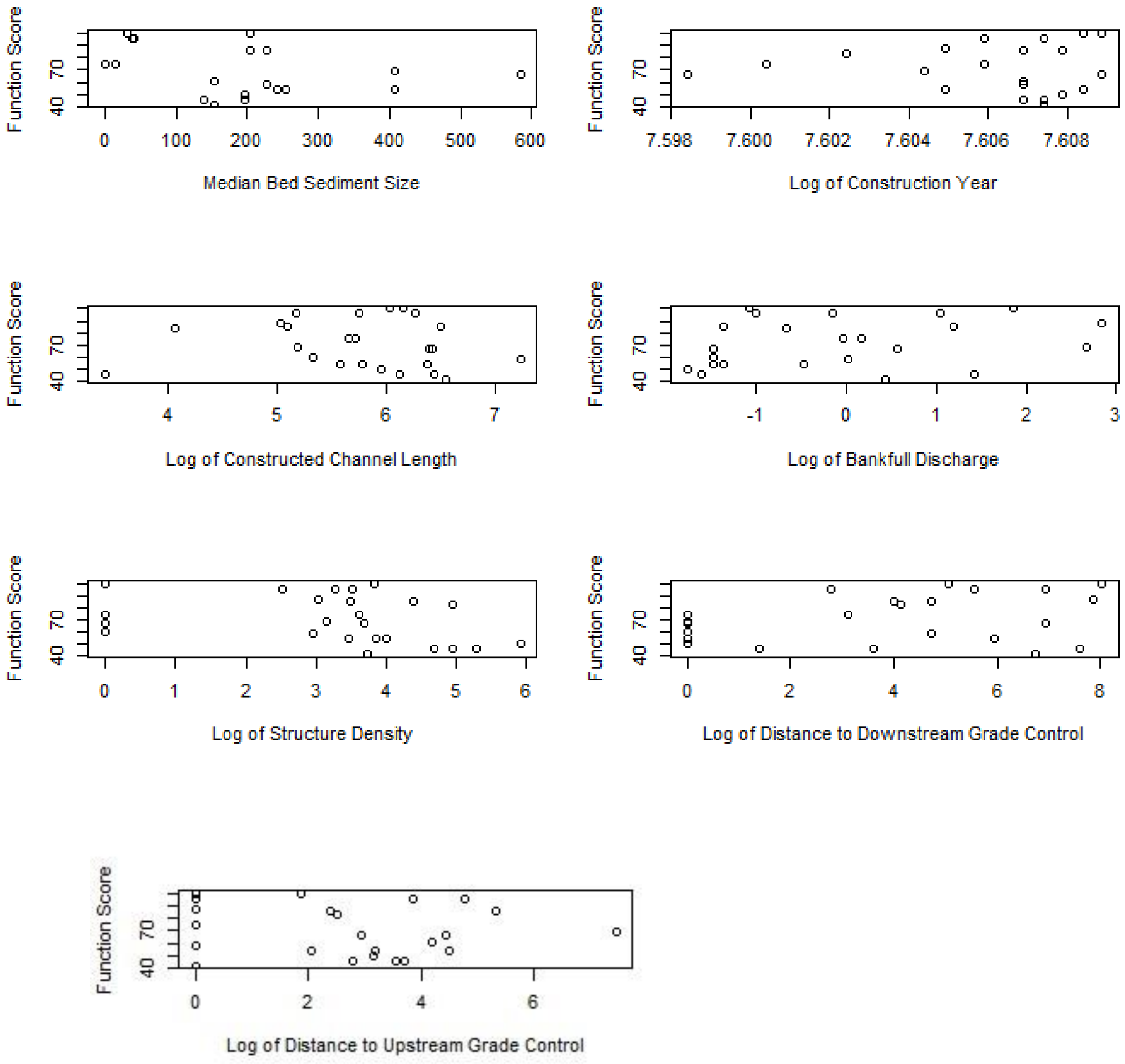


Figure D-4 Function score vs project-level variables continued

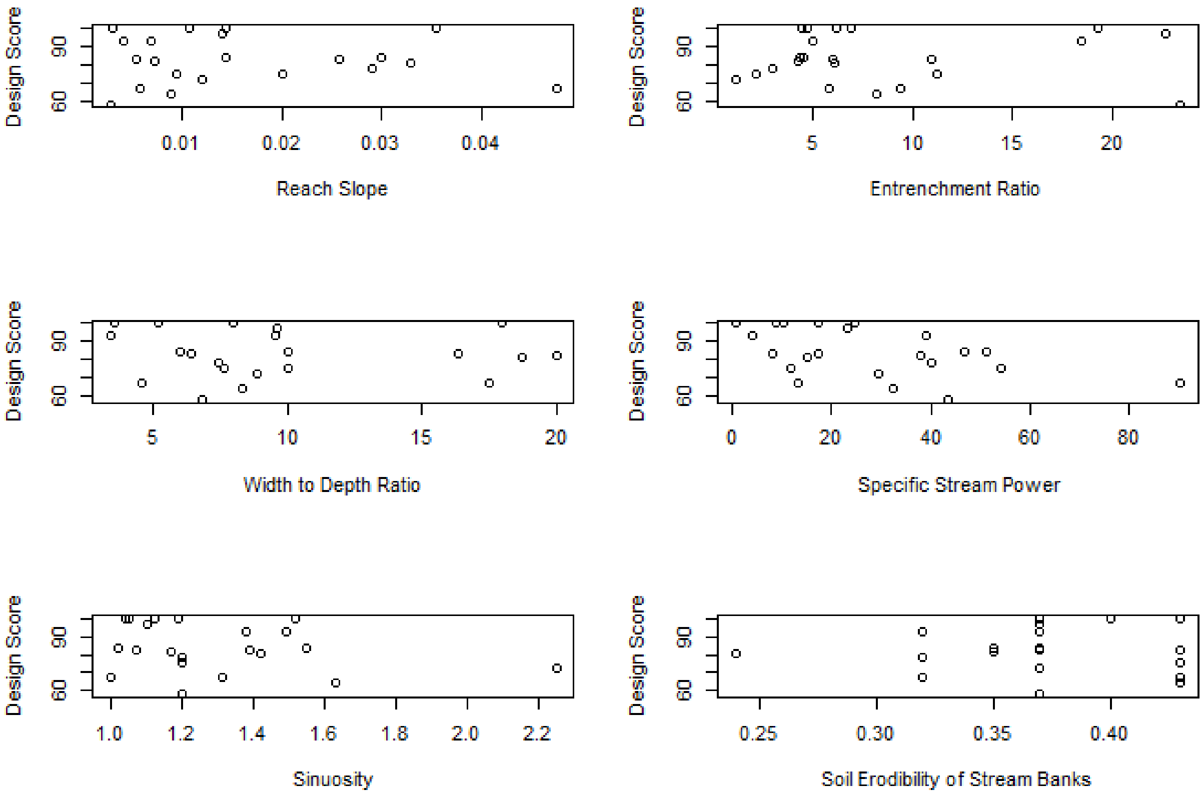


