ABSTRACT

HAMLIN, KIMBERLY MAE SPANGLER. The State of Stream Restoration in the North Carolina Piedmont: An Assessment of Instream Structure Durability and Stream Bank Erosion. (Under the direction of Dr. Theodore Henry Shear).

I evaluated 583 instream structures in 19 stream restorations that were between 4 and 12 years old, focusing on damage to structure components and surrounding banks. These structures included rock cross vanes, single arm vanes, j-hook vanes, rootwad revetments, and boulder revetments. I also calculated Bank Erosion Hazard Indices (BEHIs) for the stream restorations and six reference streams. A threshold value for both structure condition and BEHI score was specified. This threshold value indicated the point where structure and bank condition may be questioned. Rock cross vanes and rootwad revetments were the least durable, reaching the threshold value in years 4 and 6 respectively. J-hook vanes and single arm vanes did not pass the threshold value until years 11 and 10 respectively. Boulder revetments approached but never reached the threshold value and were the most durable structures. The majority of BEHI scores in stream restorations and references were above the threshold value. No relationships were found between structure condition, structure density, or number of structures per stream and BEHI scores. This suggests erosion is the result of large scale disturbances within the watershed to which both restorations and references are reacting similarly. Limiting the number of instream structures will reduce costs associated with stream restoration. Instream structure design should be critically examined to improve or remove structures that are not contributing to restoration success. Collecting pre-restoration erosion data and reference stream bank data annually will also be useful in determining success by providing tangible evidence of improvement during the monitoring period.

The State of Stream Restoration in the North Carolina Piedmont: An Assessment of Instream Structure Durability and Stream Bank Erosion

by
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DEDICATION

For Mom and Dad. “Soon” has finally come.

"Conservation is paved with good intentions which prove to be futile, or even dangerous, because they are devoid of critical understanding..."- Aldo Leopold (1949)

BIOGRAPHY

Kim was fortunate enough to grow up in a West Virginia family who enjoyed touring the most beautiful state in the nation with their two children in tow. As a youngster, Kim felt happiest when sitting in front of a fire eating s'mores or perching herself on a boulder to bait her fishing hook and admire the mountain laurel. It took her some time to realize how much it all meant to her; approximately 20 years.

Kim began college in marine science and switched to biological sciences after her freshman year. More unsure than unguided, she made her way through the curriculum in hopes of entering veterinary school upon graduating from North Carolina State University. This was not in the cards, thankfully, and she went on to obtain an associate's degree in environmental technology from Wake Technical Community College. She remembered all those days spent fishing and running around the forest. Her epiphany inspired her to research environmental graduate programs, and her short list was eventually narrowed down to the natural science master's program with a technical option in ecological restoration at North Carolina State University.

Never one to focus on one thing at a time, Kim also completed a 50 mile race, married her law school student fiancé, and purchased a home. Although she does not regret these events, she does not recommend them to those wishing to finish their degree on time.

The future is always uncertain, but as Kim is forced into the real world she knows the strong support of her family and friends will guide her through life as it did through school. To them she is very thankful.

ACKNOWLEDGMENTS

There are many who deserve more than mere acknowledgments. My parents were instrumental in making secondary education possible. My grandmother taught me when life gets tough, just get tougher. My brother kindly allowed me to squat in his home in exchange for cleaning services and good company. He also introduced me to the wonderful world of good beer, and to that I am grateful.

Thanks to my husband, Blake, who attended law school and worked full time so we could eat food with nutritional value. I know you feel you could have done more, but your love and support was all I needed, and you went above and beyond to prove both.

And of course thanks go to my family and friends who offered words of advice and encouragement along the way. I hope to one day return the favor.

Logistically this would not have been possible without the guidance of my committee members: Dr. Theodore Shear, Dr. Ryan Emanuel, and Dr. Paige Puckett. Your direction forced me to always ask, “Is this important news?”

Hours in the field were luckily spent with entertaining folks: Drew Blake, the faithful assistant; Megan Malone, my predecessor into the world of stream restoration thesis work; Fang Yuan who never complained once about getting stuck in blackberry bushes; and Yari Johnson who provided hours of great stories (and also educational advice). This was supplemented by considerable input from my lab crew Pat Chess, Jose Jimenez, Amanda Johnson, Kim Shumate, Ashley Steele, Joseph Sullivan, and Ryan Unks.

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INTRODUCTION

My goal was to determine the durability of instream structures in North Carolina Piedmont stream restorations that were four to twelve years old. I was interested in the effect of age on incidences of instream structure failure. In addition to structure assessments, I evaluated bank erosion potential to detect relationships between instream structure installation and stream bank stability.

Stream restoration strives to improve water quality through reducing erosion. The associated expense has raised questions to the sustainability of the practice; especially in North Carolina. A recent study found the median stream restoration project cost in North Carolina was $596,518 compared with $18,800 nationwide (Sudduth, *et al.*, 2007). The higher cost is due to an increasing number of stream restorations in the southeast involving stream channel reconfigurations and incorporating engineered instream structures (Sudduth, *et al.*, 2007).

