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Experimental Farm Rock Weirs as an Erosion Control Option for Missouri Streambanks

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EXECUTIVE SUMMARY

Missouri landowners dealing with streambank erosion problems are searching for affordable and effective techniques that they can use to address existing erosion issues and protect their property from further erosion. This search is complicated because the eroding streambank is often a symptom of a larger problem occurring elsewhere within the watershed. Consequently, finding an effective erosion control method can be difficult for a landowner unless they receive appropriate professional assistance. The limitations of currently available methods in terms of high cost, difficult installation, or inapplicability to larger stream systems have caused landowners to try techniques that are ineffective and may lead to increased instability.

As a result, the Missouri Department of Conservation (MDC) decided to evaluate farm rock weirs as a potential low cost alternative to a bendway weir project for controlling excessive streambank erosion. The difference between farm rock weirs and traditional bendway weirs are three fold: 1) farm rock weirs are made from shot rock (quarry rock not graded out to a specific size) instead of graded out rip rap, 2) farm rock weirs are not keyed into the bed of the stream, and 3) farm rock weirs are not keyed into the bank. These changes were made to reduce the costs associated with a weir approach while hopefully still stabilizing the bank. Five projects were constructed at four MDC Conservation Areas using farm rock weirs. The projects were built between October 2005 and April 2007 and were all tested by multiple high flow events.

This technique had mixed results. Four of the five projects were repaired, modified, or failed. The two projects built on Jakes Creek were the most successful farm rock weir projects. Both Jakes Creek project's shifted the channel away from the streambank and got deposition between the weirs, despite having several weirs lose length. Weirs at all projects lost length because they were not keyed into the bed of the stream. The Dry Branch farm rock weir project failed due to inadequately sized rock that washed away. The project was repaired with larger shot rock but is in the process of failing again via the same mechanism. The Weaubleau Creek project failed when weirs three and four lost length and allowed flow to get behind weir five. Weir five was repaired and length was added back to weir four and since the project has moved the thalweg away from the eroding bank. However, little deposition occurred between the weirs and recent flows have resulted in erosion behind weirs three and four that will eventually result in the failure of the project unless it is repaired. The Middle Fork project was a complete failure with flow getting behind weirs two through five and causing them to be washed away.

Overall three of the five projects protected the project streambank during the course of the study, but only one project did so without at least some repair, modification, or added expense. The two complete failures and the repairs needed at two other projects were due to inadequately sized rock, and lack of bed and streambank keys. Given these results, careful consideration needs to be given to whether or not to use the farm rock weir approach at a site because if maintenance is required, the savings over a traditional bendway weir project are lost or greatly reduced. The results from these projects show that while this approach may have limited potential in most cases the traditional approach will be the better choice. Additional modifications to the farm rock weir approach could result in a technique that does have real potential. However, without further study it is uncertain that any modification will reduce the savings over a traditional bendway weir project. The farm rock weir approach should not be attempted by a landowner without the assistance of an experienced professional and at this stage is not an approach we would recommend to landowners.

Keywords: streambank stabilization, erosion, erosion control, stream, landowner assistance

INTRODUCTION

Background

Erosion and deposition are natural and essential components of all stream systems. Erosion and deposition provide nutrients, create habitat diversity, and allow for channel adjustment to natural and anthropogenic stream alterations at multiple scales within the watershed (Van Haveren and Jackson 1986, Cramer et al. 2000, Fischenich and Allen 2000, Schmetterling et al. 2001, Price and Karesh 2002). However, human activities have altered many stream systems to a point that they can no longer maintain a natural form (Henderson 1986, Biedenharn et al. 1997, Church 2002, Washington State Aquatic Habitat Guidelines Program 2002). Such disturbances result in channel instability, excessive rates of erosion, and deposition.

The amount of erosion that occurs is dependent on the balance between the relative erodibility of channel material and the strength of hydraulic forces acting upon that material. Streambank stability and erosion resistance are also influenced by vegetation, physical features, and soil composition. Hydraulic forces acting on the streambank are controlled by factors such as vegetation, flow regime, sediment supply, channel gradient, and other watershed characteristics. The interactions of these factors control the natural erosion rates of a stream keeping it in a quasi-balance called dynamic equilibrium (Leopold et al. 1964, Bates 1998, Fischenich 2001a, Church 2002). A stream in dynamic equilibrium can sustain some disturbance without altering its natural state (Fajan and Robinson 1985, Henderson 1986, Gore and Shields 1995, Fischenich 2001b). Dynamic equilibrium is lost when there is an imbalance between flow regime, sediment supply (amount and type of materials), stream power (capacity of the stream to move sediment), and streambank strength, which are often influenced by human activities.

Activities such as urbanization, channelization, channel armoring, dredging, or construction of dams, levees, roads, and bridges may cause a loss of dynamic equilibrium and initiate excessive erosion. Vegetation clearing in the riparian zone may also result in loss of dynamic equilibrium at local or watershed scales (Bohn and Buckhouse 1986, Henderson 1986, USDA-NRCS 1996, Grubbs et al. 1997, Caverly et al. 1998, Simon and Steinemann 2000, Price and Karesh 2002, Shields and Knight 2003). Activities affecting the riparian vegetation along a stream can result in streambanks that are less stable, less cohesive, and more easily eroded (Bohn and Buckhouse 1986, Meadows 1998). Riparian vegetation is also critical to slowing flood waters from overbank flows, and its removal can cause increased erosion during floods.

Once a channel becomes unstable, accelerated erosion will occur through a variety of site specific mechanisms. Understanding the causes and mechanisms of the erosion is vital prior to attempting a streambank stabilization project if long-term stability is to be achieved (USDA-NRCS 1996, Biedenharn et al. 1997, Bates 1998, Meadows 1998, Kondolf et al. 2001, Washington State Aquatic Habitat Guidelines Program 2002). Disturbances at all scales activate physical processes within the streambank that result in accelerated erosion. Typical mechanisms of streambank failure include: 1) toe erosion, 2) surface erosion, 3) local scour, 4) mass failure due to overly saturated soils, 5) subsurface entrainment via groundwater seepage, 6) avulsion (major channel movement) after high flow events or due to excessive aggradation, and 7) ice scour (Henderson 1986, Grubbs et al. 1997, Bates 1998, Palone and Todd 1998, Washington State Aquatic Habitat Guidelines Program 2002). Streambank stabilization projects should use techniques that address the onsite mechanism(s) of streambank failure, but also should consider the fundamental causes of streambank failure for long-term stability (Cramer et al. 2000, Simon and Steinemann 2000).

Understanding which factors have been altered is critical before trying to address erosion problems. Some factors to consider for site-specific treatments include: 1) channel bed stability, 2) streambank height, 3) streambank material, 4) bed gradient, 5) flow regime, and 6) curvature of the stream (Bowie 1982, Derrick 1996, Gray and Sotir 1996, Fischenich and Allen 2000, Fischenich 2001a, Moses and Morris 2001). The factors listed above interact to determine the rate and type of erosion that occurs at a site and whether or not a certain technique is appropriate (Leopold et al. 1964, Li and Eddleman 2002). Once the fundamental cause and mechanism of failure has been identified, an appropriate approach can be determined for addressing the problem. The best approach may be cessation of the activity causing the problem and allowing the system to recover on its own. Unfortunately, addressing the overall problem and allowing for natural recovery may not be an appealing option in all situations, and a stabilization project may be necessary (Roper et al. 1997). In addition, if the erosion poses a threat to infrastructure or other valuable resources then an engineered stabilization project may be needed. Regardless of the stabilization technique, the ultimate goal should be to slow erosion enough to allow for the growth of a dense, woody riparian corridor to increase the likelihood of long-term streambank stability.

If a streambank stabilization technique is going to be used, it is critical to determine which technique is most appropriate for that situation prior to implementation. Techniques that are appropriate in one situation may not be appropriate in another. Therefore, prior to using new techniques, stream managers must determine the types of situations where they are, and are not, appropriate. To do this, we must understand the hydraulic forces acting upon the streambank and affecting its stability, and the technique's ability to address those forces and affect the streambank's resistance to erosion and its stability.

Missouri Streams

The majority of rivers and streams in Missouri have been dramatically altered over the last 200 years by human activities. These alterations have caused numerous problems including channel instability and excessive erosion. Sediment is considered the largest pollutant of our streams and is one of the most challenging and costly environmental hazards in the United States (Bowie 1982, Henderson 1986, National Research Council 1992, Becker 1993, Waters 1995, Biedenharn et al. 1997, Kauffman et al. 1997).

In a survey conducted in 1991 by Larsen and Holland (1991), 49% of Missourians indicated they wanted to see more emphasis put on river and stream conservation. Weithman (1994) found in another poll in 1994 that three of the five most important aquatic resource issues were the protection of water quality, legislation to protect streams, and assistance to landowners in solving stream problems. The importance of the state's river and stream resources to its residents makes dealing with erosion problems a high priority.

Missouri landowners dealing with streambank erosion problems are searching for affordable an effective techniques that they can use to address existing erosion issues and protect their property from further erosion. This search is complicated because the eroding streambank is often a symptom of a larger problem occurring elsewhere within the watershed. Consequently, finding an effective erosion control method can be difficult for a landowner unless they receive appropriate professional assistance. The limitations of currently available methods in terms of high cost, difficult installation, or inapplicability to larger stream systems have caused landowners to try techniques that are ineffective and may lead to increased instability.

The lack of documented technique evaluations makes it difficult to determine what techniques are available and whether or not they have application in Missouri streams. This information gap is considered the largest obstacle to improve the performance of streambank stabilization projects (Simon and Steinemann 2000). Monitoring watershed and channel conditions before and after project installation is a priority to determine effectiveness of the technique. Unfortunately, most erosion control projects have not been monitored after installation. Improved monitoring is needed to learn from previous applications and improve future project designs (Simon and Steinemann 2000, Kondolf et al. 2001, Shields and Knight 2003). Only through monitoring the long-term performance of a technique can stream managers determine when and where a technique is appropriate and identify its limitations.

Technique

One of the more commonly used techniques in streambank stabilization is bendway weirs. A traditional bendway weir is a rock structure that is keyed into the streambank and extends upstream into the channel at approximately a 20-degree angle from perpendicular to the streambank. Bendway weirs alter the direction of flow away from the eroding streambank and push it back to the center of the channel. The goals of this approach are protect the toe of the streambank from further erosion, promote deposition of sediment at the toe of the bank, and shift the thalweg (deepest part of the channel) away from the bank. They are effective on streams of all sizes, use less rock than earlier types of rock barbs (Derrick 1996, Biedenharn et al. 1997, Northcutt 1998, Sotir 1998, Johnson 2003), and have been adapted successfully to smaller streams (Derrick 1996, Derrick 1998, Smith and Wittler 1998, Wittler and Andrews 1998). The costs associated with a bendway weir project include the price of rock ($3-$15 per ton), cost of rock transportation ($4-$10 per ton), heavy equipment operation ($50-$150 per hour) to install the weir, and the cost of consulting with a professional engineer to design the structure. These costs exceed what most landowners can afford without considerable cost-share support. As a result, while bendway weirs offer a potential solution to erosion problems their associated costs make them unavailable to many landowners.

This project tested farm rock weirs as a potential alternative to bendway weirs. The farm rock weir experimental technique was designed to be a cost-effective approach to potentially achieve the same goals as a bendway weir project. The cost reduction comes from using less expensive shot rock and less total rock to build the structures instead of the large amounts of rock rip rap used in bendway weirs. The objectives of this study were to examine the performance of the farm rock weirs and determine: 1) the extent of continued erosion or deposition at the toe of the bank, 2) if the slope of the streambank is reduced following construction, 3) if farm rock weirs could withstand high flow events and maintain their position, and 4) if farm rock weirs are a cost effective alternative to bendway weirs.

STUDY SITES

Farm rock weirs were evaluated at five locations on stream segments within MDC conservation areas. Sites selected for this technique were limited to streams of 4th order or lower and project sites needed to have streambank heights of no more than approximately 15 feet. In addition we looked for sites where the curvature of the streambank made a weir approach the appropriate choice for the stabilization technique. Selected stream segments were located on Weaubleau Creek on Kings Prairie Access (KPA) in St. Clair County, Dry Branch on Union Ridge Conservation Area (URCA) in Sullivan County, Middle Fork on Port Hudson Lake Conservation Area (PHLCA) in Franklin County, and Jakes Creek received two of the five projects on Lead Mine Conservation Area (LMCA) in Dallas County. River and project site details are located in Table 1. Area maps showing the locations of the conservation areas in Missouri and project locations within those areas are provided in Appendix 1.