Figure D-5 Design score vs project-level variables

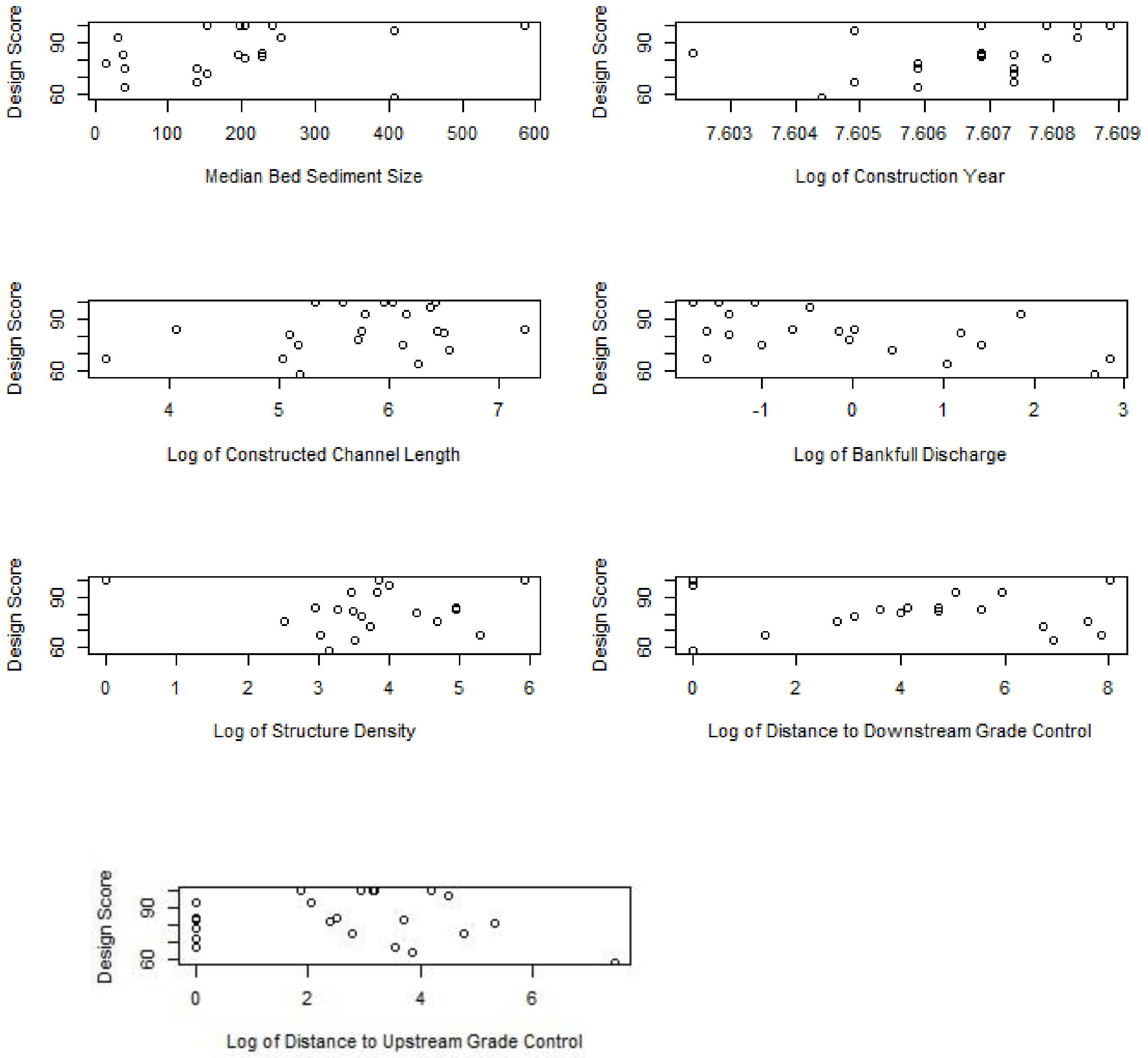


