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Experimental Farm Rock Toe Protection 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 five different streambank stabilization techniques. Farm rock toe was evaluated as a potential low cost alternative to a traditional longitudinal rip rap toe project for controlling excessive streambank erosion. The differences between farm rock toe and a traditional longitudinal rip rap toe protection approach are four fold: 1) farm rock toe is made from shot rock (quarry rock not graded out to a specific size) instead of graded out rip rap, 2) farm rock toe is not keyed into the bed of the stream, 3) farm rock toe is not keyed into the streambank at the upper and lower end of the project, and 4) instead of placing each rock, the rock is dumped from the top of the streambank and then adjusted as necessary to fill in gaps. These changes were made to reduce the cost of a rock toe protection approach while hopefully still stabilizing the bank. Six farm rock toe projects were distributed among five streams located on five MDC conservation areas across the state. The projects were built between September 2006 and February 2008 and all experienced multiple high-flow events.

The farm rock toe technique had mixed results, but four of the projects have remained stable during the length of the study. The Starks Creek project experienced numerous high flow events and protected the toe while the slope of the streambank was reduced and vegetation became established. The Weaubleau Creek project experienced the most frequent and largest flow events of any of the projects. The toe rock has stayed in place, there has been a slight reduction in streambank slope and vegetation has established on the bank. The Sulphur Branch project was only tested by a small number of flow events that resulted in no actual changes to the bank, but there has been a rapid and extensive establishment of vegetation at this site that will help protect the streambank long-term. The second of two farm rock toe projects constructed on an unnamed tributary of Fiery Fork was not tested at all because the stream shifted away from the project immediately following construction and the resulting deposition has filled in the old channel and buried the project and bank.

Two projects were considered failures. The first of two farm rock toe projects built on an unnamed tributary of Fiery Fork failed completely when all the rock from the apex of the bend downstream was washed away during a high flow event. The California Branch project is considered a failure because all the rock located at the downstream ¼ of the project has washed away. Upstream of this the rock is in place and vegetation has begun to establish on the bank, however the lower end does not have any vegetation establishment occurring and there is almost no rock still in place. Although currently there has not been any erosion of the streambank it is considered a failure because there is nothing to prevent it from occurring going forward. The two failures both appear to be due to inadequate rock size and not a flaw in the stabilization technique.

Overall four of the five projects that were tested by flow events protected the streambank during the course of the study, although one of these is now starting to fail. The sixth project built was never tested because a channel shift occurred immediately following construction taking all the pressure off the project and should not be considered a successful use of the technique. The results indicate this approach does have potential for use as a streambank stabilization technique and the information gained at five of the six projects will be applicable to improving this stabilization technique. The most important factors in the success of a traditional rip rap toe protection project are the stability of your starting point and the size of the rock used. At these six projects we did not have any issues related to not using bed or streambank keys. The lack of keys did not affect project performance because our projects started and stopped at stable points. Two of the projects were negatively impacted by using shot rock instead of rip rap as the undersized rock we received resulted in the failure and partial failure of those projects. Additional modifications to the farm rock toe approach, such as using rip rap instead of shot rock could result in a technique that has potential, and may be worthy of further investigation in the future.

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 longitudinal rip rap toe protection. Longitudinal rip rap toe protection involves the placement of rock at the toe of an eroding bank. Rip rap toe protection is used where the streambank toe is eroding and other techniques are not appropriate because the streambank is too high, the current is too strong, or the cost associated with potential failure is too expensive (Shields et al. 1995, Allen and Leech 1997, North Dakota Forest Service 1999, Moses and Morris 2001b, Johnson 2003). Using rip rap to protect the toe of a streambank is not an appropriate solution at sites that are vertically unstable. Rip rap toe protection can cost $70 -$100 per linear foot (Maryland Department of the Environment 2000) and should be used in conjunction with vegetation establishment techniques. These costs exceed what most landowners can afford without considerable cost-share support. As a result, while longitudinal rip rap toe protection offers a potential solution to erosion problems the associated cost makes it unavailable to many landowners.

This project tested farm rock toe as a potential alternative to longitudinal rip rap toe protection. The farm rock toe protection technique was designed to be a cost-effective alternative to a traditional longitudinal rip rap toe protection streambank stabilization project. The cost-reduction comes from using less expensive shot rock and less total rock to build the project. The objectives of this study were to examine the performance of farm rock toe 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 toe could withstand high flow events and maintain its position, and 4) if farm rock toe was a cost effective alternative to longitudinal rip rap toe protection.

STUDY SITES

Farm rock toe protection was evaluated at six 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 toe rock approach the appropriate choice for the stabilization technique. Selected stream segments were located on Starks Creek on Mule Shoe Conservation Area (MSCA) in Hickory County, Weaubleau Creek on Kings Prairie Access (KPA) in St. Clair County, Sulphur Branch on Canaan Conservation Area (CCA) in Gasconade County, California Branch on Little Indian Creek Conservation Area (LICCA) in Washington County, and an unnamed tributary of Fiery Fork that received two of the six projects on Fiery Fork Conservation Area (FFCA) in Camden County. River and project site details are located in Table 1. Area maps showing the locations of the conservation areas within Missouri and project locations within those areas are provided in Appendix 1.