Structures are installed to stabilize restored stream channels and protect stream banks (Brown, 2000); however, some exhibit decreased structural integrity over time. High velocity flows cause damage and erosion near their placement (Ehlers, 1957; Frissell & Nawa, 1992; Roper, *et al.*, 1998; Miller & Kochel, 2010). The structures are often misused or installed incorrectly leading to expensive repairs (Frissell & Nawa, 1992). Despite this, structures have seen little changes in their designs since inception (Thompson & Stull, 2002). Most studies focus on regions outside of North Carolina where improving water quality and habitat for game fish are the main drivers of stream restoration. The expense of installation and repair has necessitated a study to determine durability of these structures and effects on surrounding banks in North Carolina streams.

Natural Channel Design

Natural channel design, developed by David Rosgen (1994), is one method of stream restoration practiced in the United States. This method uses characteristics of natural stream morphology and data on relatively undisturbed reference streams to design the dimensions of the stream to be restored (Rosgen, 1994). Large deviations from the designed stream conditions after restoration indicate instability (Rosgen, 1996). Stabilization is important in reducing sediment from washing into the stream as flood waters move through the channel. A majority of the stream restoration projects in North Carolina are designed using this technique, and most of them rely on instream structures to stabilize the restored or newly created channel (Miller & Kochel, 2010).

Critics of natural channel design argue natural lateral migration of the stream channel is reduced, partly due to bank hardening as a consequence of the rigid structures installed (Lave, 2009). This prevents the channel from naturally adjusting to changes in the frequency and duration of floods and could lead to damages to instream structures. One study found 60% of instream structures in southwest Oregon and Washington were damaged and 18% had failed after two to ten year magnitude floods (Frissell & Nawa, 1992). They assessed 161 fish habitat structures in 15 restorations that were 2 to 8 years post construction to determine habitat creation success. Miller and Kochel (2010) found that stream channels in North Carolina restored using natural channel design were prone to instability at instream structure locations due to erosion and deposition. They found approximately 20% of structures were damaged, impaired, or had failed in 26 restored streams in the state (Miller & Kochel, 2010). They studied restorations one to six years after construction located mainly in the western mountains with a few located in the central Piedmont.

Types of Structures

Grade control structures, such as cross vanes, weirs, and drops, are installed when there are lateral constraints on channels with steep slopes. The restored or created channel must gently drop in elevation to meet the existing channel at the terminus of the restoration. This is common practice in urban areas with infrastructure or landowner concerns near the stream edge (Bernhardt & Palmer, 2007). Grade control decreases flow velocity and reduces the erodible forces on the banks resulting in less sediment washed downstream. One popular grade control structure is the rock cross vane. It consists of a cross-channel sill boulder and two arms made from groups of boulders tied into the banks on both sides of the sill. The vane is backfilled to prohibit water movement through the structure. When water flows over the sill it creates a scour pool on the downstream side which provides aquatic habitat and keeps water flowing in the center of the channel.

Vanes and deflectors concentrate flow away from the banks to reduce erosional forces (Rosgen, 1996). Two types are single arm vanes and j-hook vanes. Single arm vanes are groups of boulders tied into the bank on the upstream side of the structure that direct water away from the bank on the downstream side. J-hook vanes are similar in design to single arm vanes but have several boulders that curve out into the channel upstream of the arm to create a “J” shape. Water flowing around the spaces in these boulders scours the bed and creates habitat.

Bank protection is also provided by rootwad and boulder revetments (Rosgen, 1996). Rootwads are root balls attached to large tree trunks that are pushed into the banks until only the root ball is exposed. Aquatic habitat is created when water scours the bed below the root ball. This less rigid design is sometimes referred to as a “soft” engineered structure. In contrast, boulder revetments are hard engineered structures and consist of one or more boulders placed near banks.

Modes of Failure

Grade control and flow manipulation structures share similar challenges to their structural integrity. Arm vanes, cross vanes, and j-hook vanes can experience arm washout, boulder washout, and erosion around the vane. Failure is often caused by piping, where water passes through rather than over the structure (Brown, 2000). Side cutting occurs when water is directed at the banks when it is not passing over the structure (Brown, 2000). Undercutting, boulder movement, flow directed at banks, and exposed banks compromise the structures by damaging components or by depositing sediment behind the structures that can affect durability (Miller & Kochel, 2010).

Rootwad revetments can experience side cutting (Sylte & Fischenich, 2000) as well as rapid decay of the root ball (Maryland Department of Environment, 2000). Rootwad and boulder revetment failures include washout of part or all of the structure, erosion nearby caused by undercutting and piping, and direct contact of stream flow with banks. A majority of these instream structures involve complicated designs and installations leading to potential problems.

Purpose of the Study

Examining restorations between four to twelve years old will give insight to the durability of instream structures and stream bank stability in the Piedmont of North Carolina. Previous studies focused on overall instream structure durability or on stream restorations in different regions of the United States with the goal of improving fish habitat. Evaluating stream bank stability will be important in assessing similarities between stream restorations and reference streams.

METHODS

Site Selection

Sites were selected from publicly available stream restoration project monitoring reports on the NC Ecosystem Enhancement Program website. Nineteen restoration sites were chosen in the North Carolina Piedmont that were between four and twelve years old. The reports often included reference streams, and six were evaluated for erosion potential. Stream restoration sites are in Table A1 and reference streams are in Table A2 (Appendix A).