METHODS

Farm Rock Weir Design

The farm rock weir approach was designed to stop erosion by directing flow away from the streambank toe and into the center of the channel. The weir approach is often used when the curvature of the bend is so tight (highly curved) that armoring the streambank with rock would lock it into an unstable configuration, whereas weirs move the thalweg changing the curvature of the bend to a more stable configuration. Weirs are built to be ⅓ to ½ the streambank height tall and have lengths that are site dependent but do not exceed ½ the channel width at approximately a 20 degree angle upstream from perpendicular to the streambank. Weir spacing is determined by the curvature of the bank, but should be spaced no more than four times the length of the upstream weir (Derrick 1996). Weir spacing should be reduced as the radius of the curvature of the bend gets smaller. Tighter bends will require a higher number of weirs and those projects will have a higher cost as a result.

The farm rock weir projects were built according to the guidelines used to build a bendway weir project; however, they were not designed with the help of an engineer and instead were built based on the height, angle, and spacing guidelines described above. The differences between farm rock weirs and bendway weirs are three fold: 1) farm rock weirs are made from shot rock instead of graded rip rap, 2) farm rock weirs

Table 1. River and site details for the five farm rock weir projects. The watershed area is for the area located upstream of the site only and not the entire watershed.

	Weaubleau Creek	Dry Branch	Middle Fork	Jakes Creek 1	Jakes Creek 2
River Basin	Osage	Chariton	Boeuf	Niangua	Niangua
Physiographic Region	Ozark Plateau	Chariton River Hills	Ozark Plateau	Salem Plateau	Salem Plateau
Stream Order	4	3	3	4	4
Reach Gradient	11 ft./mi	22 ft./mi	47 ft./mi	26 ft./mi	26 ft./mi
Watershed Area	121 mi^2	2 mi^2	3 mi^2	27 mi^2	27 mi^2
Bank Height	12 ft.	10 ft.	8 ft.	6 ft.	8 ft.
Bank Length	450 ft.	150 ft.	170 ft.	250 ft.	300 ft.
Number of Weirs	5	2	5	3	8

are not keyed into the bed of the stream, and 3) farm rock weirs are not keyed into the streambank (Figure 1). The initial approach to building the farm rock weirs was to aim for having the median size of the shot rock used is equivalent to the size of rip rap (200-230 lbs. or 1.3-1.5 ft. in diameter). These changes were made in order to reduce the costs associated with a traditional bendway weir approach while still potentially stabilizing the streambank.

The project design at each site varied based on the site specific conditions. In addition other changes to construction and design were made to account for lessons learned building earlier projects. The first farm rock weir project Jakes Creek Site 1 was installed on Jakes Creek in October 2005 and consisted of three weirs. The Jakes Creek Site 2 farm rock weir project was constructed in February of 2007 and consisted of eight weirs. The Dry Branch farm rock weir project consisted of only two weirs and was built in June of 2006. In September of 2006 the five weir project was built at the Weaubleau Creek site. The final farm rock weir project consisting of five weirs was built on Middle Fork in April 2007.

Monitoring

Project monitoring consisted of pre-construction monitoring (to quantify reference condition prior to stabilization efforts), post-construction monitoring (to establish post-construction baseline for evaluation of future project performance), and post-flow monitoring (to determined project performed after high stream flow events). Post-flow monitoring was conducted on an annual basis following spring flow events and additionally following any flow events that caused significant changes to the projects. Each project was monitored through a minimum of five flow events that exceeded ¾ the height of the streambank and the streambank appeared to have become more stable, or project failure occurred.

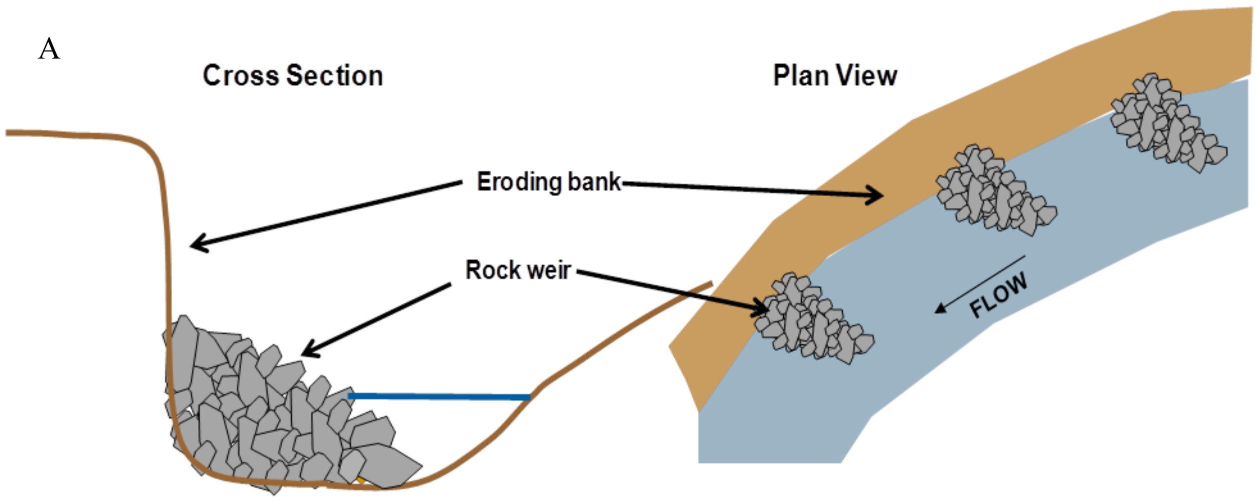
Monitoring consisted of physical surveying, Global Positioning System (GPS) mapping, photo points, and flow monitoring. The physical survey was conducted using a Trimble 5605 DR Total Station from 2005 - 2009 and a Nikon Nivo 5.M Total Station from 2010 - 2011 to measure cross channel transects, a longitudinal profile of the channel thalweg, and a longitudinal profile through the center of the project's weirs. All transects ran from a benchmark on the eroding streambank to the top of the gravel bar across the channel. Transects were located at the center of each weir, halfway between the weirs, and downstream of the last weir. The longitudinal profile of the thalweg started at the head of the first riffle downstream of the project and followed the thalweg to the head of the first riffle upstream of the project. The weir longitudinal profile started at the transect located downstream of the last weir and was surveyed through the center of each weir to just upstream of the first weir. Project features including the weirs, the toe of the eroding bank, the top of the eroding bank, the wetted channel, the gravel bars, the opposite bank, benchmarks, and other features were mapped with sub-meter accuracy GPS unit (Trimble Geo XT) to make a map of each site. In addition, the GPS unit was used to record locations where water depth was measured. These data were used to create a depth profile of the entire wetted channel area in ArcMap v9.3.1. Permanent photo points were established to create a visual record of changes through time. Photos were taken at least twice a year and during all surveys. A Levelogger® (Solinst Gold Model 3001 LT F30/M10) was placed in the stream and paired with a Barologger® (Solinst Gold Model 3001 LT F5/M1.5) on the streambank to monitor flow. The Levelogger® is a pressure transducer that uses changes in pressure to track changes in stage. The Levelogger® can accurately track stage when paired with a Barologger® to account for changes in barometric pressure. The Levelogger®s were maintained in the stream channel year-round.

RESULTS

Jakes Creek Site 1

The Jakes Creek Site 1 project has experienced numerous flow events (Figure 2). These included a flow event in the spring of 2006 that caused the log weir project downstream to fail. There were also six flow events in 2008 and one in 2009 that reached stages higher than the top of the eroding streambank (6 ft.). The largest recorded flow to test this project occurred in September 2008. The stream's stage rose from 1.6 ft. to 9.1 ft. in six hours, representing a stage 3 ft. above the top of the eroding bank. In 2009, a large flow event occurred sometime between June and October that caused the Levelogger® to be lost. Because of that, there is no flow record for that time period. In 2010 and 2011 there was only a single flow event greater than the top of the streambank that tested the project.

Weir two lost approximately 7 ft. of length between project construction and the 2008 physical sur-



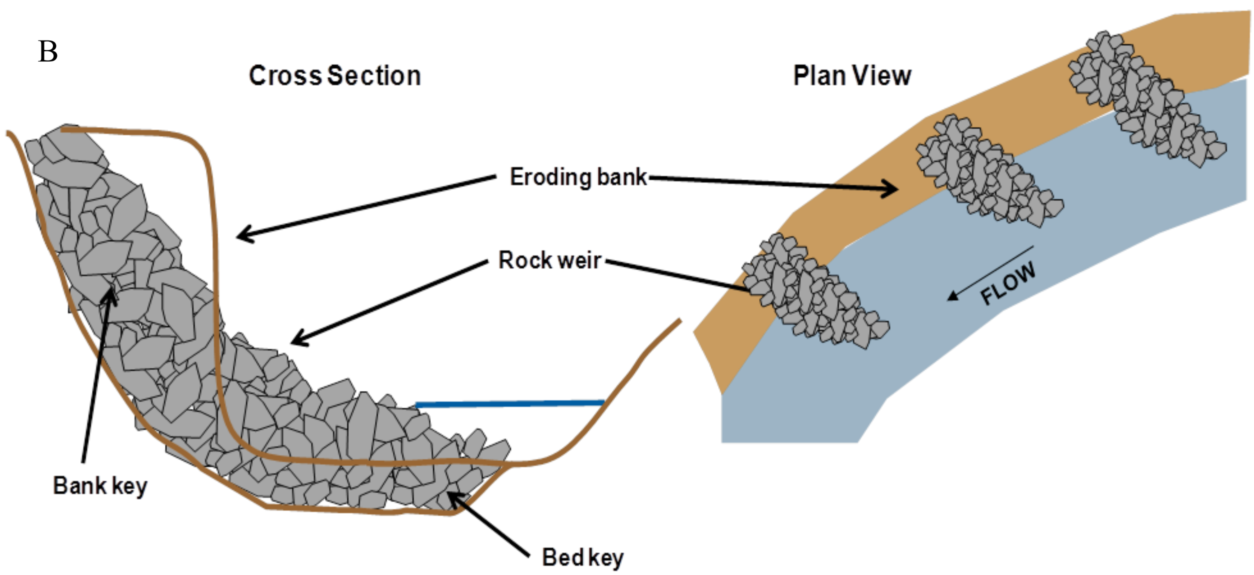


Figure 1. (A) Cross section and plan view of a generic experimental farm rock weir project. (B) Cross section and plan view of a generic traditional bendway weir project.

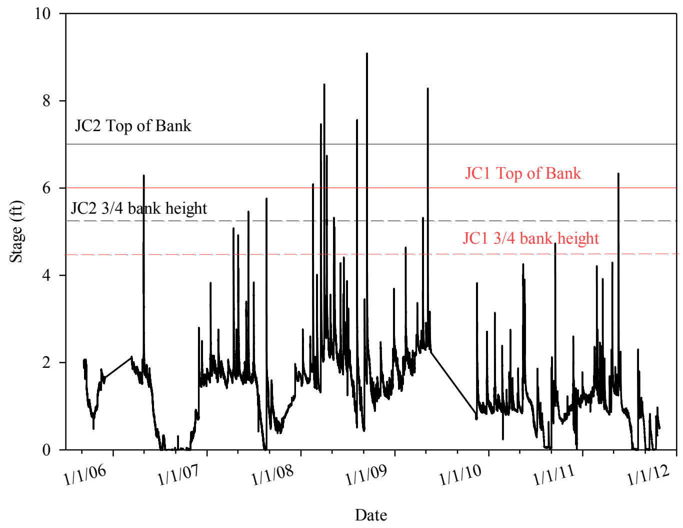


Figure 2. Levelogger® data from Jakes Creek for fall 2005 through 2011. Data are missing from May 2009 until November 2009 due to a lost Levelogger®. The red solid and dashed lines represent the top and ¾ of the streambank height at Jakes Creek site 1. The black solid and dashed lines represent the top and ¾ of the streambank height at Jakes Creek site 2.

vey (Figure 3); however, the weir had been built longer than the original design and the project was still working as expected so there was no plan to repair the project. An unplanned repair was made to weir two between October 2008 and March 2009. The repair consisted of adding approximately 4 ft. of length back to weir two (Figure 4). The repair was made by area staff without consulting with the rest of the project team.

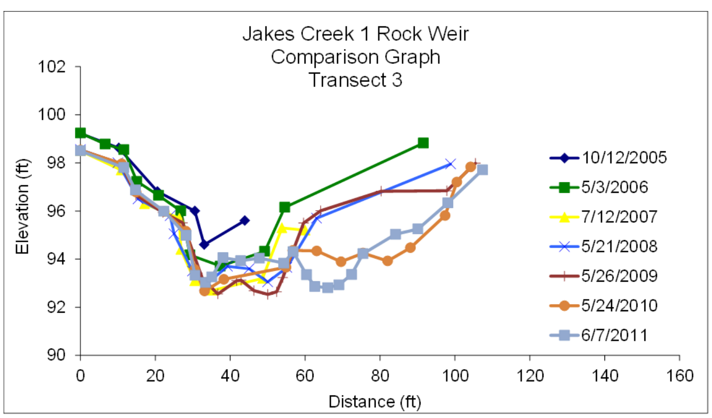


Figure 3. Physical survey data for transect three, which runs down the center of weir two, for the post-construction survey (10/12/2005) and six post-flow surveys (5/3/2006, 7/12/2007, 5/21/2008, 5/26/2009, 5/24/2010, and 6/7/2011).