METHODS

Farm Rock Toe Design

The farm rock toe protection approach was designed to stop erosion by armoring the toe of the streambank in order to protect it from the erosive force of the river (Figure 1). Rock covers and extends along the streambank until it connects two stable points (Figure 2). The farm rock toe approach was selected in order to provide a cost effective alternative to rip rap toe protection that still achieved a stabilized streambank. The differences between farm rock toe and a traditional approach are four fold: 1) farm rock toe is made from shot rock instead of graded out rip rap, 2) farm rock toe is not keyed into the bed of the stream, 3) farm rock toe is not keyed into the streambank at the upper and lower end of the project, and 4) instead of placing each rock, the rock is dumped from the top of the streambank and then adjusted as necessary to fill in gaps. The initial approach to building the farm rock toe 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 longitudinal rip rap toe protection approach while hopefully still 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 Starks

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

	Starks Creek	Weaubleau Creek	Sulphur Branch	California Branch	Fiery Fork 1	Fiery Fork 2
River Basin	Little Niangua	Osage	Gasconade	Meramec	Little Niangua	Little Niangua
Physiographic Region	Salem Plateau	Ozark Plateau	Interior Ozark Highlands	Salem Plateau	Ozark Plateau	Ozark Plateau
Stream Order	4	4	2	2	3	3
Reach Gradient	29 ft./mi	11 ft./mi	60 ft./mi	64 ft./mi	70 ft./mi	70 ft./mi
Watershed Area	35 mi^2	121 mi^2	2 mi^2	1.5 mi^2	3.6 mi^2	3.6 mi^2
Bank Height	10 ft.	12 ft.	8 ft.	6 ft.	6 ft.	6 ft.
Bank Length	183 ft.	397 ft.	239 ft.	85 ft.	232 ft.	232 ft.

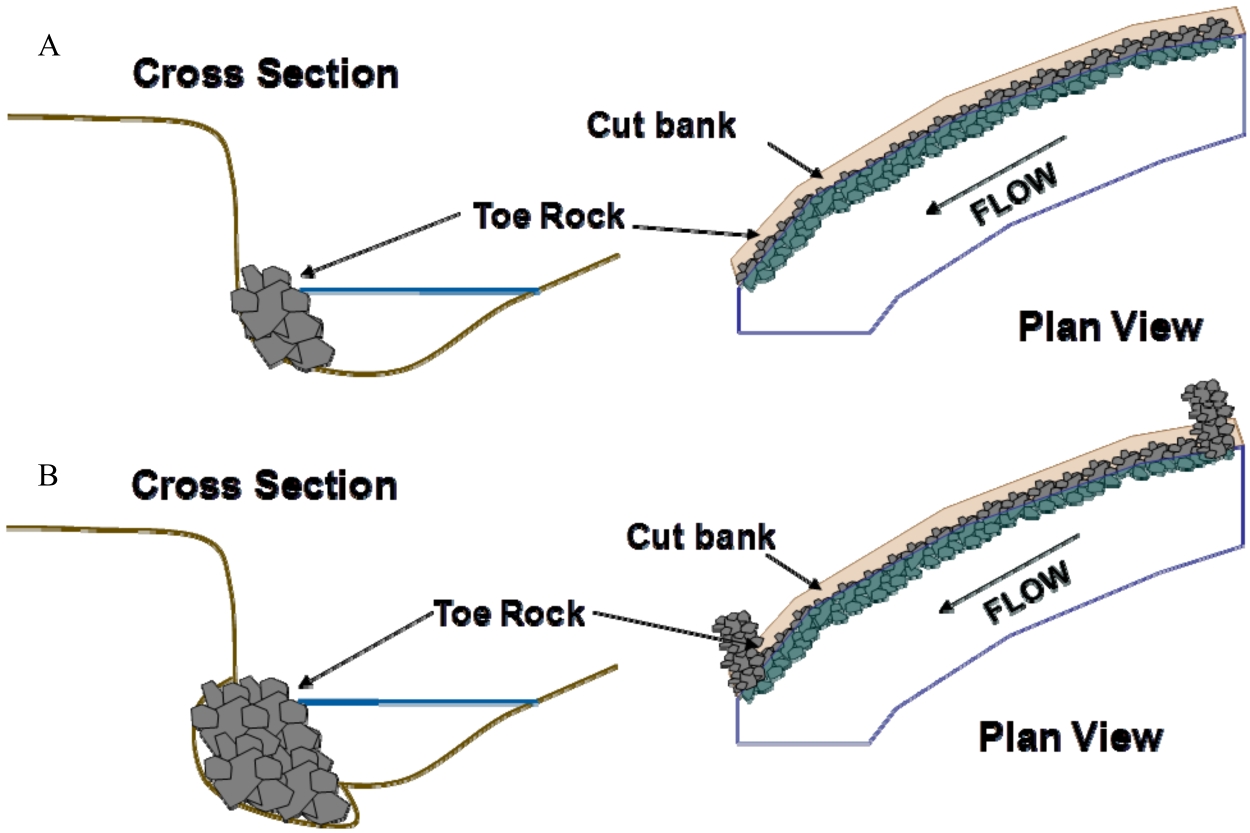

Figure 1. (A) Cross section and plan view of a generic experimental farm rock toe project. (B) Cross section and plan view of a generic traditional rip rap blanket project.