Assessment of Instream Structure Durability

Durability was determined by examining modes of failure of individual rock cross vanes, single arm vanes, j-hook vanes, rootwad revetments, and boulders. Each structure was assigned a score of zero to five. A score of zero indicated there was little to no damage to the structure components or surrounding banks, and the structure was functioning as intended. A score of three indicated concerning damage to the structure and banks which compromised structure function but not to the extent it was ineffective. A score of five indicated severe damage to the structure and complete failure of function resulting in severe erosion to surrounding banks. A structure score of three or more was designated as the threshold value where structural integrity may be questioned. Each structure was photographed and catalogued.

Rock Cross Vanes

Cross vanes were assessed using Puckett's Rock Cross Vane Rapid Assessment Tool (Puckett, 2007, unpublished data). This worksheet provides a rating scale to determine failure of rock cross vanes. A total of 203 rock cross vanes were assessed.

Vanes and Boulders

Rating scales were devised to identify modes of failure for single arm vanes, j-hook vanes, and boulders by observing these structures in stream restorations. The worksheet was modeled after Puckett's tool since these structures have similar components to rock cross vanes. A total of 98 single arm vanes, 101 j-hooks, and 69 boulders were assessed.

Rootwad Revetments

Rootwad revetments were assessed using a rating scale devised from observing rootwads in restored streams. These "soft" engineering structures protect banks until natural woody vegetation is established (Rosgen, 1996). The presumption is that once the rootwads decay, natural woody vegetation will stabilize the banks. A total of 112 rootwad revetments were assessed.

Bank Erosion Hazard Index (BEHI)

Channel stability was measured using a modified version of David Rosgen's Bank Erosion Hazard Index (BEHI) worksheet (Rosgen, 1996; Rathbun, 2008). This worksheet provides scores for characteristics of channel conditions to generate an overall score related to erosion potential (Rosgen, 1996). Banks with high BEHI scores are quickly eroding and in danger of causing severe damage (score of 30 or more); lower BEHI scores indicate more stable conditions (score of 0-30). A score of 30 was designated as the threshold value for both stream restorations and reference streams. The following is a list of BEHI criteria and units.

- Bank height/bankfull depth (ratio)
- Root depth/bank height (ratio)
- Root density (%)
- Bank angle (degrees)
- Surface protection (%)

Points are also given for type and status of bank material. Bank material type can move the BEHI score up or down (bedrock = low erosion potential, sand = high erosion potential), and stratified, unstable layers increase the BEHI score. Bank characteristics were evaluated at a designated point to obtain a BEHI score. The length of stream section with similar bank conditions was measured. Measurement ended when there seemed to be an apparent change in bank structure or stability. The aim was to generate BEHI scores for the majority of the stream restoration reach. Obtaining BEHI scores is common practice in the last year of monitoring of North Carolina stream restorations.

Data Analyses

Mean structure condition scores were compared with stream restoration age. Structures were assumed to be in perfect condition at construction (score zero at age zero). Many monitoring documents report components as 100% functional at the time of construction. This includes structure condition and bed and bank conditions. Asymptotic curves were fit to the data using SigmaPlot (SigmaPlot, Version 8, Systat Software). Structure condition scores were also used to calculate half-lives for structure types.

Weighted averages of BEHI scores were calculated for each stream. Perfect bank conditions were assumed at age zero and a chronosequence of the scores was created using SigmaPlot. As with structure condition scores, an asymptotic curve was fit to the data starting at age zero. Another asymptotic curve was fit starting at age four to detect if the assumptions affected the output.

Scatterplots of mean structure condition scores and weighted BEHI scores for stream restoration sites were created using JMP 8 (JMP, Version 8, SAS Institute Inc.). Total number of structures and structure densities per stream were also compared to weighted BEHI scores using JMP 8. Since rootwad revetments have different objectives than hard engineered structures, all analyses were calculated with rootwads included and excluded.