Photo monitoring gives a good visual representation of how the channel has responded to the project in a positive manner (Figure 5). The photos show that the thalweg has moved away from the eroding streambank and deposition has occurred between the weirs.

A GPS map of the distribution of water depths in the channel shows the thalweg has moved away from the toe of the streambank and out beyond the tips of the weirs (Figure 6). During the 2009 flow event that resulted in the loss of the Levelogger®, the main flow of the channel shifted away from the project and now flows through what was middle of the opposing gravel bar. The channel shift was caused by changes upstream of the project. Since 2009, the redirected flow through the bar has accelerated deposition between weirs one and two. So far this change in flow approach has benefited the project, but the new angle of approach could eventually cause problems for weir three since low flow is no longer being affected by weirs one and two. These channel changes are shown in the physical surveys (Figure 3). Details on streambank movement along each transect indicates the streambank has remained stable with only the most downstream transect showing any change as a result of erosion (Table 2). The streambank slope has been reduced for the two transects between the weirs and for the transect located downstream of the last weir.

Jakes Creek Site 2

The Jakes Creek Site 2 project has experienced numerous flow events in 2007 through 2011 (Figure 2). Flow data from 2007 show only two flow events greater than ¾ the height of the top of the bank. In 2008, record amounts of precipitation fell; four flow events reached a stage greater than the height of the eroding streambank (7 ft.). The largest recorded flow to test this project occurred in September 2008 when stage rose from 1.6 ft. to 9.1 ft. in six hours. In 2009, there was one additional recorded flow event that was higher than the top of the bank. A second large flow event occurred sometime between June and October that year that caused the Levelogger® to be lost; because of that there is no flow record for that time period. Since 2009, the project has experienced only one event that went over ¾ of the streambank height flow which occurred in 2011.

During 2008, some of the stream flow was redirected away from the eroding streambank and through the opposing gravel bar. The shift occurred downstream of the first two weirs and appears to be a result of the project in combination with channel changes upstream of the project. Since 2008, the percentage of the flow that is taking the new channel has continued to grow. A GPS map created following project construction in 2007 shows the location of

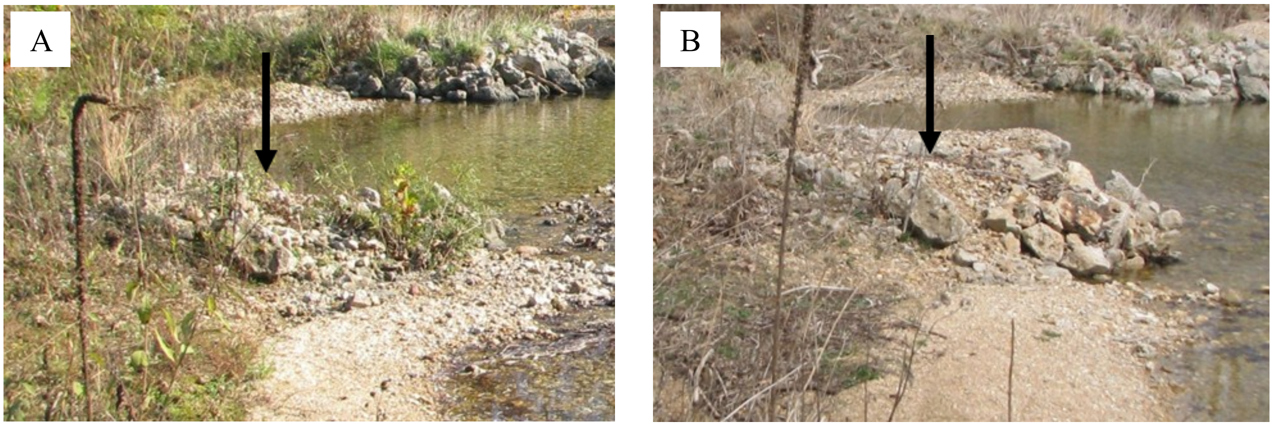


Figure 4. Photos of Jakes Creek site 1 weir two before and after unplanned repair. (A) Weir two October 2008. (B) Weir two March 2009. The arrows are pointing to the same rock in each photo.

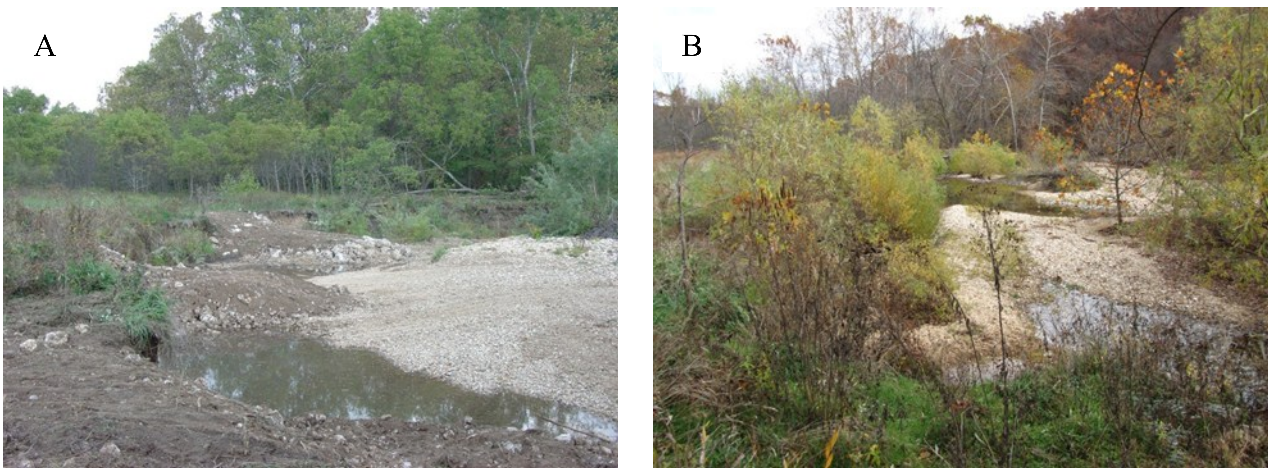


Figure 5. Monitoring photos for Jakes Creek site 1 farm rock weir project. (A) Looking downstream following construction in October 2005. (B) Looking downstream in October 2011.

Table 2. Streambank movement and changes in streambank slope at the Jakes Creek site 1 rock weir project between the post-construction survey in October 2005 and the final survey in June 2011. Tip of weir is the point where the top surface of the weir stops. End of weir represents the location where the weir rock ends and streambed begins. Erosion is represented by negative movement in the streambank and deposition is represented by a positive movement in the bank. Transect numbers increase as you move downstream.

	Top of streambank (ft.)	Toe of streambank (ft.)	Tip of Weir (ft.)	End of Weir (ft.)	Bank Slope 10/2005	Bank Slope 6/2011
Transect 1	1.40	---	-5.05	-1.98	---	---
Transect 2	-2.19	0.59	---	---	1.77	0.83
Transect 3	1.38	---	-2.35	0.35	---	---
Transect 4	-0.44	-0.71	---	---	1.03	0.97
Transect 5	-0.46	---	-4.26	0.55	---	---
Transect 6	-3.90	-3.52	---	---	1.16	1.01

base flow at that time and the concentration of depth along the eroding bank. The GPS map that was created in 2011 shows the shift in base flow as well as the loss of depth against the eroding streambank (Figure 7). Photos taken following construction and various flow events show how the channel changed from 2007 -2011 (Figure 8).

The project itself has survived all the flow events and thalweg shifts. There has been streambank movement along all transects, but this movement has resulted in the slope of the streambank decreasing for 10 of the 16 transects (Table 3). All weirs have lost length, especially weirs four, five and six. Those weirs all lost at least 8 ft. of length off the tip of the weir and weir five lost more than 12 ft. Part of this lost length is due to the gravel bar that has formed at the weir edges burying the tips of the weirs, but there has also been a substantial loss of rock at the tips of the weirs. So far the loss of weir length has not affected the functioning of the project. The physical survey data for transect 11 show the streambank movement and the shifting of the thalweg (Figure 9).

Dry Branch

The Dry Branch rock weir project was the first rock weir project to fail. The project survived two flow events that were greater than ¾ the height of the streambank before a failure occurred following the flow event on May 6, 2007. This rain event created an approximately 10.5 ft. rise over the average flow during the previous week. The stage rose from approximately 1 ft. to a height of 11.5 ft. in two hours, which represents a flow 2.5 ft. above the top of the streambank (Figure 10). The flow caused extensive damage to the project and resulted in its failure.

Following the failure of the project in May 2007, a post-failure survey was conducted. A visual inspection of the project following failure as well as the data collected during the survey made it clear that the project did not fail because flow cut under or behind the project, but because water picked up all but the largest pieces of rock and carried them away (Figure 11). Because of the nature of the failure, the project was repaired by rebuilding it with larger rock on September 12, 2007.

Following repair work, a new post-

Table 3. Streambank movement and changes in streambank slope at the Jakes Creek site 2 rock weir project between the post-construction survey in February 2007 and the final survey in June 2011. Tip of weir is the point where the top surface of the weir stops. End of weir represents the location where the weir rock ends and streambed begins. Erosion is represented by negative movement in the streambank and deposition is represented by a positive movement in the bank. Transect numbers increase as you move downstream.

	Top of streambank (ft.)	Toe of streambank (ft.)	Tip of Weir (ft.)	End of Weir (ft.)	Bank Slope 2/2007	Bank Slope 6/2011
Transect 1	1.23	---	-7.80	-3.12	0.43	0.18
Transect 2	-1.34	-0.57	---	---	1.38	1.10
Transect 3	0.68	---	-3.21	-0.56	0.46	0.48
Transect 4	-1.28	-1.94	---	---	1.69	0.86
Transect 5	-2.12	---	-1.31	-2.31	0.53	0.48
Transect 6	-2.68	-1.57	---	---	1.09	0.98
Transect 7	-0.06	---	-8.93	-8.64	0.48	0.48
Transect 8	-6.66	-0.53	---	---	5.60	0.97
Transect 9	-1.93	---	-12.02	-15.82	0.52	0.66
Transect 10	-7.57	-2.88	---	---	1.67	0.63
Transect 11	-1.01	---	-7.97	-6.16	0.43	0.53
Transect 12	-2.91	1.17	---	---	0.92	0.60
Transect 13	1.20	---	-0.21	-2.96	0.39	0.53
Transect 14	-1.60	-3.62	---	---	0.72	0.74
Transect 15	-4.99	---	-1.53	-2.47	0.92	0.57
Transect 16	-7.18	-4.40	---	---	1.17	0.73

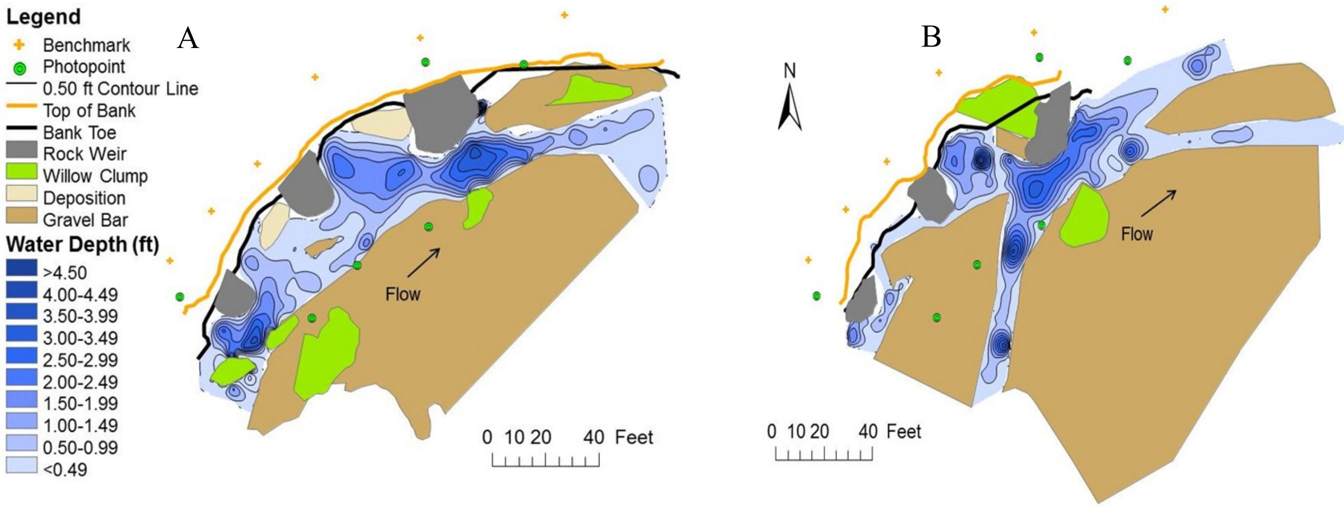


Figure 6. Channel depth profile map of Jakes Creek site 1 rock weir project (A) May 2009 and (B) June 2011.