Figure 2. Rock being dumped at the toe of the bank. (A) Dump truck used during project construction at Weaubleau Creek. (B) Backhoe used during project construction at Sulphur Branch.

Creek and Weaubleau Creek farm rock toe projects were both built in September of 2006. The Starks Creek project was the only project built by placing all the rocks using a backhoe instead of dumping the rock from the top of the bank and then spreading it around. The placement was done because of the presence of Niangua darter (federally listed as threatened) at this location. The Fiery Fork Site 1 farm rock toe project was built on the unnamed tributary of Fiery Fork in April 2007 and Fiery Fork Site 2 was built in February 2008. The California Branch farm rock toe project was built in May 2007. The Sulphur Branch project was built in June of 2007 and was overbuilt. The farm rock toe covered ¾ of the streambank height instead of the targeted ⅓ to ½ of the streambank height.

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 and a longitudinal profile of the channel thalweg. All transects ran from a benchmark on the eroding streambank to the top of the gravel bar or streambank across the channel, except for the California Branch project. Those transects started on the opposite streambank and ran to the top of the eroding bank. Transects were evenly distributed down the length of the project. 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. Project features including the toe rock, top of the eroding bank, wetted channel, gravel bars, opposite bank, benchmarks, and other features were mapped with a 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 in the project 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) placed away from the stream to monitor flow. The Levelogger® is a pressure transducer that uses changes in pressure to track changes in stage. 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

Starks Creek

The Starks Creek project was tested by numerous flows that exceeded ¾ the height of the streambank and went over the top of the eroding streambank since construction (Figure 3). In addition to the flows shown on the stage graph there were at least two flow events between April and June 2007 that were not recorded because of a malfunction with the Levelogger® in late March that was not detected until July. During 2008, the project was tested by four flow events that reached stages above the top of the bank. Those events caused a streambank located upstream to wash

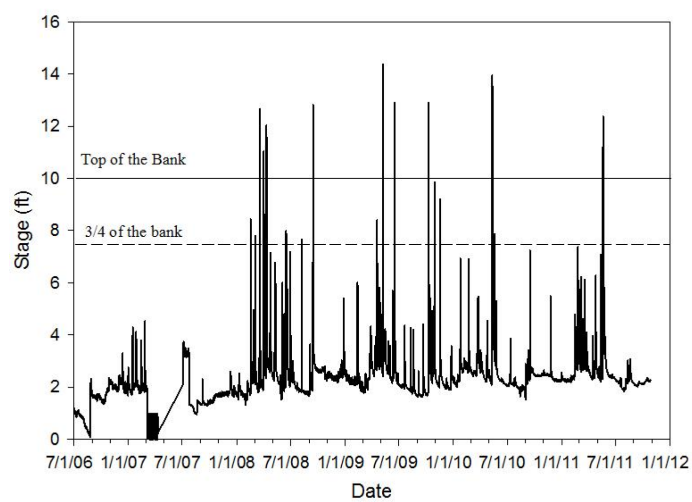

Figure 3. Levelogger® data from Starks Creek for 2006 through 2011. Data are missing from March 2007 until July 2007 due to a Levelogger® malfunction.

Figure 4. Photos of the stream approach to the Starks Creek farm rock toe project. (A) Looking upstream of project in April 2007. (B) Looking upstream of project in July 2011. Yellow arrow is pointing at same tree.

out, changing the streams approach to the project. These changes continued in the fall of 2008 as the streambank directly upstream began to fail as well. Starks Creek had three more flows in 2009 that went over the top of the bank. Included in this was a flow with a stage over 14 ft. which represents the highest flow recorded at this site during the study. This flow caused the opposite streambank upstream of the project to completely fail causing dramatic change in the stream's approach to the project (Figure 4). In both 2010 and 2011, the project was only tested by a single high flow event. These flows continued to cause changes to the streambank upstream of the project. GIS maps from September 2006, June 2008, July 2010, and July 2011 show how much change has occurred in the channel upstream of this project (Figure 5). The toe rock project withstood all of these flow events and has worked despite the changes in the stream morphology above the site with deposition and vegetation establishment occurring at the project site (Figure 6).