RESULTS

Structure Durability

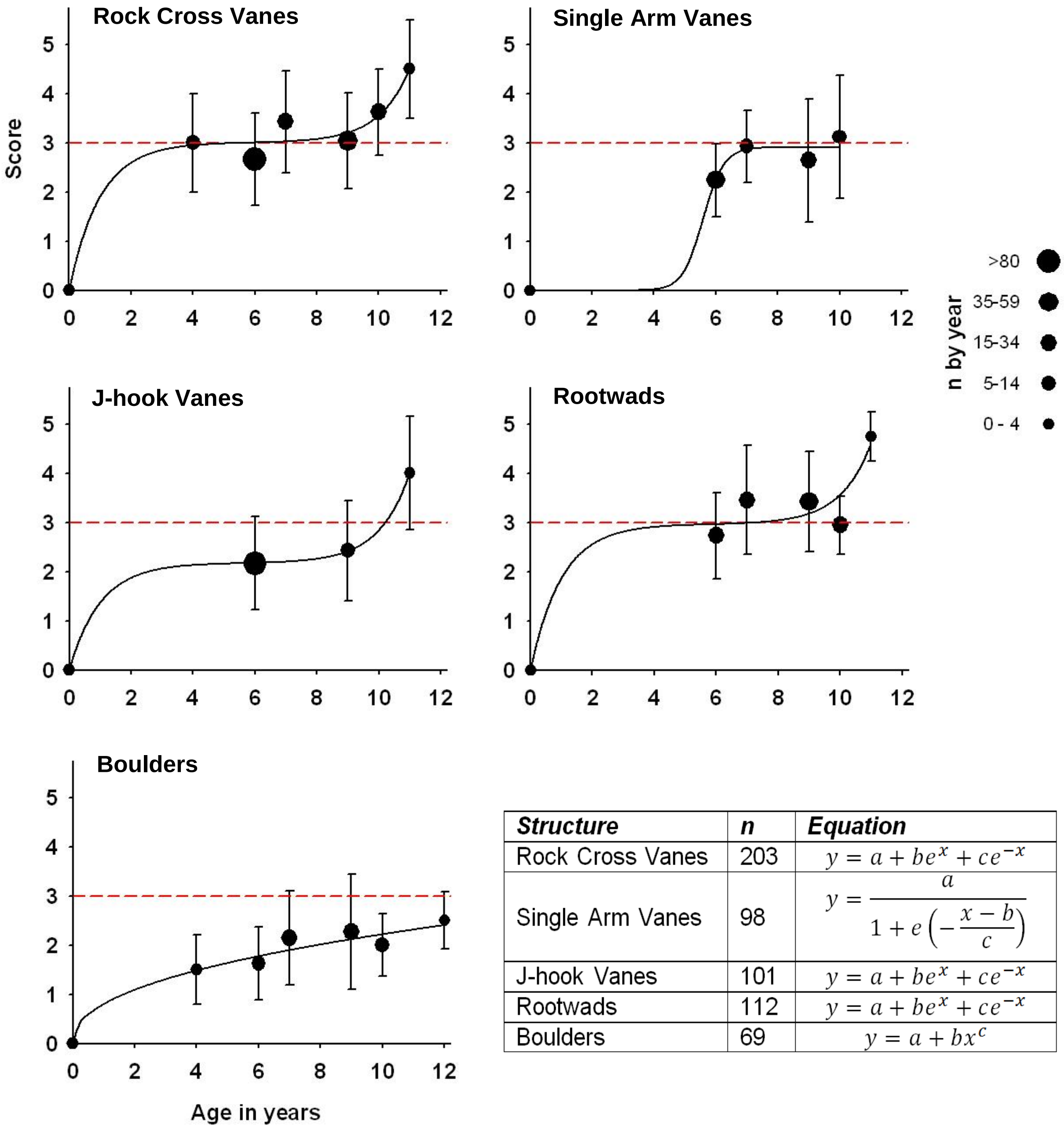
Mean rock cross vane scores reached the threshold value at year four and remained steady through year nine. Structural integrity decreased after year nine, reaching an average score of 4.5 by year eleven (Figure 1a).

Mean single arm vane scores at year six were approximately two. Scores approached the threshold value in years seven through nine and reached the threshold value in year ten with a score of approximately 3 (Figure 1b).

J-hook vane mean scores in years six and nine were just above two, but by year eleven the average score was approximately four (Figure 1c).

Rootwad revetment mean scores were similar to scores for rock cross vanes. Average scores reached the threshold value by year six and were steady until year ten (Figure 1d). At year eleven the average score was approximately five.

Boulders exhibited the least damage over time. From years four to twelve the average score slowly climbed to about 2.5 (Figure 1e). Only one stream restoration was 12 years old and contained only boulders according to design plans.



Structure	***n***	***Equation***
Rock Cross Vanes	203	$y = a + be^{x} + ce^{-x}$
Single Arm Vanes	98	$y = \frac{a}{1 + e\left(-\frac{x-b}{c}\right)}$
J-hook Vanes	101	$y = a + be^{x} + ce^{-x}$
Rootwads	112	$y = a + be^{x} + ce^{-x}$
Boulders	69	$y = a + bx^{c}$

Figure 1 – Average Condition Scores of Instream Structures in Each Age Class. Asymptotic curves were fit for average condition scores of (a) rock cross vanes, (b) single arm vanes, (c) j-hook vanes, (d) rootwad revetments, and (e) boulder revetments. The error bars represent 1 standard deviation. A score of three and above was designated as the threshold value where structural integrity was compromised.

Table 1 – Structure Type Half-lives

Structure	***Half-life (years)***
Rock Cross Vanes	6.5
Single Arm Vanes	10.9
J-hook Vanes	15.6
Rootwads	4.9
Boulders	24.3

Table 1 shows the half-lives for each structure type. Rootwads have the shortest half-life at 4.9 years, followed by rock cross vanes with a half-life of 6.5 years. Single arm vanes and j-hook vanes have half-lives of 10.9 years and 15.6 years respectively. Boulders have the longest half-life at 24.3 years.

Bank Erosion

Weighted BEHI scores in stream restorations approached the threshold value at age four in both curves (Figure 2). The BEHI scores surpassed the threshold value by age six and remained relatively constant through age twelve (Figure 2). The average weighted BEHI score for reference streams was 34, with a range of 29 to 42.

Figure 2 – Weighted BEHI Scores for Stream Restorations and Reference Streams. A BEHI score of 30 or more was designated as the threshold value where bank erosion became concerning. Asymptotic curves were fit starting at ages 0 and 4 to note if assumptions affected the output.

Structure and Bank Erosion Relationships

Structure condition was not related to average weighted BEHI scores (Figure 3 a-b). Weighted BEHI scores were also not related to the total number of structures per stream (Figure 4 a-b) and the structure density per stream (Figure 5 a-b). Excluding rootwad revetments from the analyses had no effect.