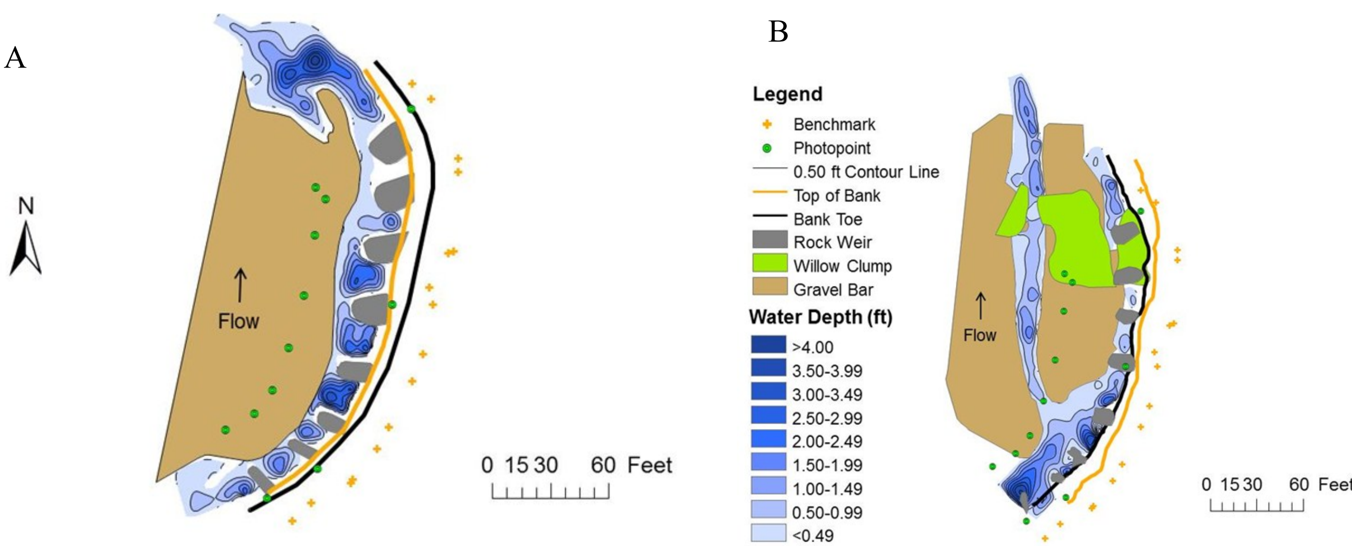


Figure 7. Jakes Creek site 2 farm rock weir project GPS map including depth profile. (A) February 2007. (B) June 2011.

Figure 8. Jakes Creek site 2 (A) Looking upstream following project construction February 2007. (B) Looking upstream April 2008. (C) Looking upstream November 2009. (D) Looking upstream June 2011.

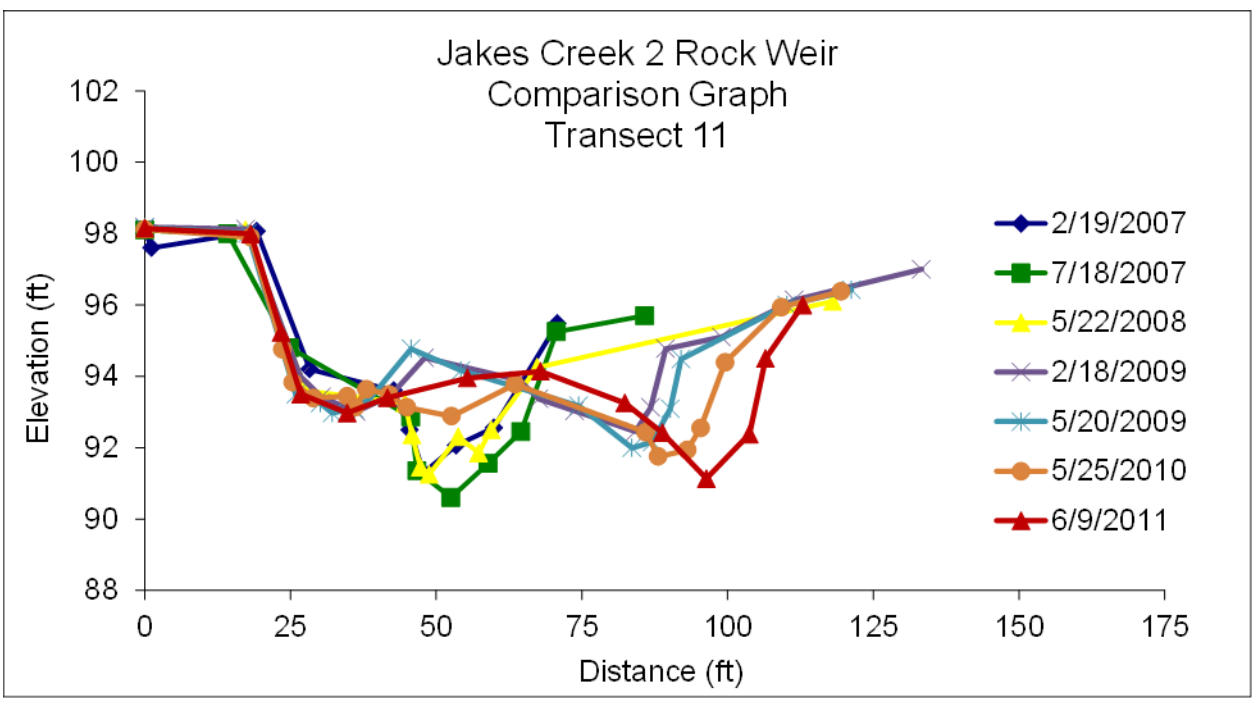


Figure 9. Survey data for transect 11 for the post-construction survey (2/19/2007) and six post-flow surveys (7/18/2007, 5/22/2008, 2/18/2009, 5/20/2009, 5/25/2010, and 6/9/2011).

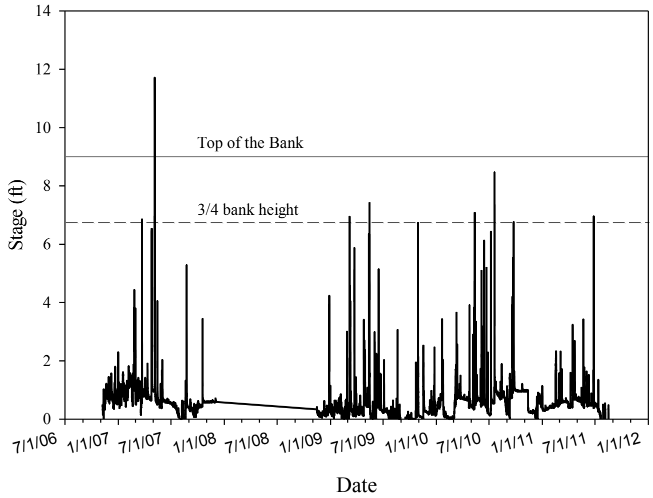


Figure 10. Levelogger® data from Dry Branch for 2006-2007 and 2009-2011.

construction survey was completed on December 3, 2007. During 2008, the rebuilt project experienced multiple flow events. Unfortunately we have no data on the exact sizes of these flow events because Leveloggers® were lost on two separate occasions. Post-flow monitoring occurred on August 4, 2008 to track project performance since reconstruction. In late 2008, a new Levelogger® was placed in the stream. From 2009 through 2011, Dry Branch had seven flow events that reached a stage height greater than ¾ the streambank height (Figure 10). During these flow events the project lost length off the tips of the weirs. Weir one has lost most of its length and is now little more than a rock hard point and weir two has lost both height and length (Figure 11). In addition, flow coming off the field behind the streambank has caused erosion between weir one and two (Figure 12). This erosion has contributed to flow getting behind weir two and eroding the bank

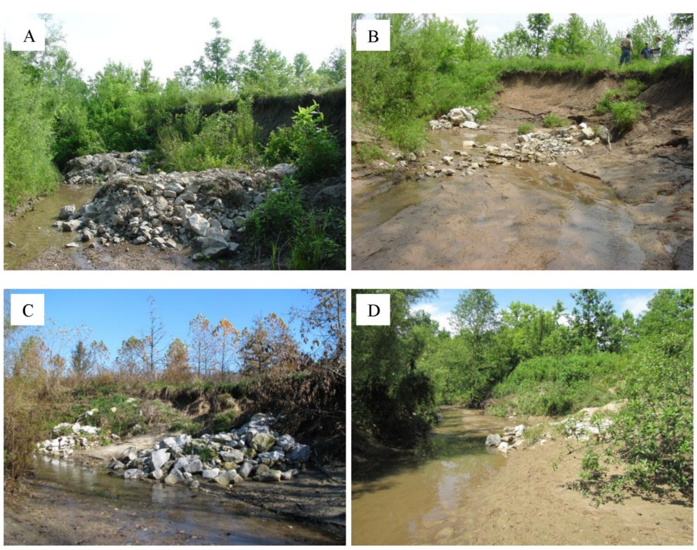


Figure 11. Monitoring photos from Dry Branch farm rock weir project. (A) Looking upstream following construction in July 2006. (B) Looking upstream following failure in May 2007. (C) Looking upstream following repair in October 2008. (D) Looking upstream in July 2011.

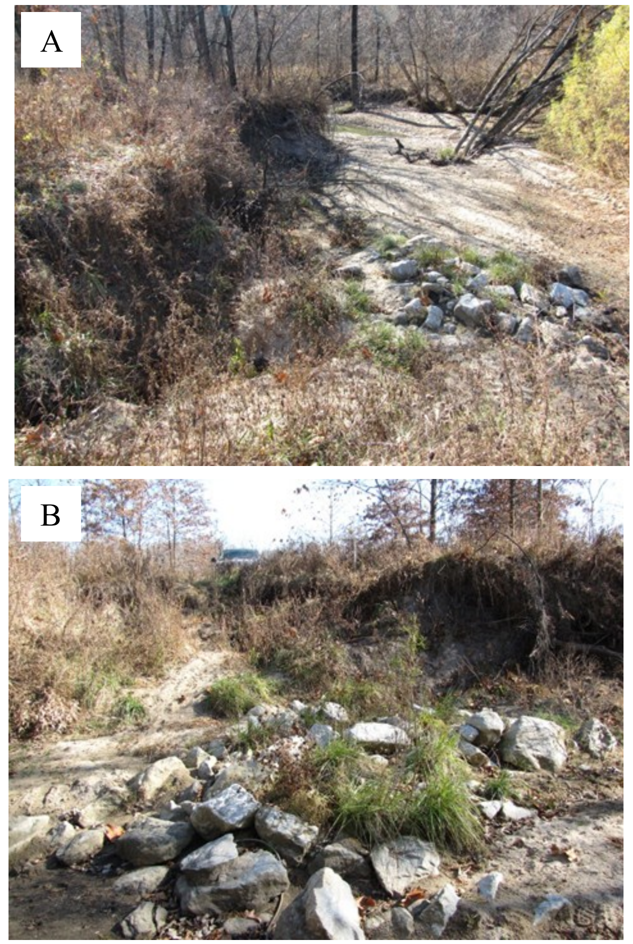


Figure 12. Eroded area at the Dry Branch farm rock weir project caused by flow coming off a field behind the bank. (A) Looking at erosion from top of the streambank November 2011. (B) Looking at eroded area from the channel November 2011.

There have been dramatic changes in this project since initial construction. The project has slowly moved toward failure even after repairs were made. Upstream of weir two the bank's slope has decreased since original project construction, but from weir two downstream the slope has increased (Table 4). There has been a large amount of erosion at both the top and toe of this streambank since original construction, which could be expected given that it failed once and was repaired. However, if you compare the changes that have occurred since construction with those since the project has been repaired you can see that the majority of the erosion has occurred since project repair (Table 5). The erosion caused by the field runoff has

Table 4. Streambank movement and changes in streambank slope due to erosion at the Dry Branch rock weir project between the post-construction survey in July 2006 and the final survey in July 2011. Tip of weir is the point where the top surface of the weir stops. End of weir represents the location where the weir rock ends and streambed begins. Erosion is represented by negative movement in the streambank and deposition is represented by a positive movement in the bank. Transect numbers increase as you move downstream.