Figure D-5 Function score vs project-level variables continued

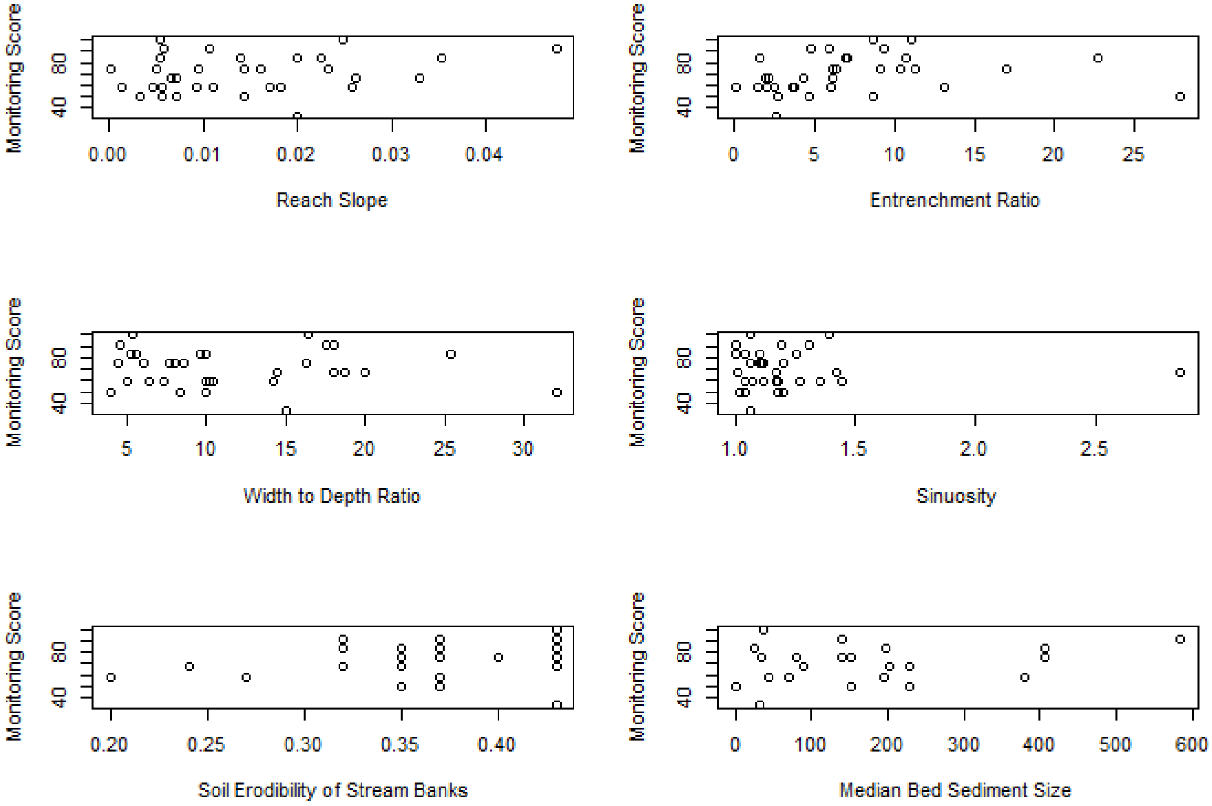


Figure D-6 Monitoring score vs project-level variables