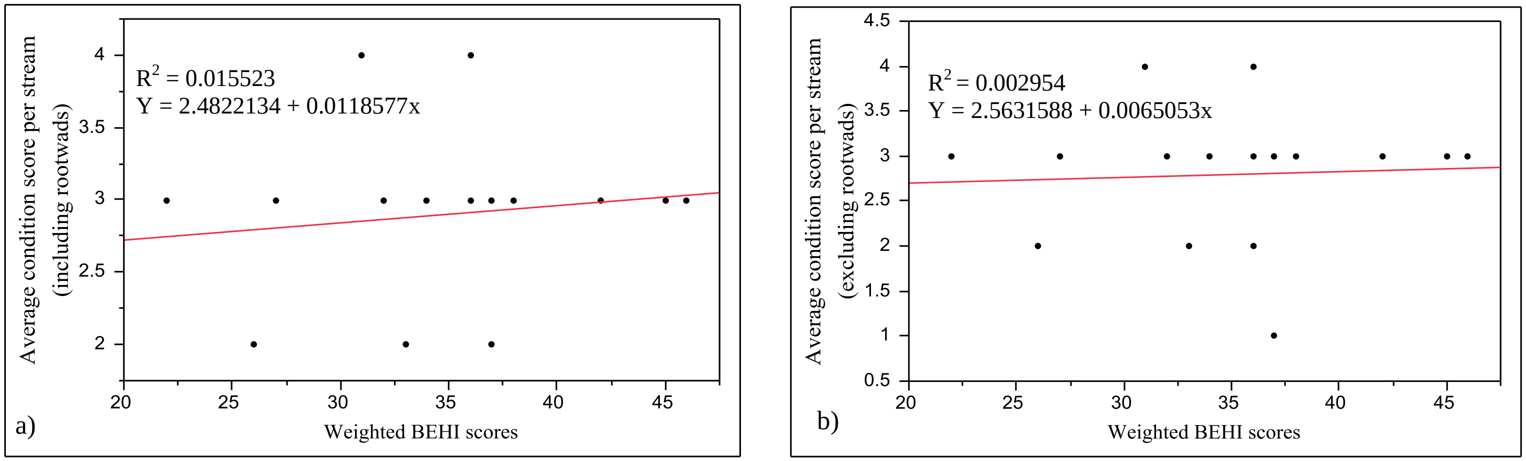


Figure 3 – Comparison of Average Structure Condition Scores and Weighted BEHI Scores a) including rootwads and b) excluding rootwads.

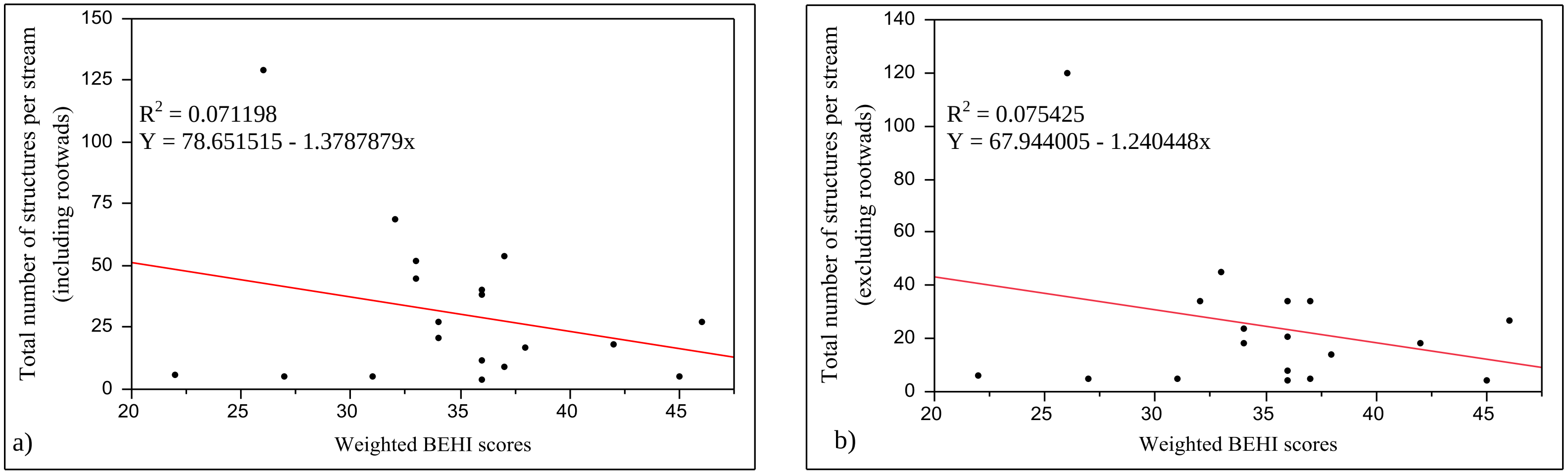


Figure 4 – Comparison of Total Number of Structures and Weighted BEHI Scores a) including rootwads and b) excluding rootwads.