	Top of streambank (ft.)	Toe of streambank (ft.)	Tip of Weir (ft.)	End of Weir (ft.)	Bank Slope 7/2006	Bank Slope 7/2011
Transect 1	-1.87	0.55	---	---	0.84	0.58
Transect 2	-4.58	---	-10.35	-9.81	0.82	0.47
Transect 3	-11.59	-4.24	---	---	0.62	0.35
Transect 4	-8.09	---	-3.89	-3.47	0.83	1.62
Transect 5	-18.99	-25.65	---	---	0.81	1.31

contributed to this from transect three downstream, but the loss of length of weir one has left weir two unprotected and greatly contributed to all the erosion seen on the lower end of the project. So while the upper end of the project has developed vegetation and appears to be stabilizing, the lower end is continuing to erode. The Dry Branch project has succeeded only in shifting the erosion slightly downstream.

Weaubleau Creek

The Weaubleau Creek project experienced three flow events that were more than ¾ the streambank height in 2007 as well as two more in early 2008 (one of which went over the top of the bank, 10 ft.) before failing at the end of March in 2008 (Figure 13). The project started to fail during this flow event due to changes that had occurred as a result of previous flow events. Because farm rock weirs are not initially keyed into the bed of the stream the way that traditional bendway weirs are, the streambed around the tip of the weir developed a scour hole from velocity currents going around the weir. The rock off the tip of the weir then fell into the hole created by the scour and eventually protected itself from any further scour. However; this process causes the weir to lose some of its effective length. In this case, weirs three and four lost enough length to allow flow to get behind weir five (Table 6, Figures 14, 15). The loss of length caused weir five to fail.

Despite flow getting behind weir five, the rest of the project performed as planned. The thalweg had shifted away from the eroding streambank and deposition occurred between all other weirs. As a result, the project was repaired by rebuilding weir five and adding length to weir four in August 2008. After repairs were completed, the largest flow occurred in September 2008 and the project survived without further damage. The project was tested by two flows greater than the top of the bank, one of which was over 16 ft. in stage in 2009, and by three more flows that were greater than the top of the streambank in 2010. Despite the failure and repairs to fix weirs four and five in 2008, this project appeared to be working prior to 2011 (Figure 16). Photo monitoring demonstrated the

Table 5. Streambank movement and changes in streambank slope due to erosion at the Dry Branch rock weir project between the post repair survey in December 2007 and the final survey in July 2011. Tip of weir is the point where the top surface of the weir stops. End of weir represents the location where the weir rock ends and streambed begins. Erosion is represented by negative movement in the streambank and deposition is represented by a positive movement in the bank. Transect numbers increase as you move downstream.

	Top of streambank (ft.)	Toe of streambank (ft.)	Tip of Weir (ft.)	End of Weir (ft.)	Bank Slope 12/2007	Bank Slope 7/2011
Transect 1	-2.02	-3.60	---	---	0.59	0.58
Transect 2	-2.78	---	-7.90	-7.16	1.07	0.47
Transect 3	-10.34	3.61	---	---	0.91	0.35
Transect 4	-7.64	---	-4.84	-3.77	1.28	1.62
Transect 5	-14.59	-17.70	---	---	1.02	1.31

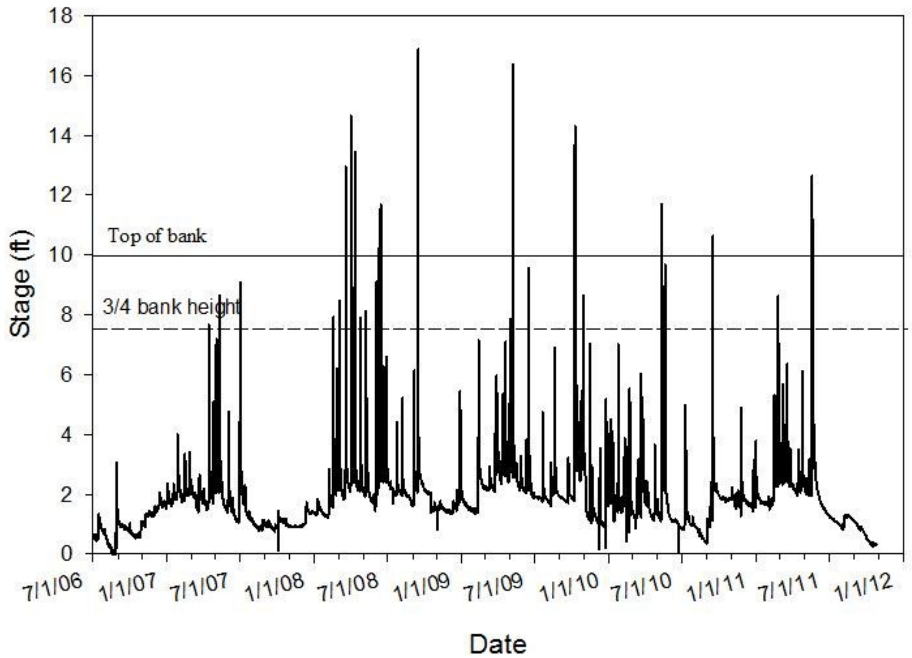


Figure 13. Levelogger® data from Weaubleau Creek for 2006 through 2011.

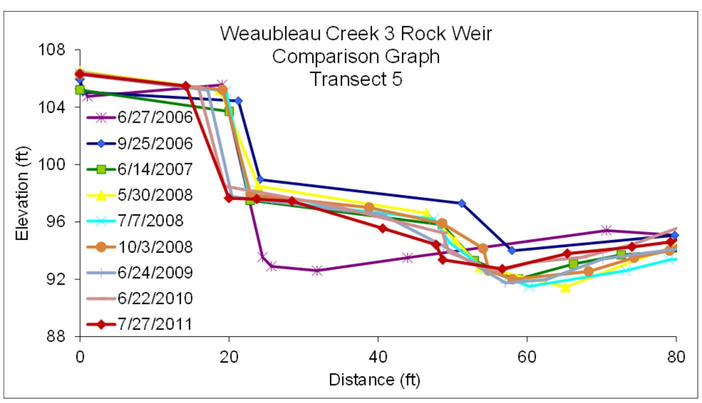


Figure 14. Transect five survey data for Weaubleau Creek. Transect five runs across the middle of weir three. Survey data from pre-construction survey (6/27/2006), post-construction survey (9/25/2006), and seven post-flow surveys (6/14/2007, 5/30/2008, 7/7/2008, 10/3/2008, 6/24/2009, 6/22/2010, and 7/27/2011).

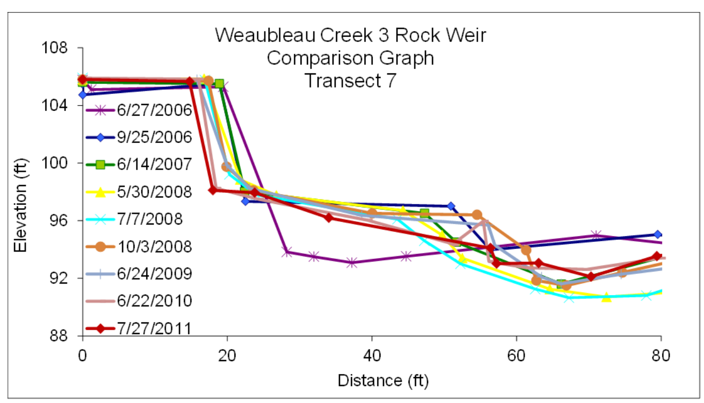


Figure 15. Transect seven survey data for Weaubleau Creek. Transect seven runs across the middle of weir four. Survey data from pre-construction survey (6/27/2006), post-construction survey (9/25/2006), and seven post-flow surveys (6/14/2007, 5/30/2008, 7/7/2008, 10/3/2008, 6/24/2009, 6/22/2010, and 7/27/2011).

shifting of the thalweg away from the toe of the streambank (Figure 17). In 2011, two additional flow events that went over the top of the streambank occurred and resulted in erosion beginning to occur behind both weirs three and four (Figure 18). Flow events in spring 2012 continued to erode these areas that are not protected because farm rock weirs are not keyed into the streambank and this erosion will eventually result in the failure of this project unless repairs are made.

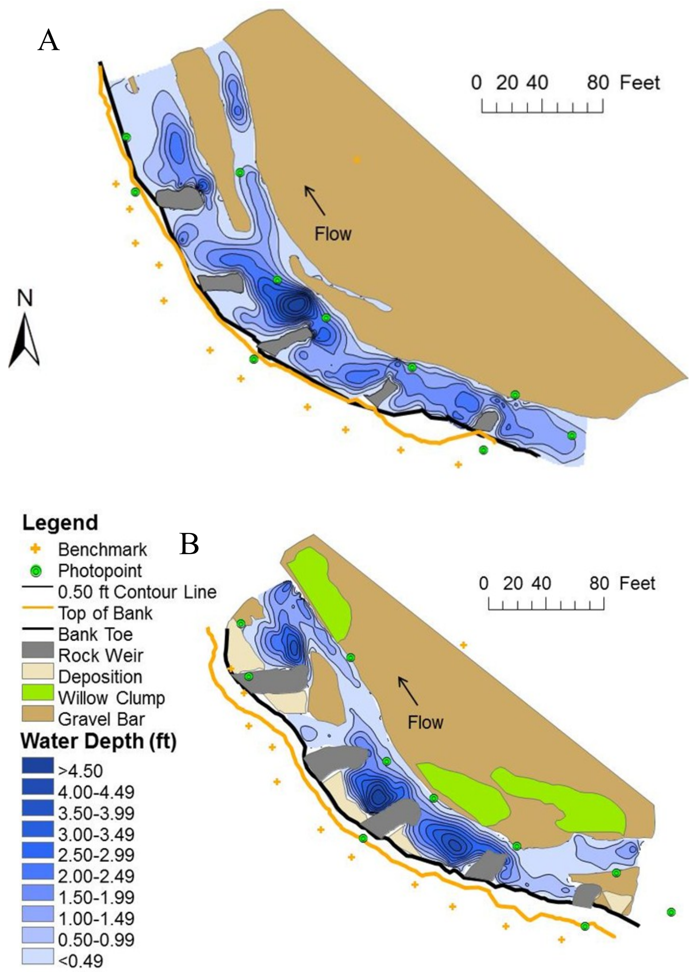


Figure 16. Channel depth profile map of Weaubleau Creek rock weir project. (A) June 2007. (B) June 2010.

Middle Fork

The Middle Fork project failed for the same reason as the Weaubleau Creek project, the lack of keys, but at this site there were other contributing factors. The first two flow events that reached a height greater than ¾ the streambank height occurred in February and April 2008 (Figure 19). These flow events began the failure process. A later flow event caused the complete failure of the project. The size of flow that caused the complete failure is unknown because it took out the root wad where the Levelogger® was attached and the Levelogger® was not recovered.

Photo monitoring does give a good indication of what caused the failure (Figure 20). The weirs at this project were built longer than originally intended due to the loss of length expected based on what we observed at other projects. Instead of extending ½ way across the base flow wetted channel these weirs extended across ⅔ to ¾ of the wetted channel width. Photos taken after construction show that much of the rock in the weirs was smaller than the cobble of the streambed and the vegetated cobble bar when the project was constructed in spring 2007. 2007 was a very dry year on this creek with there being virtually no flow from mid-summer until the spring of 2008 that resulted in vegetation beginning to establish in the base flow channel (Figure 19). The initial high flow events in February and April of 2008 caused the upper streambank area to start eroding and allowed flow to start working behind the weirs. Once this process started it could not be stopped by the project because there were no keys protecting the weirs. When an additional high flow event occurred in the summer of 2008 it resulted in the failure of weirs three, four, and five (Figure 21). Ultimately, the project failed because the lack of keys, the rock used for the weirs, and the unvegetated eroding streambank were less resistive to the erosional forces than were the streambed and the vegetated and consolidated cobble bar. From a construction standpoint, the most significant factors were the lack of keys, the incorrect length of the weirs, the size of the rock used, and the fact that farm rock was not graded to a standardized specification that allows the rock to interlock and hold together better. As a result of these design flaws the project could not withstand the velocities without washing away. The decision was made following failure not to repair this project but instead to use a more traditional approach to fixing this bank.

Table 6. Change in weir length on Weaubleau Creek between construction (9/2006) and project failure (5/2008).