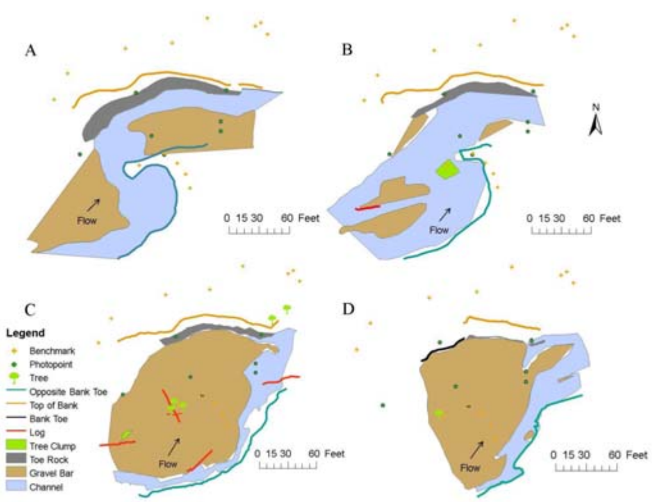

Figure 5. GIS maps of the Starks Creek farm rock toe project. (A) Post-construction map September 2006. (B) Channel changes June 2008. (C) Channel changes July 2010. (D) Channel changes July 2011.

Despite large amounts of erosion occurring on the banks surrounding this project, this site has remained stable. For the first two and a half years the project survived numerous high flows and performed as planned. The thalweg shift that occurred in 2009 resulted in large amounts of deposition at the toe of the streambank and between the streambank and the new channel. The physical surveys, which were conducted post-construction and following flow events each year from 2007-2011 show how the channel shifted away from the bank. The original thalweg that was against the streambank has filled in with deposition and in places it has shifted more than 100 ft. away from the bank. The survey data appear to show that there has been erosion at the toe of the streambank for five of the seven transects (Table 2). However this movement is actually due to deposition of material that has formed a new gravel bar in front of the eroding streambank and that has covered up the original toe of the bank, resulting in the toe moving back and up the streambank (Figure 7). This is confirmed by the fact that the slope has been reduced for six of the seven transects with the other transect remaining the same.

Weaubleau Creek

The Weaubleau Creek project experienced the most frequent and largest flow events of any of the farm rock toe protection projects (Figure 8). Three

Figure 6. Photos of the Starks Creek farm rock toe project. (A) Looking downstream following construction in September 2006. (B) Looking downstream in October 2011.

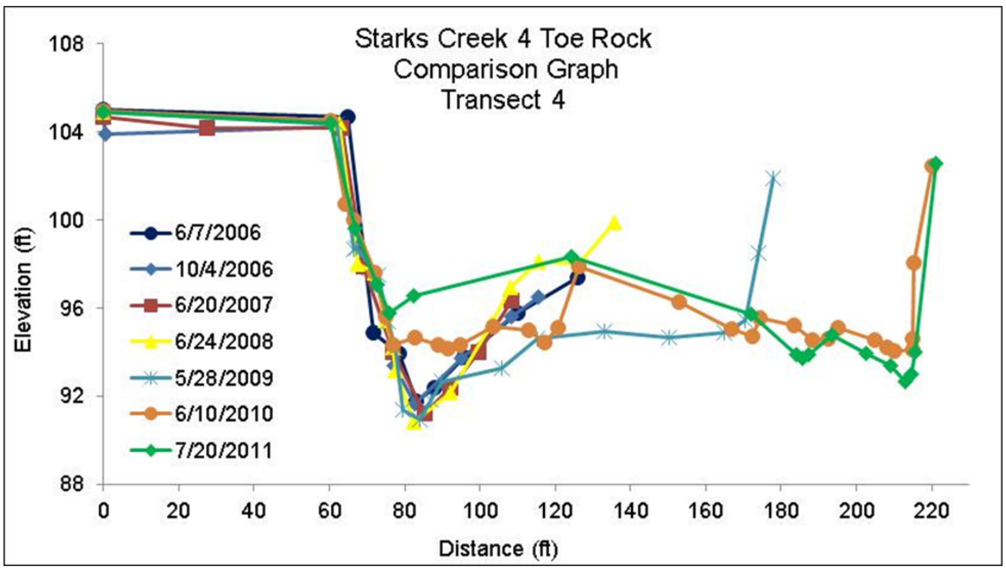

Figure 7. Physical survey data for transect four covering the pre-construction survey (6/7/2006), post-construction survey (10/4/2006), and five post-flow surveys (6/20/2007, 6/24/2008, 5/28/2009, 6/10/2010, and 7/20/2011).