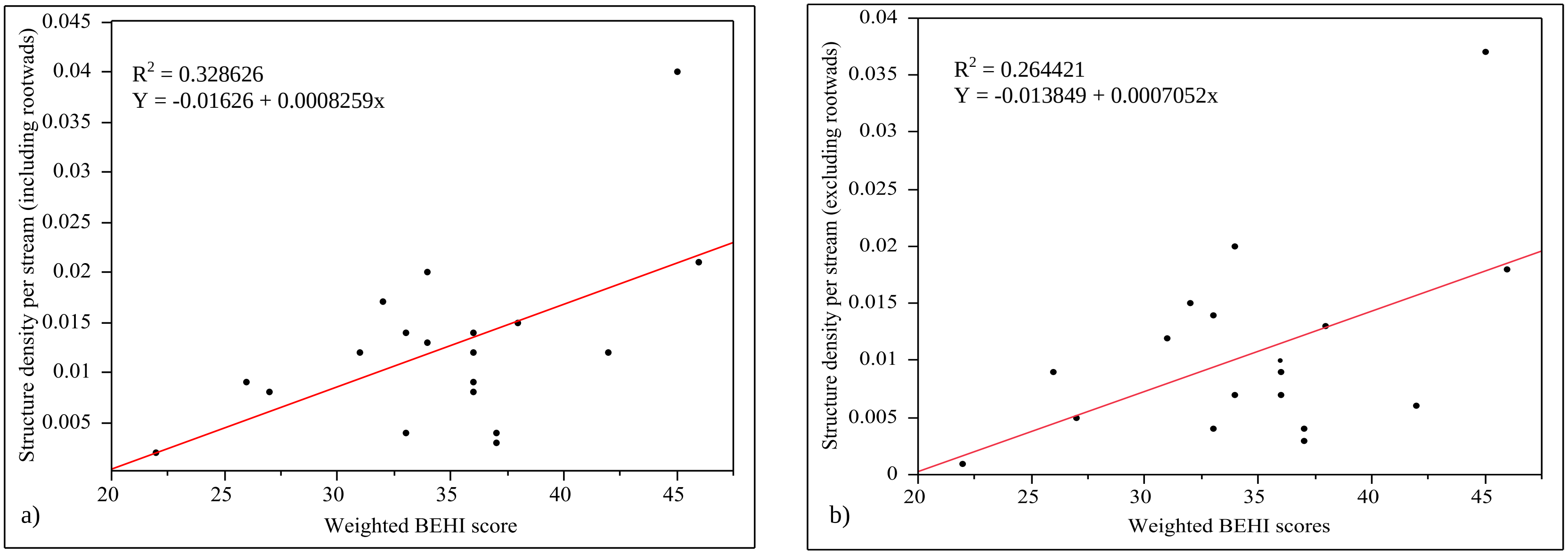


Figure 5 – Comparison of Structure Density and Weighted BEHI Scores a) including rootwads and b) excluding rootwads.

DISCUSSION

Several studies have examined the durability of instream structures, but many are from regions where creating and restoring fish habitat is the main goal of stream restoration. One study reviewed literature and gives an example instream structure lifespan of 15-20 years (Hicks and Reeves, 1994). The investigators wanted to determine if instream structures could potentially promote fish habitat in New Zealand. Another study from southwest Oregon and Washington estimated the half-life for instream structures at 10-15 years (Frissell and Nawa, 1992). A United States Department of Agriculture report for the Klamath River tributaries projected lifespans for instream structures similar to single arm vanes, j-hook vanes, boulders, and rootwads at 50 years (Olsen & West, 1991). This was calculated using the age of the structure and the percentage of the structure intact. However, instream structures in North Carolina Piedmont stream restorations are degrading within five to eight years after installation.

Of all the hard engineered structures, rock cross vanes suffered the highest occurrences of damage in this study. The half-life for rock cross vanes was 6.5 years. There were problems with arm and sill failure due to insufficient backfill and improper alignment. Rock cross vanes also experienced erosion directly downstream of the arms either due to side cutting of water or flow expansion out of the vane. This was preventing the establishment of woody vegetation in some cases. Miller and Kochel (2010) reported similar results with rock cross vanes experiencing the most instances of damage among the structures they surveyed. Rock cross vanes are complex structures involving many footer and arm boulders. Correctly sizing boulders and properly backfilling the vane are important in decreasing spaces in the structure where water can pipe through. The complicated design leads to difficult installation and repair which can become expensive.

Single arm vanes were the third most durable structures. The scores passed the threshold value at age ten and the half-life for single arm vanes was 10.9 years. Problems resulted from erosion behind boulders which compromised stability. This was either due to improper alignment of the vane or insufficient backfill which allowed water to move behind the arm and dislodge boulders. Occasionally, the arm vanes were too steep which resulted in undercutting of the footer boulders. Erosion occurred once the boulders were washed away from the bank. Although not as complicated or expensive to install and repair as rock cross vanes, careful placement and sizing of boulders is still important to the success of these vanes.

J-hook vanes were more durable than single arm vanes, and surpassed the threshold value after nine years and had a half-life of 15.6 years. Problems and causes for j-hook vane failures were similar to those for single arm vanes. In addition, j-hook vanes experienced problems with scour pool development when arm boulders fell into the pool.

Rootwad revetments reached the threshold value six years after construction, but held constant up to year ten. The half-life for rootwads was 4.9 years. Rootwads were also highly impacted according to Miller and Kochel (2010). Most problems resulted from bank erosion behind the root ball leading to shifting of the rootwad or footer boulders. Rootwad protection is only needed until woody vegetation becomes established; however, when parts of the structure fail, vegetation has a difficult time growing on the eroding bank. Other problems included the rootwad being installed too high from base flow exposing the majority of the rootwad to air.

The continued exposure of the moist root ball to air lead to faster decay of the root ball. This coupled with lack of vegetation reduced the stability of the structure.