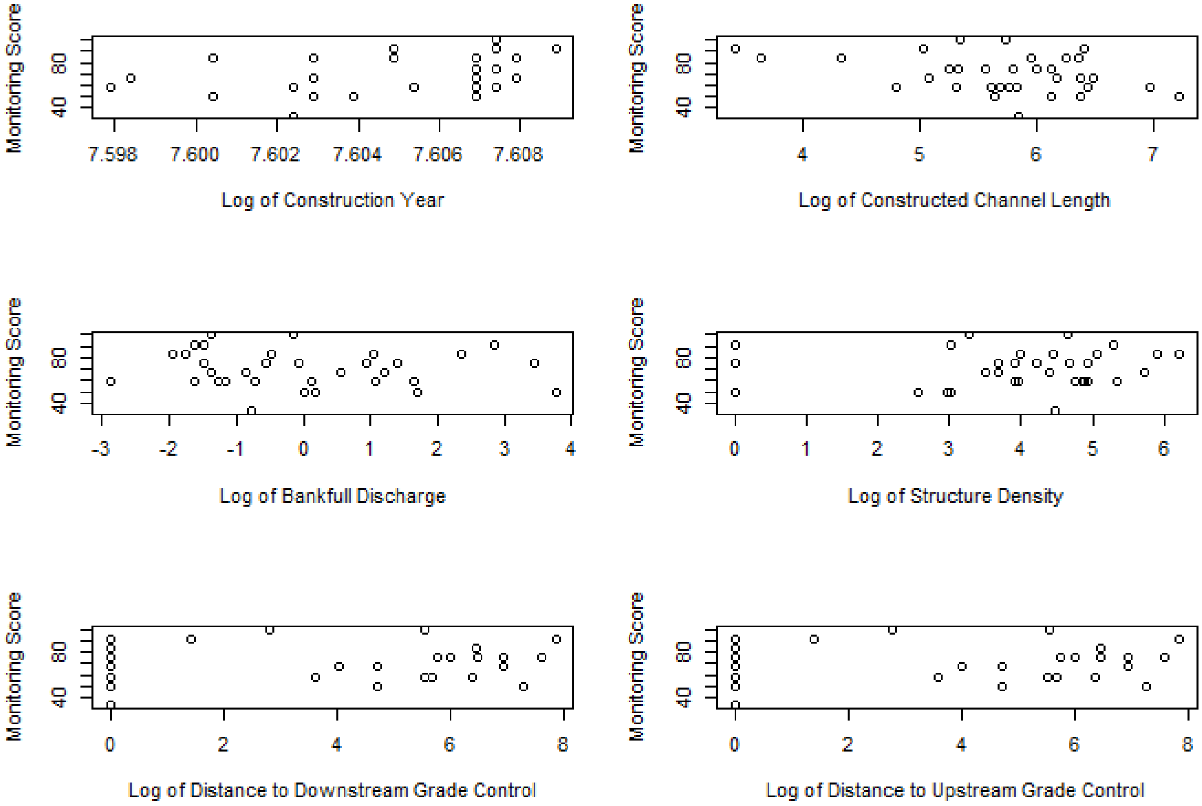


Figure D-6 Monitoring score vs project-level variables continued