Table 2. Streambank movement and changes in streambank slope due to erosion at the Starks Creek farm rock toe project between the post-construction survey in October 2006 and the final survey in July 2011. 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 Movement (ft.)	Toe of streambank Movement (ft.)	Bank Slope 10/2006	Bank Slope 7/2011
Transect 0	-1.56	3.84	0.33	0.19
Transect 1	-1.05	0.47	0.37	0.26
Transect 2	-2.30	-3.43	0.51	0.46
Transect 3	-0.88	-1.03	0.65	0.57
Transect 4	-2.87	-1.10	0.75	0.56
Transect 5	-2.58	-3.99	0.83	0.84
Transect 6	-6.64	-2.46	2.53	1.35

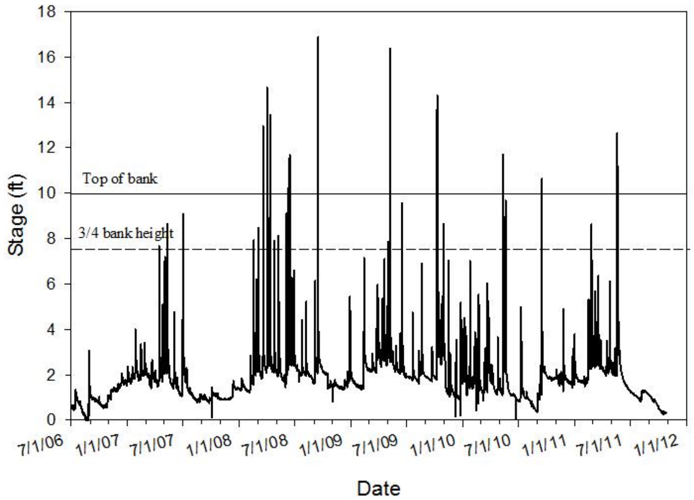

Figure 8. Levelogger® data from Weaubleau Creek for 2006 through 2011.

flow events in 2007 reached a stage between ¾ the height of the streambank and the top of the bank. The project was tested by numerous flow events in 2008, including six that went over the top of the bank. The largest of these flow events reached a stage >16.5 ft. and represented a 14 ft. rise over the average flow during the previous week. In 2009, the project was tested by two flow events that went over the top of the bank, one of which was over 16 ft. in stage. In 2010 and 2011, the project was tested by two more flow events each year that topped the eroding bank. The project survived all of these flow events and appears to be working as planned (Figure 9). The number and size of the flow events that have tested this project have given an excellent baseline for evaluating the performance of this project.

The physical surveys, which were conducted pre-construction, post-construction and following flow events each year from 2007-2011, show the streambank stability since project construction. We have seen a small amount of erosion at the top of the streambank for all transects and deposition at five of the six transects (Table 3). The apparent deposition is due to the toe rock settling into areas of scour and not due to deposition of new sediment, but there was enough rock in place for it to do this without affecting the project's ability to protect the bank. Streambank movement resulted in a slight reduction in streambank slope that was evident for five of the six transects. Transect four gives a good example of how the addition of the toe rock and the small amount of erosion at the top of the streambank has resulted in a streambank with a more moderate slope (Figure 10). The reduced slope along with vegetation establishment has made this project successful.

Sulphur Branch

The Sulphur Branch project has only been tested by a few flow events since construction (Figure 11). Following construction, the project did not experience any flow events during the rest of 2007. In the spring of 2008, the project was tested by at least one and potentially multiple flow events that reached a stage greater than ¾ of the streambank height. Unfortunately, the number and size of those flow events are unknown because during one flow event the Levelogger® was lost and not replaced until June 2008. Following replacement of the Levelogger® there was one flow event greater than ¾ of the streambank height in both 2008 and 2009, and in 2010 the project was test-

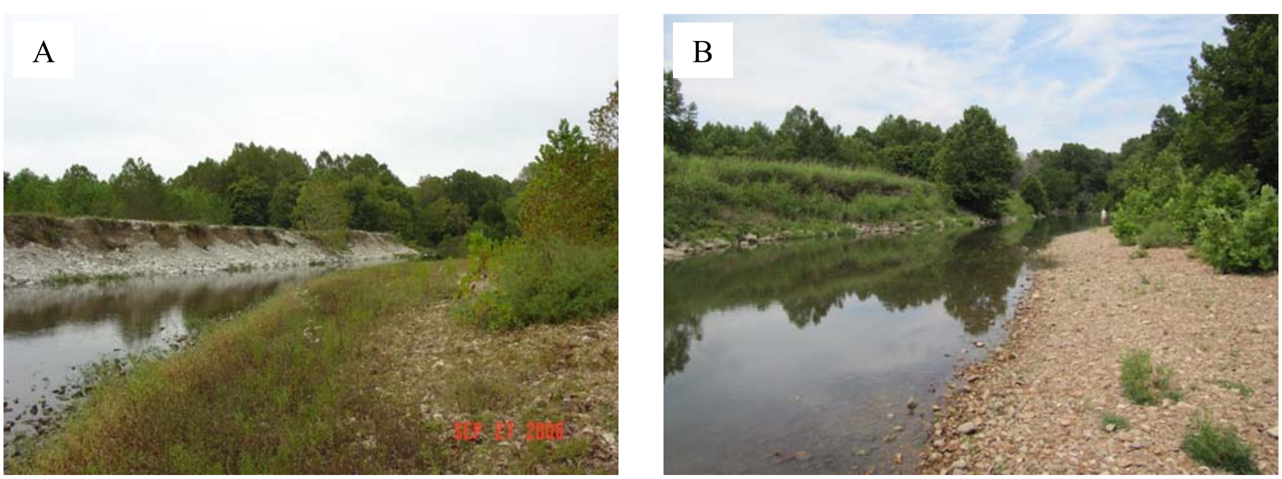

Figure 9. Photos of the Weaubleau Creek farm rock toe project. (A) Looking downstream following construction in September 2006. (B) Looking downstream in August 2011.