Boulder scores approached but never reached the threshold value. Similar results were seen in coastal Oregon streams restored to improve fish habitat; all boulder structures were intact after ten years (House, 1996). This may be due to the simplicity of these structures. Many are placed near the bank to provide protection but do not require footers or other complicated components. Problems with boulders resulted from bed and bank erosion around the structures. Undersized boulders experienced movement during high velocity flows. The half-life for boulders was 24.3 years.

The average structure condition, total number of structures, and structure density were not related to weighted BEHI scores. This suggests erosion is the result of larger scale disturbances. Stream conditions deteriorated regardless of instream structures as evidenced by similar BEHI scores in reference streams. Reference streams are vulnerable to flash flooding and urban storm runoff; reasons prompting stream restoration in the first place. Consequently, the reference streams themselves were degraded but suitable because they shared similar characteristics to the desired channel to be created. However, restored streams with high BEHI scores do not appear successful in reducing the amount of sediment transported downstream. To ensure efforts to reduce erosion are working, bank erosion should be measured before construction begins to render more decisive conclusions on stream restoration success. Both restoration and reference stream bank erosion should be further investigated to identify causes of instability and monitored to observe if the banks stabilize.

Implications for Restoration

Stream restoration relies heavily on reducing erosion by installing instream structures; however, these structures are exposed to stressors that compromise their structural integrity. Damaged structures can alter the surrounding channel by directing flow toward the bank resulting in complete structure failure if proper repairs are not made. The long term sustainability of a stream restoration depends on the stream's capability of naturally stabilizing itself. Limiting the number of structures installed in stream restorations can reduce costs associated with installation and repair and allow for more natural migration of the stream channel. More effort can then be directed to pre-construction data collection, monitoring, and maintenance.

Watershed scale changes that affect the degraded channel should be closely studied. The information can be used to create a more resilient stream channel using instream structures only when necessary. Instream structure designs should be critically examined to determine which are successful and which need to be redesigned or abandoned. Open dialogue between contractors, designers, and academia can further our understanding of how stream restoration is evolving. With more research into all aspects of stream restoration we can only improve on the current state of the practice.

Conclusion

When a degraded stream is restored the banks are stabilized using bank hardening structures. This bank hardening is important to protect the newly formed stream channel; however, the channel is prohibited from adjusting to flood events as it would naturally. This alters the way water moves through the channel and has unintended consequences. The structures are subjected to high velocity flows that dislodge components which cause further damage and erosion.

Careful design and planning may help reduce the damage incurred by instream structures. More complicated structures should be installed as closely to the design as possible. The structure components should be sized correctly for the channel and the expected and predicted flows. Designing streams with fewer and less complicated structures will reduce repair costs after large flood events. Simple structures such as boulder revetments were the most durable in this study, while the most complicated structures, rock cross vanes and rootwads, were the least durable.

Ultimately, collecting baseline data on pre-construction bank conditions is the most important tool for advancing the practice of stream restoration. Bank conditions should stabilize in the newly created stream and continue to promote a healthy riparian area. Subsequent evaluations of restored bank conditions through the monitoring period compared with simultaneous evaluations of reference stream bank conditions allow for more concrete determinations of success and failure. This information will also be useful in evaluating the usefulness of instream structures.

REFERENCES

Bernhardt, E. S., & M.A. Palmer. 2007. Restoring Streams in an Urbanizing World. Freshwater Biology 52(4):738-751.

Brown, K. 2000. Urban Stream Restoration Practices: An Initial Assessment. Ellicot City, MD. Center for Watershed Protection.

Ehlers, R. 1956. An Evaluation of Stream Improvement Devices Constructed Eighteen Years Ago. California Fish and Game 42:203-217.

Frissell, C. A., & R.K Nawa. 1992. Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington. North American Journal of Fisheries Management 12:182-197.

Hicks, B.J., & G.H. Reeves. 1994. Restoration of Stream Habitat for Fish Using In-stream Structures. Restoration of Aquatic Habitats. Selected papers from the second day of the New Zealand Limnological Society 1993 Annual Conference. Department of Conservation.

House, R. 1996. An Evaluation of Stream Restoration Structures in a Coastal Oregon Stream, 1981-1993. North American Journal of Fisheries Management 16:272-281.

JMP, Version 8. SAS Institute Inc., Cary, NC. 1989-2007.

Lave, R. 2009. The Controversy Over Natural Channel Design: Substantive Explanations and Potential Avenues for Resolution. Journal of the American Water Resources Association 45(6):1519-1532.

Maryland Department of the Environment. 2000. Maryland’s Waterway Construction Guidelines. Maryland Department of the Environment Water Management Administration, Baltimore, MD.

Miller, J. R., & R.C. Kochel. 2010. Assessment of Channel Dynamics, In-stream Structures and Post-project Channel Adjustments in North Carolina and its Implications to Effective Stream Restoration. Environmental Earth Science 59:1681-1692.

Olsen, A. D., & J.R. West. 1989. Evaluation of Instream Fish Habitat Restoration Structures in Klamath River Tributaries, 1988/1989. Yrecka, California: U.S. Dept. Of Agriculture, Forest Service, Pacific Southwest Region.

Puckett, P. R. 2007. The Rock Cross Vane: A Comprehensive Study of an In-stream Structure (Unpublished Doctoral Dissertation). Retrieved January 2010 from North Carolina State University Theses and Dissertations Database.

