Improving the Success of Stream Restoration Practices – Revised and Expanded
Final Report
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1. Awardee Information

Organization Name: Virginia Tech
Project Leader: Tess Thompson
Grant Number: 13970

2. Project Summary

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

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

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

Stream restoration is frequently undertaken in urban watersheds to reduce channel erosion and sediment and associated nutrient loads, and to protect infrastructure. However, study results indicated that increased development within the contributing watershed following project construction was correlated with reduced design lifespan, despite the presence of stormwater management practices. Therefore, future development should be considered in stream restoration designs. Additionally, projects in larger watersheds and catchments with higher discharge and specific stream power were less durable, likely due to greater hydraulic

forces on the channel and instream structures. This finding was supported by the positive correlation between bed particle size and design success. Therefore, the use of larger rock sizes is important for channel stability in urbanized watersheds where channel migration cannot be allowed to protect infrastructure. Because instream structures limit natural channel migration and are typically constructed with materials of sizes that are not naturally found in these stream systems, existing stream physical processes will not maintain these structures; therefore, organizations should plan for routine monitoring and maintenance of stream restoration projects where instream structures are used.

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

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

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

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

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

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

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

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

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

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

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

3. Restoration Research Award Program Narrative Questions

a. What was/were your key restoration research question(s)?

1. Are specific watershed, site, or design characteristics that are correlated with a greater risk of project or structure failure?
2. Should 2D HEC-RAS models be used for stream restoration design?

b. What are the results for your research question(s)?

- See summary provided above, as there are numerous watershed and design characteristics associated with successful projects and in-stream structures.

c. List and describe the regulatory presentations and trainings provided.

Withers, U.S., Thompson, T., and Smith, E. Linking stream restoration success with watershed characteristics. Presented at ASCE Environmental Water Resources Institute conference, Pittsburgh, PA, May 19-23, 2019.

Withers, U.S., Thompson, T., and Smith, E. Linking stream restoration success with watershed characteristics. Presented at American Ecological Engineering Society conference, Asheville, NC, June 3-6, 2019.

Withers, U.S., T. Thompson, E. Smith, and W.C. Hession. 2019. Linking stream restoration success with watershed, practice, and design characteristics. Presented at the Mid-Atlantic Stream Restoration Conference, Baltimore, MD, Nov 18 - 20 2019.

Thompson, T. 2020. Linking stream restoration success with watershed and design characteristics. Presentation at the Pooled Monitoring Forum: Restoration Research to make Science and Regulatory Connections, June 9, 2020.

Thompson, T. 2020. Instream structures: Existing design guidance and research insights. Presentation to the Maryland Stream Restoration Association, Nov 5, 2020.

Smith, B.S., Thompson, T. 2021. On the design of instream structures in the mid-Atlantic United States: An investigation of the design, project, and watershed variables that affect success. Presented at the 2021 American Ecological Engineering Society Conference, Virtual, May 25-26, 2021.

Withers U.S., Thompson T., Smith E. 2021. Linking stream restoration success with watershed and design characteristics. Presented at ASCE Environmental Water Resources Institute conference, June 7-11, 2021.

Thompson, T., Smith, E. 2021. Improving the success of stream restoration practices. Presentation at the Pooled Monitoring Forum, June 16, 2021.

d. How can the findings be used for the regulatory community, for practitioners, for researchers, and others?

- It is recommended that stream restoration projects undertaken to mitigate stream impacts be targeted in watersheds that have similar or less urban land cover as the watershed where the impact occurred. This siting criterion will increase the likelihood that the impacted stream functions can be restored.
- Study results indicated that increased development within the contributing watershed following project construction was correlated with reduced design lifespan, despite the presence of stormwater management practices. Therefore, future development should be considered in stream restoration designs.
- The use of larger rock sizes is important for channel stability in urbanized watersheds where channel migration cannot be allowed to protect infrastructure.
- Because instream structures limit natural channel migration and are typically constructed with materials of sizes that are not naturally found in these stream systems, existing stream physical processes will not maintain these structures; therefore, organizations should plan for routine monitoring and maintenance of stream restoration projects where instream structures are used.
- Because stream restoration success is multi-faceted and can significantly vary based on assessment method (biological function, geomorphic function, infrastructure protection), it is important that specific, individual goals are stated for each project and that monitoring requirements be targeted to assess each project goal.
- In designs where bank stability is not critical, the use of dense woody vegetation with coir fiber fabric is recommended instead of stone toe, as woody vegetation is less expensive, easier to replace, and has decreasing failure risk as compared to stone toe structures, as vegetation stability and density increase with time as the vegetation grows.
- Stream restoration projects should take into account potential changes in watershed hydrology and sediment supply due to future development.
- Development of national design standards (such as by the American Society of Civil Engineers) is recommended to improve structure performance and to minimize liability for professional engineers, as concerns over professional liability can lead to more conservative stream restoration designs and the use of hard materials, such as boulders, since design data are more available for rock than for wood and live vegetation.
- It is recommended that Maryland update the 2000 MDE design guidance for stream restoration to reflect recent research findings.
- It is recommended that instream structures, particularly those constructed of rock, be used only for infrastructure protection or to protect adjacent stream reaches from channel degradation, such as incision caused by knickpoint migration. Additionally, regulatory agencies should allow some degree of channel movement for stream restoration projects where infrastructure protection is not critical.
- Comparison of the predicted water surface elevations, velocities, and shear stresses for the 1D and 2D HEC-RAS models indicated the 2D model better represented stream hydrodynamics overall. Additionally, the 2D model captured areas of high shear along the channel boundary that could cause structure flanking.

e. What future research is needed?