	Construction Length (ft.)	Length at Failure (ft.)	Change (ft.)
Weir 3	27.1	22.6	-4.5
Weir 4	28.4	17.5	-10.9

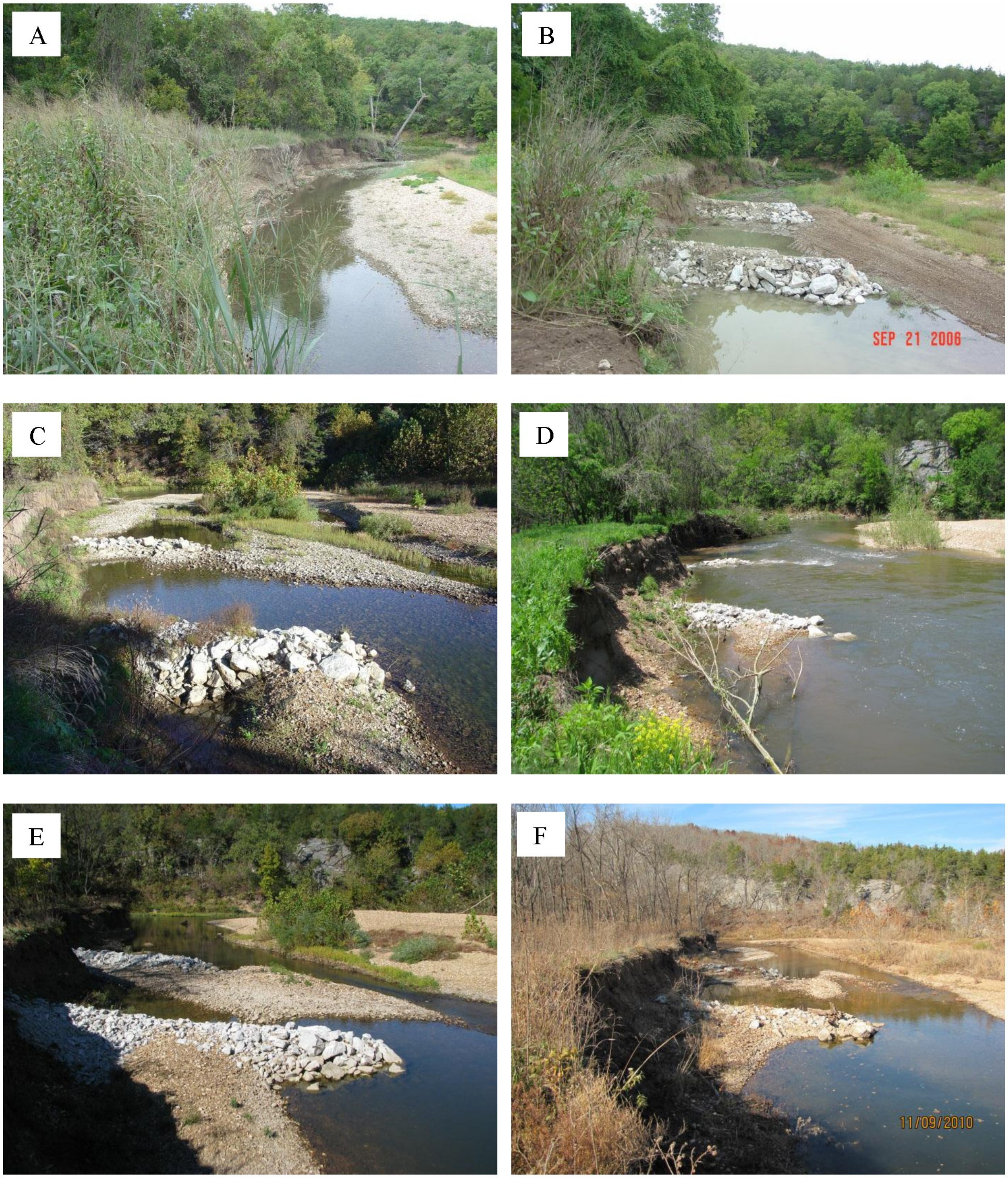


Figure 17. Photo monitoring of weirs four and five at the Weaubleau Creek rock weir project. (A) Prior to construction October 2005. (B) Post-construction September 2006. (C) Channel changes October 2007. (D) Following failure of weir five May 2008. (E) Following project repair October 2008. (F) Post-flow November 2010.

Figure 18. Erosion of key of weir three at the Weaubleau farm rock weir project June 2012. (A) Weir three from across the channel. (B) Looking upstream at weir three.

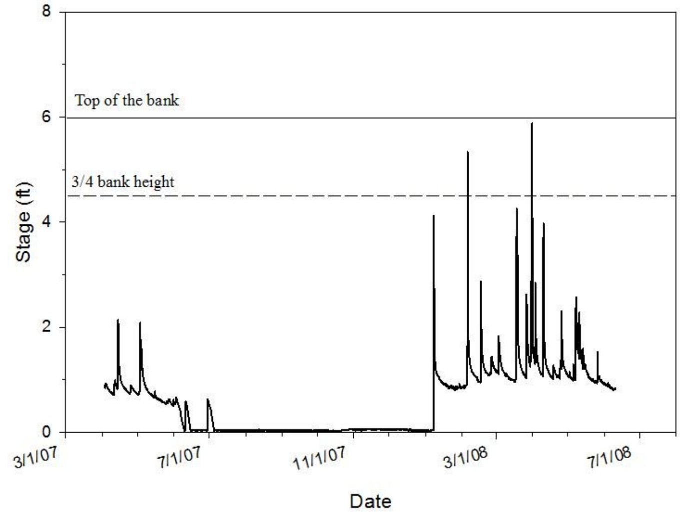


Figure 19. Levelogger® data from Middle Fork for 2007 - 2008.

Technique Performance

Five farm rock toe projects were installed between October 2005 and April 2007. The farm rock weir technique has produced a variety of results. Four of the five projects have either failed and needed repairs or have required maintenance following construction. The reasons for the repairs and maintenance have varied from project to project, ranging from inadequate rock size to a variety of project design issues.

The first objective for monitoring the farm rock weir technique was to determine extent of continued erosion or new deposition of sediment that occurred along the toe of the streambank between the weirs. To successfully achieve this objective the farm rock weir project needed to move the thalweg away from the toe of the streambank out beyond the tips of the weirs, have deposition occur between the weirs along the toe, and protect the eroding bank. Of the five projects that were built, the two projects constructed on Jakes Creek were the most successful. Both projects successfully moved the thalweg away from the toe along the entire length of the project, had deposition between the weirs, and vegetation began to establish at the toe of both banks. The Weaubleau Creek project suffered a partial failure and had to be repaired in 2008. Following repair it succeeded in moving the thalweg away from the toe, but there has been little to no deposition between the weirs and at the toe and erosion has started to occur behind weirs three and four where there are no keys. Dry Branch and Middle Fork, the two projects that were complete failures, have seen continued streambank erosion and no deposition as a result of their failures. Overall the farm rock technique was successful at moving the thalweg at four of the five projects in the short term, but the lack of deposition left them vulnerable to failure. Two of those projects are now failing and experiencing erosion at the streambank toe; so overall the technique was unable to consistently achieve this objective.

The second monitoring objective was to deter-

Figure 20. Middle Fork farm rock weir project. (A) Looking downstream following construction in April 2007. (B) June 2008. (C) Following project failure in November 2008. (D) Looking upstream following project failure November 2008.

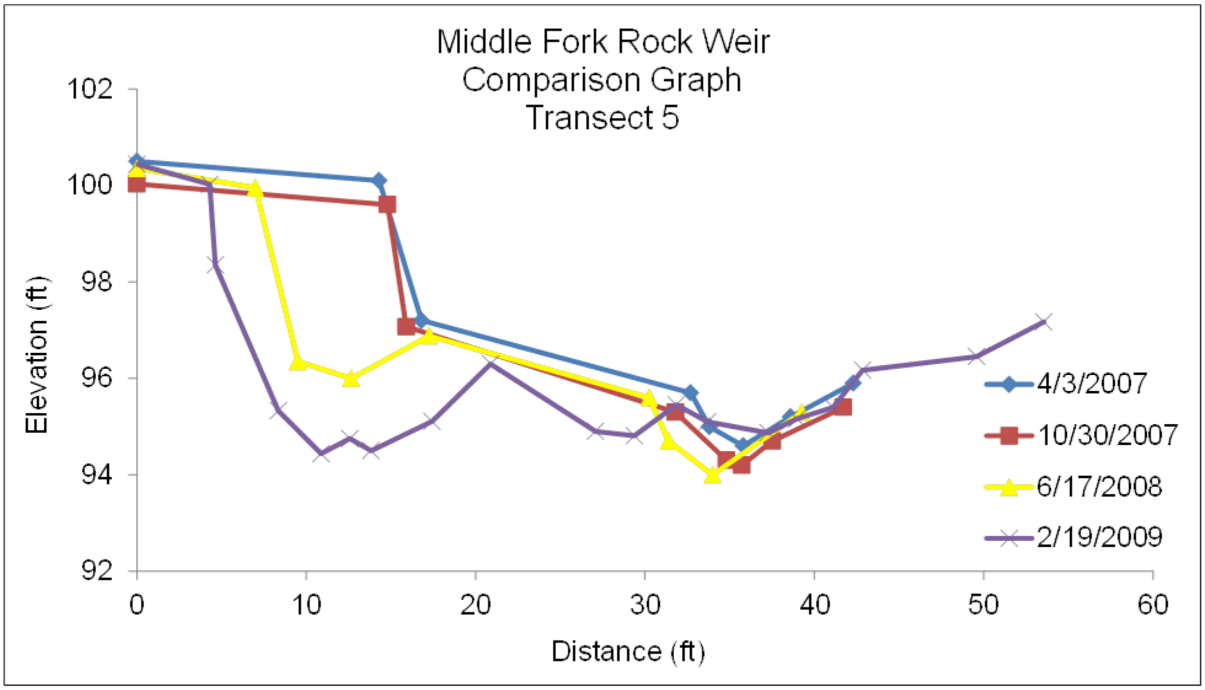


Figure 21. Survey data for transect five for the post-construction survey (4/3/2007) and three post-flow surveys (10/30/2007, 6/17/2008, and 2/19/2009).

mine if the streambank would achieve a stable slope through erosion of the upper part of the streambank while the toe was protected or deposition at the toe created a more moderate streambank slope. Three of the five projects have seen a slight reduction of the slope of the streambank between the weirs. At the two Jakes Creek projects the slopes of the banks were reduced due to some slight erosion of the top of the streambank and deposition at the toe. The combination of erosion and deposition has given the banks a more moderate slope in certain areas, but neither streambank has achieved a moderate slope along its entire length. The Weaubleau Creek project has also seen a slight reduction in the slope of the streambank because of some erosion at the top of the bank, but it has not seen any deposition and has not achieved a more moderate streambank angle. The erosion caused by the failures at Dry Branch and Middle Fork has led to an increase in streambank slope. The exception being transect three at Dry Branch but this result is complicated because it is located where we are getting the streambank erosion from field runoff. The runoff has caused the top of the streambank to erode very rapidly and has actually caused deposition at the toe. So while the slope makes it appear like the streambank is back-sloping and becoming more stable--at this location that is not actually the case. The results at all five sites demonstrate that the farm rock technique will only promote a moderate streambank angle if a large amount of deposition occurs between the weirs, which is not an unusual result with a traditional bendway weir project, but is not something we saw at any of these projects. Therefore the farm rock technique has failed to achieve this objective at these sites.

The third objective was to determine if farm rock weirs maintained their position or started to wash away. There were two aspects to looking at this objective. The first was to determine if the lack of keys in the bed and streambank would make the farm rock weir technique more vulnerable to failure. The first thing we noticed at all five projects was that the weirs lost length following the first flow events the projects experienced. The loss of length at the tip of the weir appears to occur because unlike a traditional bendway weir the farm rock weirs are not keyed into the streambed and are not made of standardized graded rock that interlocks with itself. The large farm rock of the weir is laid on top of the streambed. When high flows occur the streambed at the tip of the weir scours away and causes the rock at the tip of the weir to fall into the scoured area. Eventually the weir appears to key itself into the bed through this process, but not until it has lost a portion of its effective length. At Weaubleau Creek the loss of weir length did affect project performance. The loss of length from weirs three and four in combination with the lack of a streambank key for weir five caused the partial failure of the project. Repairs were made and the weirs have maintained their length since repair. However, in 2011 and 2012 the upper streambank behind weirs three and four began to erode and the project appears to be failing a second time due to the lack of streambank keys. At Middle Fork we attempted to apply the lessons learned from the other projects and build the weirs longer than initially planned in order to account for the anticipated length that would be lost. During the initial high flow events, the area behind the weirs began to erode and allowed flow to work behind the weirs causing the project to fail. The Middle Fork project demonstrates that while it is important to account for length that may be lost using the farm rock weir approach, it is also important not to over build the weirs.

The second part of objective three focused on determining if the use of shot rock instead of rip rap made the project more vulnerable to failure because of the rock washing away. The size of the shot rock that we used varied dramatically between the five projects and even between loads that were used at the same project. Weirs at multiple projects lost rock because it was not large enough to stay in place and was picked up and carried away by the current. At the second Jakes Creek project all eight weirs lost height and width because the smallest rock was washed away. At Dry Branch the initial failure was directly related to the size of the rock used. Prior to failure, we noted the shot rock used to build this project was smaller than the rock used in any other farm rock weir project. The Dry Branch project was rebuilt with larger rock in September 2007, but even though the shot rock used the second time was much larger than the rock used originally, the weirs have still sustained damage. Again it appears the rock has simply been picked up and moved downstream.