Rathbun, J. 2008. Standard Operating Procedure: Assessing Bank Erosion Potential Using Rosgen's Bank Erosion Hazard Index (BEHI). Retrieved July 15, 2010 from Michigan Department of Environmental Quality, Lansing, MI.

Roper, B.R., D. Konnoff, D. Heller, & K. Wieman. 1998. Durability of Pacific Northwest Instream Structures Following Floods. North American Journal of Fisheries Management 18:686-693.

Rosgen, D.L. 1994. A Classification of Natural Rivers. Catena 22:166-169.

Rosgen, D.L. 1996. Applied River Morphology. Wildland Hydrology. Pagosa Springs, Colorado.

SigmaPlot, Version 8. Systat Software, Inc. San Jose, California.

Sudduth, E. B., J.L. Meyer, & E.S. Bernhardt. 2007. Stream Restoration Practices in the Southeastern United States. Restoration Ecology 15(3):573-583.

Sylte, T.L., & J.C. Fischenich. 2000. Rootwad Composites for Streambank Stabilization and Habitat Enhancement, EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-21), U.S. Army Engineer Research and Development Center. Vicksburg, MS.

Thompson, D. M., & G.M. Stull. 2002. The Development and Historic Use of Habitat Structures in Channel Restoration in the United States: The Grand Experiment in Fisheries Management. Géographie physique et Quaternaire 46(1):45-60.

APPENDICES

Appendix A

Table A1 – Stream Restorations Evaluated for Instream Structure Durability and Bank Erosion

Stream	Location	Latitude and Longitude	Year Constructed	Linear Feet Restored	Types of Structures Installed
Abbotts Creek	Wake	35° 46' 23.10"N 78° 43' 46.17"W	1999	1580	vanes, rootwads
Benbow Park	Guilford	36° 3' 8.11"N 79° 46' 25.89"W	2004	1915	vanes, rootwads
Bold Run	Wake	36° 1' 58.61"N 78° 35' 24.37"W	2007	1629	vanes, rootwads
Brown Bark Park	Guilford	36° 5' 45.16"N 79° 51' 7.15"W	2004	2855	vanes, rootwads
Chavis Park	Wake	35° 46' 7.87"N 78° 37' 49.21"W	2002	2015	vanes
Ellerbee Creek	Durham	36° 1' 19.89"N 78° 56' 11.71"W	2004	6279	vanes, rootwads
Forest Hills Park	Durham	35° 58' 48.84"N 78° 54' 43.68"W	2005	2900	vanes
Kentwood Park	Wake	35° 46' 30.23"N 78° 41' 40.39"W	2002	1400	vanes, rootwads
Oakwood Cemetery	Wake	35° 47' 10.51"N 78° 37' 39.69"W	1999	200	vanes
Richland Creek	Wake	35° 48' 11.52"N 78° 43' 31.80"W	2002	415	vanes
Rocky Branch Phase I	Wake	35° 47' 20.47"N 78° 41' 8.43"W	2002	3300	vanes
Rocky Branch Phase II	Wake	35° 46' 53.17"N 78° 40' 14.13"W	2005	1580	vanes, rootwads
Rocky Branch Phase III	Wake	35° 47' 0.25"N 78° 40' 28.63"W	2007	1380	vanes, rootwads
Smith & Austin Creeks	Wake	35° 57' 18.17"N 78° 30' 11.54"W	2002	11000	vanes, rootwads
South Fork Creek	Alamance	35° 50' 41.65"N 79° 20' 57.68"W	2004	3203	vanes, rootwads
Speight Branch	Wake	35° 43' 8.75"N 78° 45' 14.91"W	2001	1470	vanes
Spring Valley Park	Guilford	36° 2' 14.97"N 79° 48' 45.96"W	2004	1409	vanes, rootwads
Yates Mill Tributary	Wake	35° 43' 48.26"N 78° 42' 2.66"W	2000	4000	vanes, rootwads

Table A2 – Reference Streams Evaluated for Bank Erosion

Reference Stream	Location	Latitude and Longitude	Linear feet
UT to Lake Jeanette	Guilford	36° 9' 13.18"N 79° 49' 8.40"W	571
UT to Lake Wheeler	Wake	35° 42' 5.38"N 78° 42' 2.54"W	1363
UT to Mine Creek	Wake	35° 51' 2.46"N 78° 39' 31.50"W	unknown
Morgan Creek	Durham	35°55’24.45”N 79°06’54.62”W	1268
Sal’s Branch	Wake	35° 53' 20.08"N 78° 45' 14.87"W	1580
Brookhaven Park	Wake	35°51’12.81”N 78°41’08.58”W	unknown

Appendix B

Figure B1 – Rock Cross Vane Damage. The channel has migrated to the right side of the structure allowing sediment to fill in the scour pool and cover the left arm.

Figure B2 – Single Arm Vane Damage. The left side of the stream has eroded down to bedrock behind the single arm vane. The backfill material has been washed out, and many of the arm boulders have shifted.

Figure B3 – J-hook Vane Damage. Sediment has deposited behind first arm boulder, and there is minor erosion of the left bank at the end of the structure.

Figure B4 – Rootwad Revetment Damage. Severe erosion occurred below and behind the root ball. The footer log has been exposed.

Figure B5 – Bank Erosion in a Stream Restoration

Figure B6 – Bank Erosion in a Reference Stream