Table 3. Streambank movement and changes in streambank slope due to erosion at the Weaubleau Creek farm rock toe project between the post-construction survey in September 2006 and the final survey in August 2011. 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 Movement (ft.)	Toe of streambank Movement (ft.)	Bank Slope 9/2006	Bank Slope 8/2011
Transect 1	-0.59	-0.06	0.63	0.70
Transect 2	-4.85	2.55	0.73	0.56
Transect 3	-1.05	3.46	0.64	0.58
Transect 4	-1.85	1.34	0.66	0.63
Transect 5	-3.47	2.25	0.89	0.62
Transect 6	-1.76	12.76	0.69	0.68

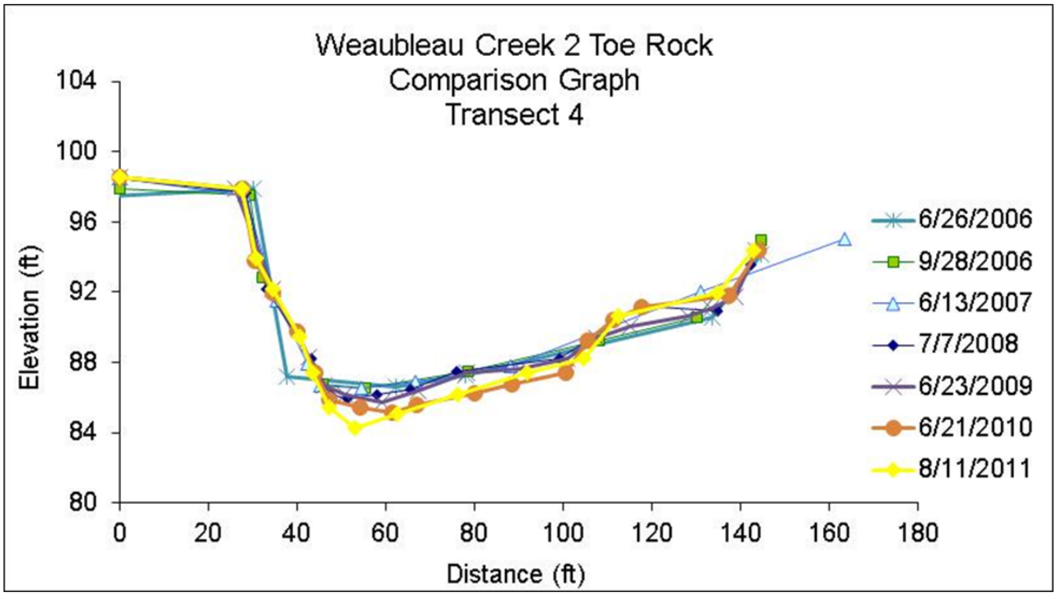

Figure 10. Physical survey data for transect four covering the pre-construction survey (6/26/2006), post-construction survey (9/28/2006), and five post-flow surveys (6/13/2007, 7/7/2008, 6/23/2009, 6/21/2010, and 8/11/2011).

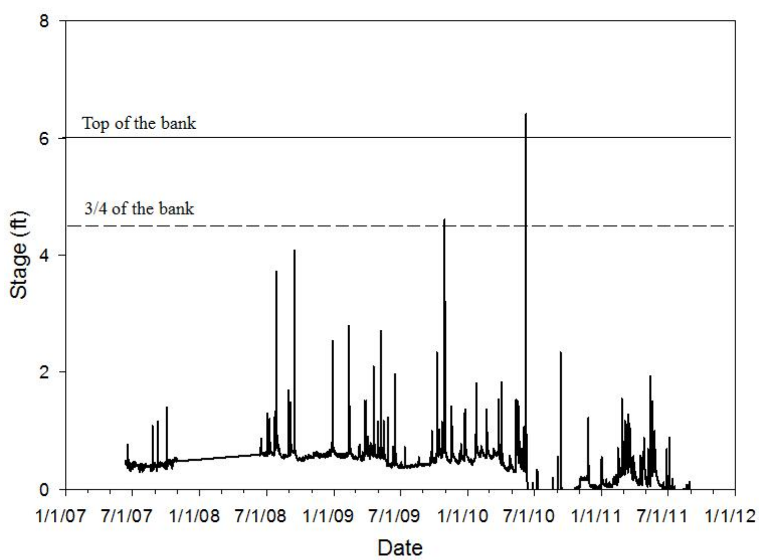

Figure 11. Levelogger® data from Sulphur Branch for 2007 through 2011. Data are missing from November 2007 until June 2008 due to a lost Levelogger®.

ed by a flow event that went over the top of the bank. There was no large flow events recorded in 2011. The small number of flow events that have occurred on this stream makes it difficult to assess the success of this project.