- More research is needed to quantify the fluvial erosion resistance (i.e. allowable stress) of typical riparian vegetation communities in the mid-Atlantic at different growth stages for use in streambank erosion analyses to reduce the hardening of stream channels in urban watersheds. In other words, if engineering design data are available, designers may be more likely to use vegetation in stream restoration designs rather than material for which we have good data, such as rock.
- Similarly, additional research is needed to provide engineering design data for materials such as wood, and the use of wood in stream restoration design. For example, where should large/small wood be placed in the stream channel? What type of density is needed to provide bank erosion control?
- Research is needed to determine if instream structures that are promoted as creating habitat, such as cross vanes, actually result in increased fish biomass, benthic macroinvertebrates, etc.
- Given that constructed riffles are commonly used in stream restoration, additional research into the design and placement of constructed riffles in the stream planform is needed. Additionally, given that riffles are a significant habitat for benthic macroinvertebrates, the impact of different designs on benthic communities is also recommended. Should finer material be "washed in" or pre-mixed before placement?
- Additional research is needed to define acceptable levels of channel migration in the mid-Atlantic region that do not result in excessive sediment loads or biological impairment for use in project assessments.

f. How and when did you provide the data for this project to the Chesapeake Bay Trust?

- Research data were provided to the CBT as a Microsoft Access database and a folder of HEC-RAS files in a Google drive on 6/28/2021.
- We will also share the HEC-RAS files with the county/agency staff.

g. Provide the citation for the scientific paper in the peer-reviewed literature that was submitted.

- Two peer-reviewed publications are currently under development and will be submitted for peer review in July and August 2021.

4. Project evaluation and lessons learned

The underlying premise of this project was to treat prior stream restoration projects as experiments, to see what could be learned from them, with the goal of improving stream restoration siting and design. There are two ways to approach such research: study a few sites in detail or conduct a more cursory study of a large number of projects. We selected the latter approach. Our original study plan was to assess the projects based on the monitoring reports. It soon became evident that the monitoring reports did not have sufficient detail to really assess the project and typically only assessed the first three years post-construction. Field assessment of the projects provided a much more comprehensive and in-depth assessment of the projects.

Ultimately, project “success” was achieved because statistically significant and physically meaningful results were revealed in the data. One consistent result/success is the influence of land cover, specifically urban land cover, on project success. It is generally understood in the stream restoration profession that stream restoration design in urban watersheds is challenging due to the limited availability of land for floodplain access, citizen concerns regarding tree removal, FEMA FIP requirements, and the flashy hydrology. This study provided objective, scientific evidence that projects constructed in urban watersheds are less likely to reestablish geomorphic processes and have durable design features. Given the number of stream restoration projects conducted in urban watersheds to meet MS4 permit requirements, this result is concerning regarding the overall effectiveness of stream restoration, as currently practiced, in achieving the Bay TMDL goals. However, study findings also suggested that stream restoration design was improving over time.

Another impactful finding was that differences among stream restoration projects were as significant as specific design features of some instream structures. This finding indicates that improvements in design review and construction oversight would likely have a direct impact on the success of stream restoration projects.

While not part of a specific research question, a significant contribution of this project was to collect design data and analyze a large number of stream restoration projects. These data have been shared with other researchers and hopefully will be available to help develop/plan future research projects.

The greatest challenge to stream restoration research in general is the fundamental nature of stream systems: streams, and the hydrology that drives them, operate on time scales that are much longer than human planning or funding horizons. Additionally, streams are complex systems where multiple interdependent variables control stream functions. So, it is difficult to control all of the relevant variables in designing a field-based research project and it is difficult to develop a sufficiently large dataset (i.e. take enough “samples”) to determine statistically significant treatment effects, given the inherent variability in the data. In many cases, the necessary sample size cannot even be determined a priori because there are no available data to even estimate sample variance. The reality of conducting field research is that there is a certain amount of luck involved. Our project benefited from the widely and unusually wet year in 2018, which stress-tested all of the projects in the study prior to our field assessments.

A greatest challenge with this particular research project was locating all of the necessary project files. While several localities were very cooperative and their agency staff spent considerable time and effort tracking down design plans and monitoring reports, documents for some older projects (20+ year old) simply could not be located. Additionally, some municipalities were hesitant about providing information to us because stream restoration is controversial. Given that digital storage is relatively easy and inexpensive now (as compared to the mid-1990s), it should be easier to locate project files in the future.

The only aspect of the project that I would have changed would have been to include field documentation of pools that were constructed as part of the project. It was clear that many of the pools had filled in or formed in different locations. Having documented the location of existing pools would have provided insight into pool spacing for future designs.

My advice to anyone conducting research, particularly research with a lot of data from multiple sources, is to have a detailed and thorough data management plan. This project was large and had multiple graduate students working on it. In these situations it is critical to store the raw data in a database, because spreadsheets are easily changed. It is also important to check all data entry and to clearly identify units and how the data were developed.