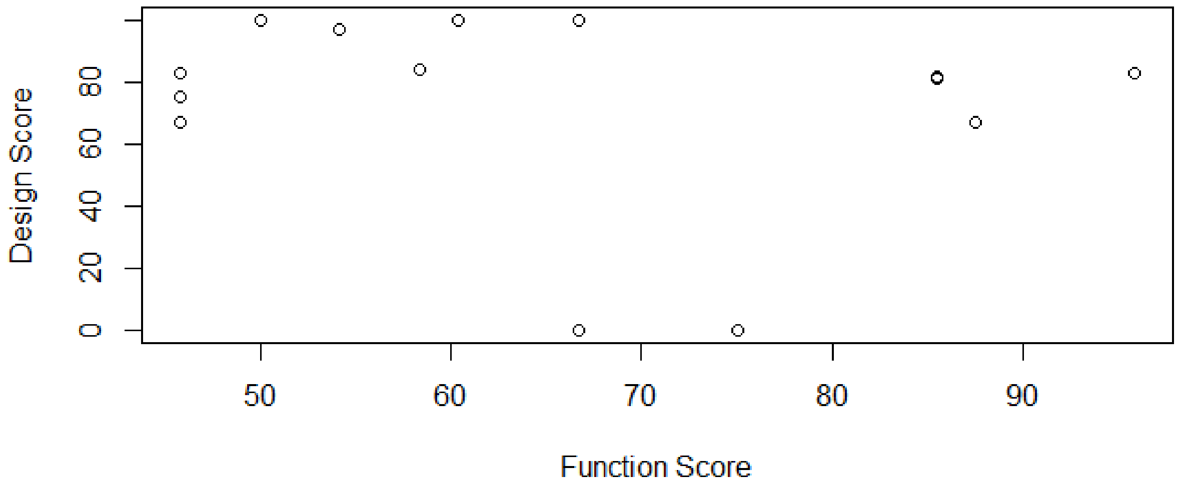


Figure D-7 Design Score vs Function score

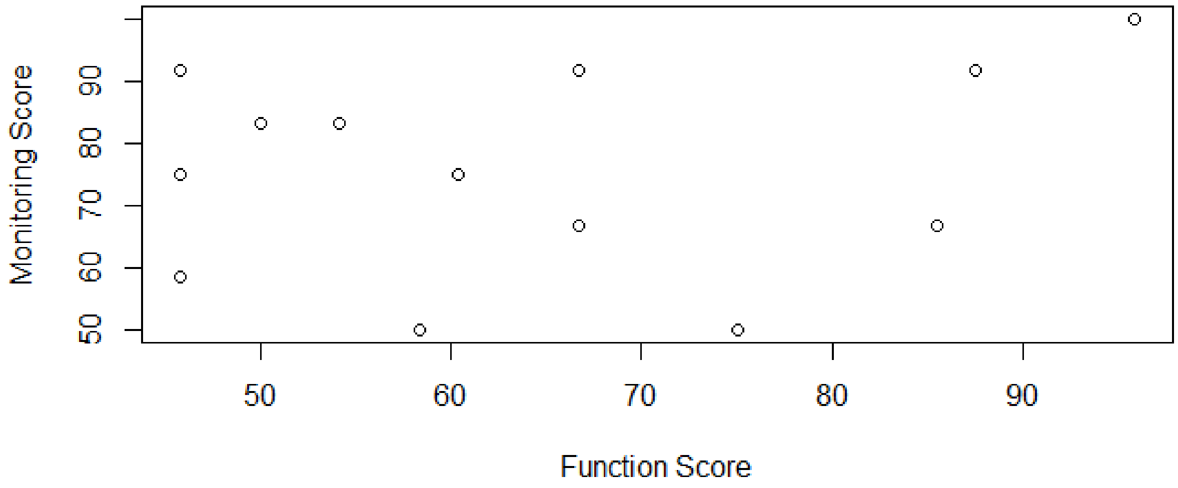