The farm rock toe project has withstood the few flow events that occurred and appears to be working as planned. Vegetation has become established throughout the entire length of the project in the toe rock; so much so that summer pictures can no longer be used to show the bank. The establishment of vegetation has increased stability greatly (Figure 12). The physical surveys, which were conducted post-construction and following flow events each year from 2008-2011, demonstrate that there has been no large changes in the streambank and that is has remained stable since project construction. Streambank movement along each transect has been minimal between the post-construction and post-flow surveys and the slope of the streambank has remained relatively stable (Table 4). There has been some loss of rock at the downstream end of the project but since this project was built so that it covered close to ¾ of the streambank height instead of the designed ⅓ to ½ of the streambank height there is still plenty of rock in that area protecting the bank.

Figure 12. Sulphur Branch farm rock toe project. (A) Looking upstream following construction in August 2007. (B) Looking upstream in September 2011. (C) Looking upstream following construction in August 2007. (D) Looking upstream in September 2011.

California Branch

Since construction the California Branch project has been tested by only a few flow events greater than ¾ of the streambank height (Figure 13). Following construction, the project was not tested by any flow events during the rest of 2007. In the spring of 2008, the project was tested by at least one and potentially multiple flow events that reached a stage of ¾ of the streambank height or higher. Unfortunately, the number and size of flow events are unknown because during a high flow event the Levelogger® was lost and not replaced until late June 2008. In 2009, there were four flow events that were greater than ¾ of the streambank height and one greater than top of the streambank event. In both 2010 and 2011, there was a single flow event that reached a stage of ¾ of the streambank height or higher.

While the toe rock project has prevented toe erosion up until this point, it has sustained damage at the downstream end of the project (Figure 14). The project has lost a large portion of the original rock in some places, particularly at the downstream end of the project. So far this loss of rock has not resulted in damage to the bank, but has left the project vulnerable to damage. The loss appears to be due to inadequate

Table 4. Streambank movement and changes in streambank slope due to erosion at the Sulphur Branch farm rock toe project between the post-construction survey in August 2007 and the final survey in September 2011. 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 Movement (ft.)	Toe of streambank Movement (ft.)	Bank Slope 8/2007	Bank Slope 9/2011
Transect 1	-3.23	-4.07	0.52	0.54
Transect 2	-0.26	-1.32	0.66	0.70
Transect 3	-1.12	-0.54	0.68	0.58
Transect 4	-0.37	1.54	0.91	0.69
Transect 5	-0.62	0.62	0.64	0.68
Transect 6	-1.14	-8.99	0.37	0.63
Transect 7	-1.87	-4.22	0.48	0.82

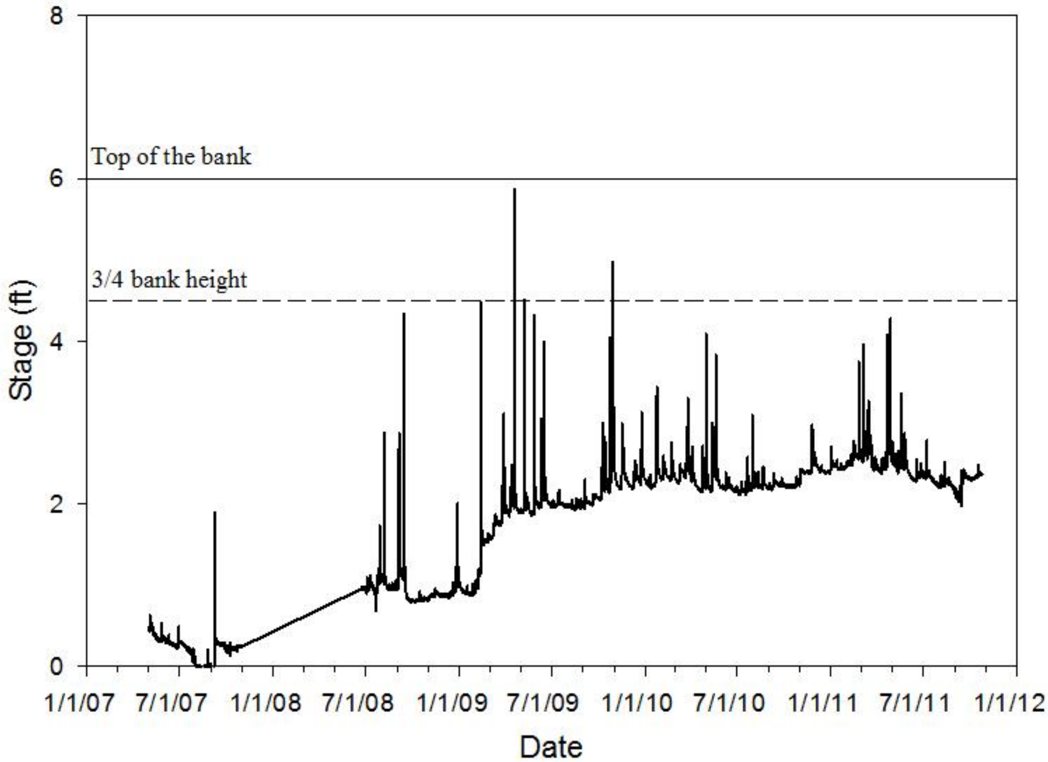

Figure 13. Levelogger® data from California Branch for 2007 through 2011. Data are missing from November 2007 until June 2008 due to a lost Levelogger®.