Technique Costs

The farm rock weir approach was intended to be a less expensive alternative to a traditional bendway weir project. In addition to examining how well the technique performed it was also vital to determine the costs associated with the technique and what savings were realized when compared to a traditional bendway weir approach. To determine the costs associated with the projects and the potential savings, we calculated the costs of building the project four different ways at each site: the experimental design with shot rock, experimental design with rip rap, the traditional design with shot rock, and the traditional design with rip rap (Table 7). On average the experimental design with shot rock saved $17.46 or 56% per foot over a traditional bendway weir built with rip rap.

It is important to note however, that repair costs can quickly eliminate most if not all the savings associated with this approach depending on the size of the repair and how often repairs need to be made. A failure due to inadequately sized rock, such as the Dry Branch project, causes the cost of the project to double and cost more than if it had been built initially with experimental rip rap or a traditional approach built with shot rock. At Weaubleau Creek the repair work increased the cost of the project by more than $6 per foot of streambank protected and additional repair work will be needed if this project is not going to fail completely. The initial project repair was still cheaper than doing a traditional approach from the beginning, but continued repair costs will quickly eliminate any savings over the traditional approach. The failure of the Weaubleau Creek project demonstrated the importance of weir placement and weir length. To save money, farm rock weirs are not keyed into the streambed or the bank. The lack of keys removes any margin of error when designing these projects. Build-

Table 7. Project costs (cost per linear foot) for an experimental farm rock weir project using shot rock and rip rap or a traditional bendway weir project using shot rock or rip rap at each site and the average costs for each. In addition the last column shows the additional cost of repairs at sites where repairs were made.

Site	Experimental Shot Rock	Experimental Rip Rap	Traditional Shot Rock	Traditional Rip Rap	Cost of Repair
Jakes Creek Site 1	$14.17/ft.	$20.04/ft.	$20.95/ft.	$30.72/ft.	---
Jakes Creek Site 2	$19.57/ft.	$25.96/ft.	$28.65/ft.	$39.29/ft.	---
Dry Branch	$11.80/ft.	$18.65/ft.	$20.50/ft.	$31.10/ft.	$10.97/ ft.
Weaubleau Creek	$8.17/ft.	$14.38/ft.	$15.17/ft.	$25.52/ft.	$6.97/ft.
Middle Fork	$15.31/ft.	$21.64/ft.	$24.40/ft.	$29.68/ft.	---
Average Costs	$13.80/ft.	$20.13/ft.	$21.93/ft.	$31.26/ft.	$8.59/ft.

ing the farm rock weirs longer to account for the loss of rock would have eliminated some of the initial savings from using this approach versus a traditional approach and it resulted in project failure at the Middle Fork project.

The alternate approaches of building the farm rock weirs with rip rap or using the traditional bendway weir design with shot rock both would have saved approximately $10.00 or 32% per foot of streambank when compared to the traditional approach. However neither of these approaches was tested and they do not address all the reasons that the experimental approach we tried failed and any repair costs using these techniques would immediately remove the savings you gain over a traditional project.

DISCUSSION

We established the limitations of the farm rock weir technique as an approach to streambank stabilization. Given the failure rate we saw and the additional expenses that would have resulted from repair, it is unlikely that someone would choose this technique over the traditional approach. Cost reduction was the goal of making changes to the original bendway weir technique; however, those cost saving measures were the main reasons that four of the five projects either failed and had to be repaired or needed maintenance to avoid failure. The cost savings associated with eliminating the keys and using shot rock made these projects more susceptible to failure than the traditional approach.

The lack of keys in the streambed and in the streambank behind each weir resulted in weirs at all sites losing length and the failure of two projects. All the farm rock weirs attempted to key themselves into the streambed after they were built. Scour of the streambed at the tips of the weirs resulted in the rock at the tip of the weir falling into that scour hole until enough rock fell into the hole to stop the process. This process shortened the effective length of the weirs. The Weaubleau Creek project initially failed, because of this process in combination with the lack of streambank keys. When weirs three and four lost length, they no longer redirected flow enough to keep it from getting behind weir five. The design of the project was altered by the change in weir length and since there was no safety factor built into the weirs in terms of a streambank key the project failed. At Middle Fork we attempted to learn from what had happened at the other projects and built the weirs longer in order to account for the expected loss in length; however, building the weirs extra-long at this project actually resulted in the project failing. There were several factors that contributed to the failure 1) the overextended weirs blocked too high a percentage of the channel backing up the flow and making it look for an easier path, 2) lack of keys in the streambank allowed the flow to divert into the streambank and around the weirs, 3) the lack of streambank and riparian vegetation on the eroding streambank created a situation where there were virtually no resisting forces in comparison to the well vegetated opposite bar, and 4) since the farm rock was not graded to a standardized specification that allows the rock to interlock and hold together better, it could not withstand the velocities and washed away. The project demonstrates that you will need to balance the potential for the weirs to lose length while not over building them. The lack of bed and streambank keys makes the farm rock weir approach extremely vulnerable to failure even with proper project design in terms of placement and weir length.

The second alteration to a bendway weir approach that was used to save money was the use of shot rock instead of rip rap. Rip rap is standardized to have a certain percentage of the rock graded out to a certain size or weight, but farm rock weirs use shot rock instead, which is made from rock of a wide range of sizes. The result of using shot rock was that at all five projects the weirs lost a significant amount of the rock that was smaller than rip rap. The rock was simply picked up during high flow events and carried downstream. Loss of rock affected the performance at all the sites but only at Dry Branch did it result in project failure. At Dry Branch the initial shot rock used to build the project was noticeably smaller than the rock used at the other projects and during a flow event almost all the rock was simply picked up and carried downstream. The project was rebuilt with larger rock, but the weirs have still sustained damage. Again it appears the rock has simply been picked up and moved downstream. Our initial approach to building the farm rock weirs was to aim for having the median size of the shot rock used is equivalent to the size of rip rap (200-230 lbs. or 1.3-1.5 ft. in diameter). That approach still leaves a large portion of the rock used to build the weirs vulnerable to being washed away, especially since the shot rock does not fit together in the way that rip rap does.

If maintenance is required for a farm rock weir project, then the savings over a traditional bendway weir project are lost or greatly reduced. Four of the five projects have been repaired, modified, or failed. The reasons have varied from site to site, but together have outlined the critical aspects of using a farm rock weir approach. The most important factors in the success or failure of a farm rock weir project are having adequately sized rock (with the majority of it being larger than the median rock size of 200-230 lbs. or 1.3 -1.5 ft. in diameter required for rip rap), placement and length of the weirs, and potential changes upstream of the project that can alter the direction of the flow as it approaches the project. Even a traditional bendway weir will not function properly if the upstream weir is flanked because channel movement upstream significantly alters how flow approaches the project. The cost-savings associated with not keying farm rock weirs into the bed and banks make them more susceptible to these problems. The failures of the experimental approach is a strong indication that engineered bendway weirs made of rip rap ultimately save time, money, and further streambank erosion.

MANAGEMENT IMPLICATIONS

Application of the lessons learned from studying these five projects could result in modifications to the farm rock weir technique that could result in cost reductions over the traditional approach and perhaps with better success. Building farm rock weirs using rip rap instead of shot rock would save $11 or 36% per foot of streambank when compared to the traditional approach. The cost is $6 or a 45% increase per foot compared to the experimental approach we used, but the extra $6 would remove any risk of getting undersized rock that would not stay in place. The modified approach would not have changed the result at either Middle fork or Weaubleau Creek where failure was caused by the lack of bed and streambank keys. In addition, this approach has not been tested so there is a lot of uncertainty about what its other limitations might be and with only $11 in saving any repairs will make it cost as much as a traditional project and still leave it potentially more vulnerable to failure than the traditional project.

The other potential alternate approach would be to use the traditional design with shot rock instead of rip rap. This approach would save more than $9 or 30% per foot versus the traditional approach. The extra $8 over the approach we used would buy you some margin of error in your design of the project because you would have keys to protect against water getting behind the weirs and loss of length at the weir tip. Building a traditional project with shot rock would have helped the situation at both Middle Fork and Weaubleau, but would not have addressed the failure at Dry Branch where small shot rock size was the cause. This alternative also would not have prevented the loss of rock we saw at all projects due to the use of small rock. We attempted to avoid this problem by asking for the largest shot rock we could get, but rock size often varied between loads from the same quarry. The result was we often got rock that was smaller than we wanted and with only $8 per foot in savings compared to the traditional approach once again any repairs will make it cost as much as a traditional project and still leave it potentially more vulnerable to failure than the traditional project. These additional approaches might be useful if you are unsure about the source of rock and the type of shot rock you can get or if using shot rock with keys would allow you to protect against project design issues, but neither has been tested so their limitations are unknown.

Overall the farm rock weir approach seems to have few advantages over using a traditional bendway weir design. The failures were due to inadequately sized rock, and lack of bed and streambank keys, which were the things we altered from the traditional bendway weir approach to try to save money. If maintenance is required, the savings over a traditional bendway weir project are lost or greatly reduced, and any riparian vegetation that has established will be removed or damaged. The choice of approach will depend on the size of the streambank and stream in question, the risks associated with a failed project, and the resources available both financially and in terms of design experience. The mixed results from these projects show that while this approach may have limited potential as a streambank stabilization technique in most cases the traditional approach will be the better choice. Additional modifications to the farm rock weir approach along with monitoring could result in a technique that does have actual potential, but without further study that is uncertain and any modifications will reduce the savings over a traditional approach making that more likely the better option. The farm rock weir approach should not be attempted by a landowner without the assistance of an experienced professional and at this stage is not an approach we would recommend to landowners.