Figure D-8 Monitoring Score vs Function score

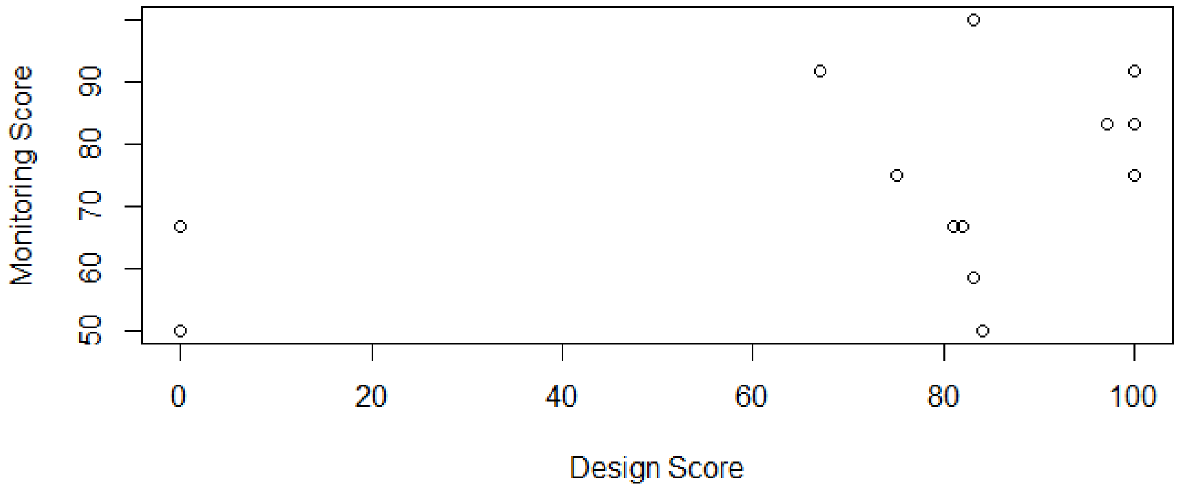


Figure D-9 Monitoring Score vs Design score