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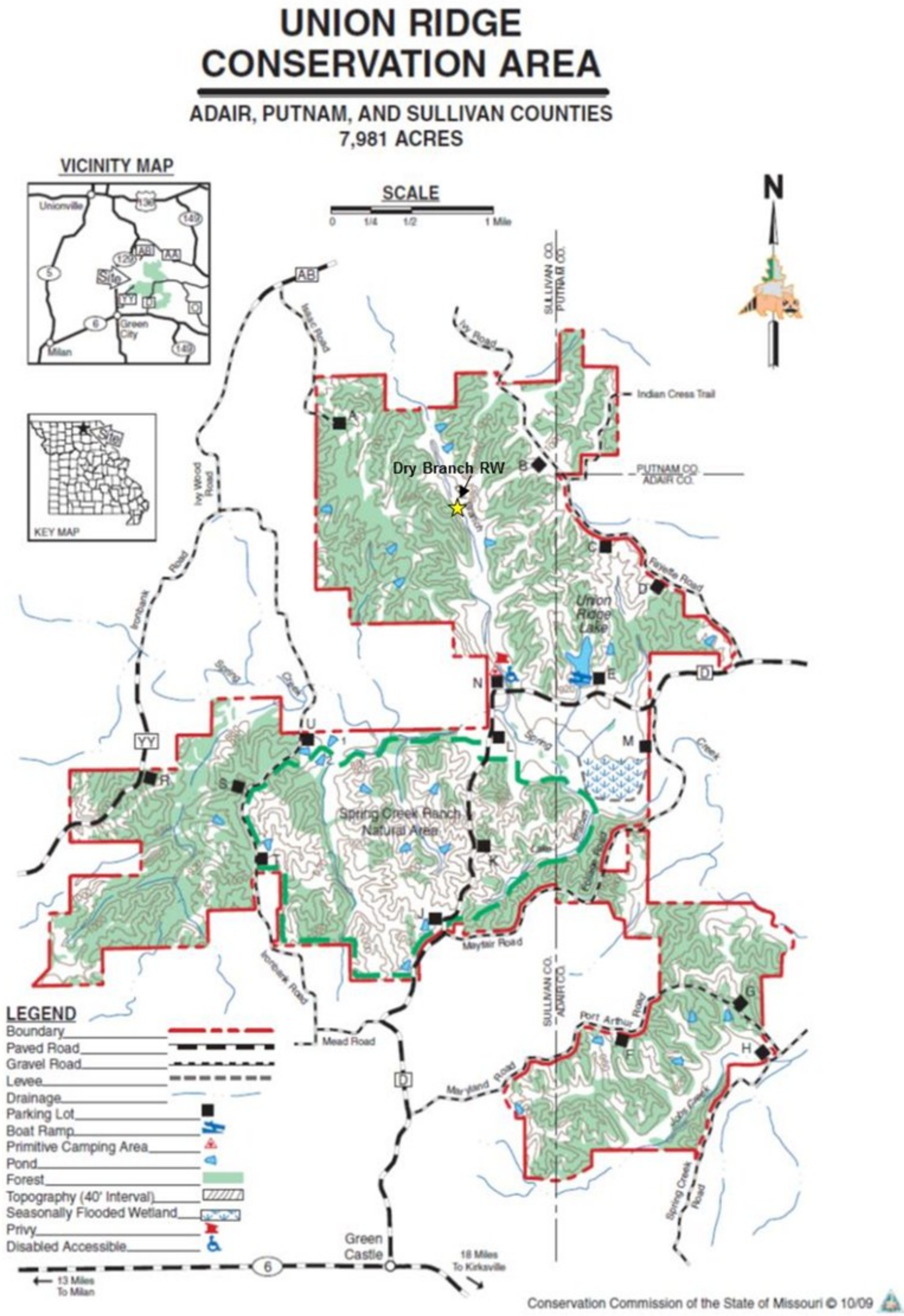
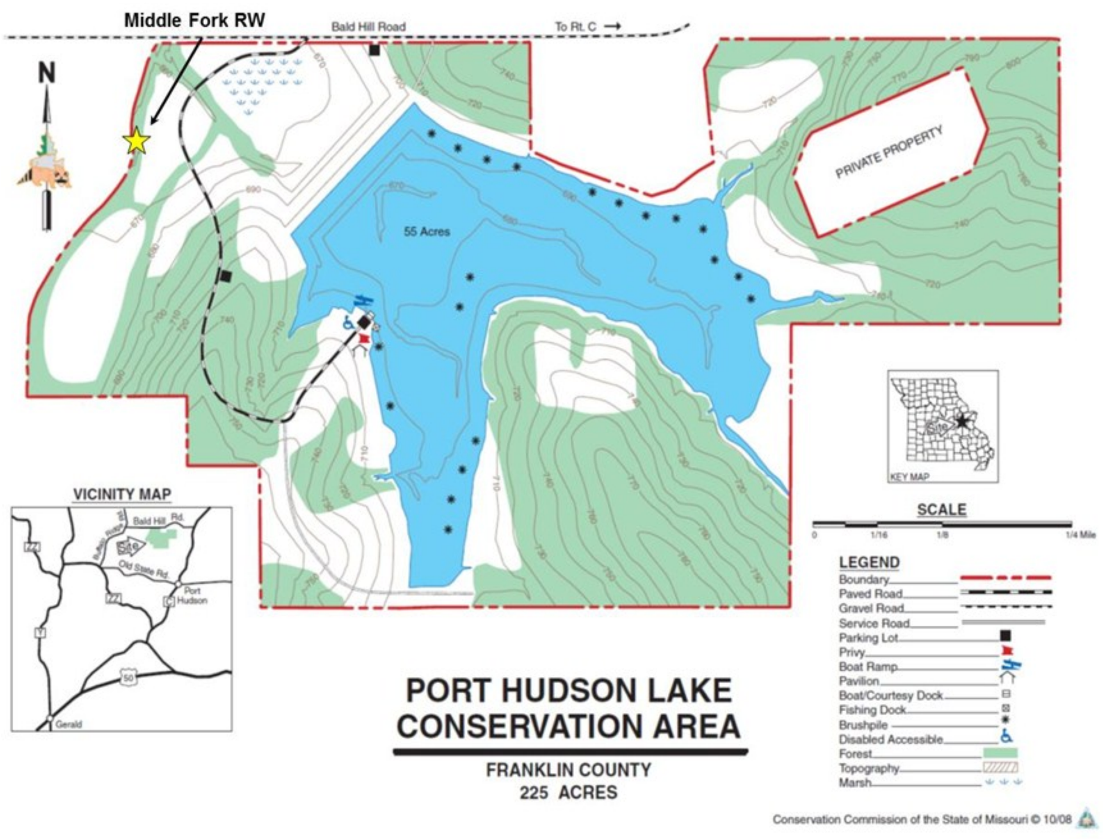
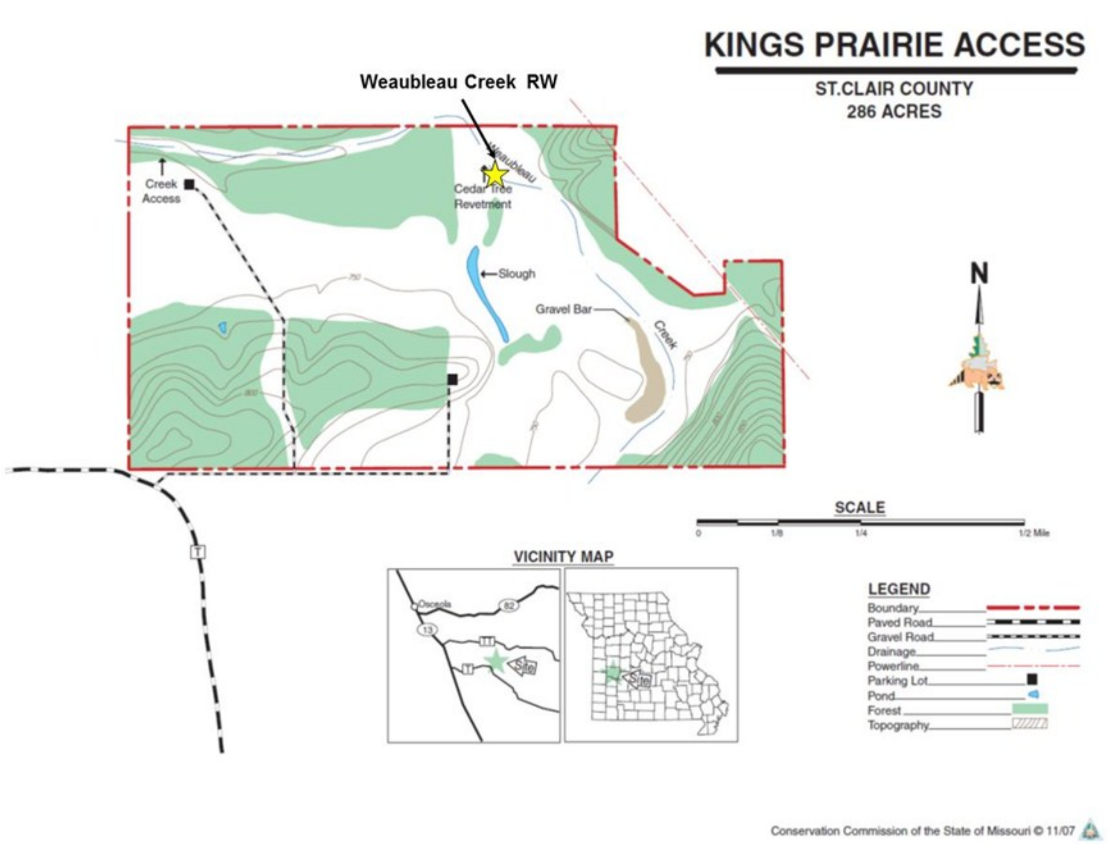
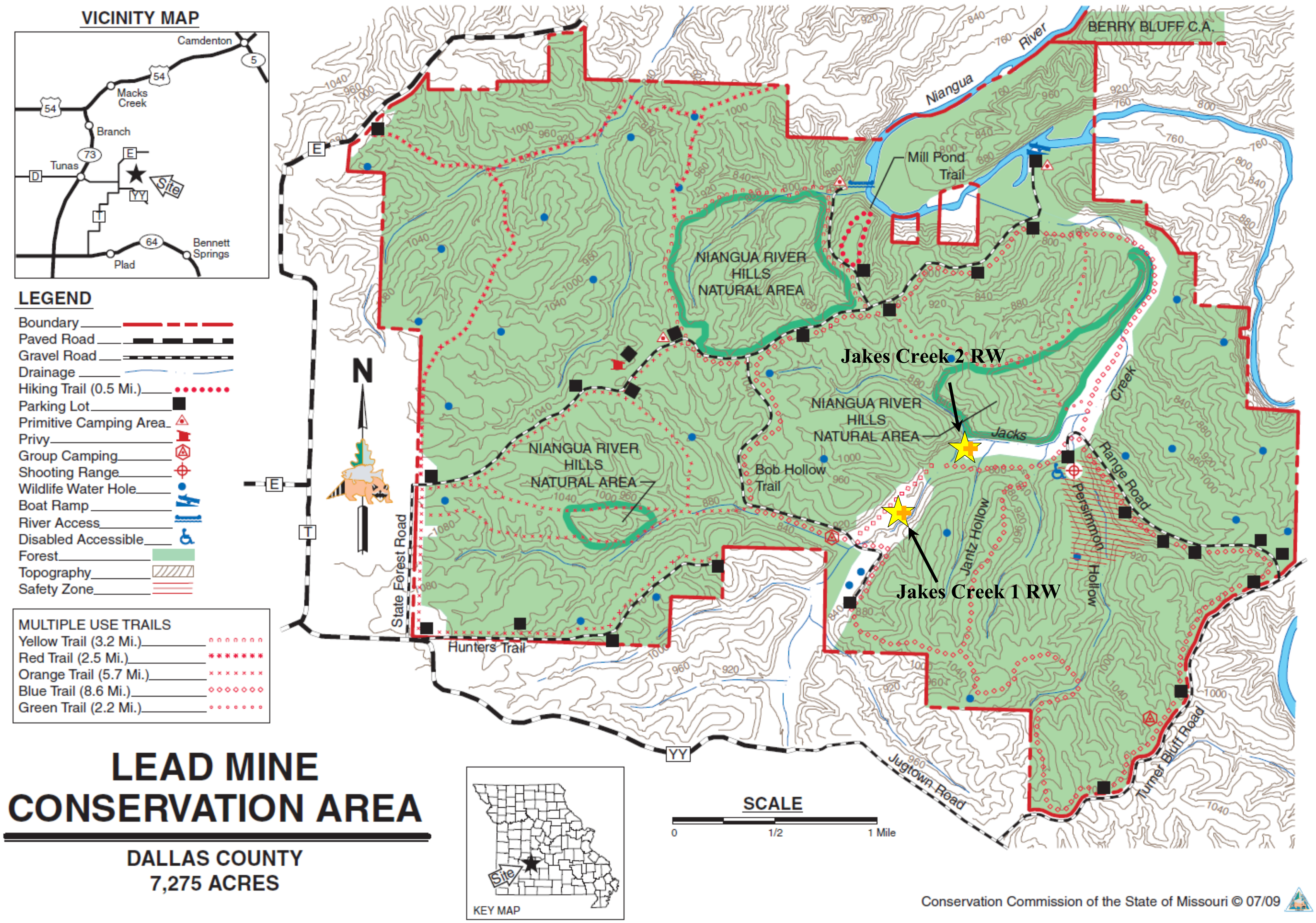
Appendices

Appendix 1: Area Maps




Middle Fork RW
Bald Hill Road
To Rt. C →
N
55 Acres
PRIVATE PROPERTY
VICINITY MAP
KEY MAP
SCALE
LEGEND
Boundary
Paved Road
Gravel Road
Service Road
Parking Lot
Privy
Boat Ramp
Pavilion
Boat/Courtesy Dock
Fishing Dock
Brushpile
Disabled Accessible
Forest
Topography
Marsh
PORT HUDSON LAKE
CONSERVATION AREA
FRANKLIN COUNTY
225 ACRES
Conservation Commission of the State of Missouri © 10/08


KINGS PRAIRIE ACCESS
ST.CLAIR COUNTY
286 ACRES
Weaubleau Creek RW
Creek Access
Cedar Tree Revetment
Weaubleau
Slough
Gravel Bar
Creek
N
SCALE
VICINITY MAP
Osceola
LEGEND
Boundary
Paved Road
Gravel Road
Drainage
Powerline
Parking Lot
Pond
Forest
Topography
Conservation Commission of the State of Missouri © 11/07


VICINITY MAP
Camdenton
Macks Creek
Branch
Tunas
Plad
Bennett Springs
Site
LEGEND
Boundary
Paved Road
Gravel Road
Drainage
Hiking Trail (0.5 Mi.)
Parking Lot
Primitive Camping Area
Privy
Group Camping
Shooting Range
Wildlife Water Hole
Boat Ramp
River Access
Disabled Accessible
Forest
Topography
Safety Zone
MULTIPLE USE TRAILS
Yellow Trail (3.2 Mi.)
Red Trail (2.5 Mi.)
Orange Trail (5.7 Mi.)
Blue Trail (8.6 Mi.)
Green Trail (2.2 Mi.)
LEAD MINE
CONSERVATION AREA
DALLAS COUNTY
7,275 ACRES
KEY MAP
SCALE
0
1/2
1 Mile
N
BERRY BLUFF C.A.
Niangua
River
Mill Pond
Trail
NIANGUA RIVER
HILLS
NATURAL AREA
Jakes Creek 2 RW
Jakes Creek 1 RW
Jacks
Creek
Bob Hollow
Trail
Jantz Hollow
Persimmon
Hollow
Range Road
State Forest Road
Hunters Trail
Jugtown Road
Turner Bluff Road
Conservation Commission of the State of Missouri © 07/09

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