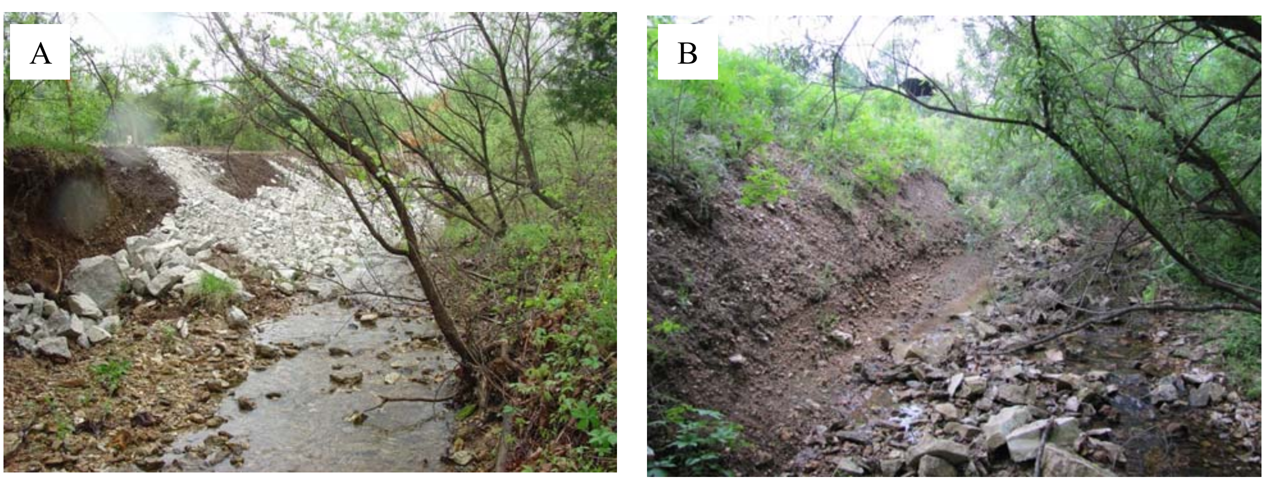

Figure 14. California Branch farm rock toe project. (A) Looking upstream following construction in May 2007. (B) Looking upstream in June 2011.

Table 5. Streambank movement and changes in streambank slope due to erosion at the California Branch farm rock toe project between the post-construction survey in June 2007 and the final survey in June 2011. 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 Movement (ft.)	Toe of streambank Movement (ft.)	Bank Slope 6/2007	Bank Slope 6/2011
Transect 1	-7.18	0.40	0.94	0.43
Transect 2	1.14	0.39	0.55	0.55
Transect 3	0.31	-2.71	0.46	0.53
Transect 4	-1.34	-1.68	0.43	0.44
Transect 5	-1.02	-2.84	0.53	0.65
Transect 6	-0.33	-2.46	0.52	0.68

rock size. The rock used was simply not large enough to stay in place and was picked up and moved downstream. Insufficient rock size appears to be the biggest issue with the approach of using shot rock instead of rip rap to build farm rock toe projects. The physical surveys, which were conducted post-construction and following flow events each year from 2008-2011, demonstrate the lack of streambank movement and the stability of the channel despite the loss of rock (Figures 15). Streambank movement has been minimal and was caused almost exclusively by the loss of rock. This rock loss has resulted in a slight increase in streambank slope along transects five and six (Table 5). The slope of the streambank at the other transects has remained virtually unchanged and vegetation is beginning to establish in the toe rock that is still in place.

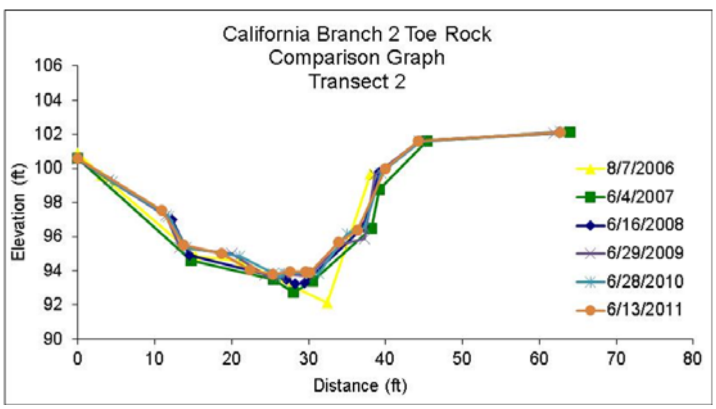

Figure 15. Physical survey data for transect two showing the pre-construction survey (8/7/2006), post-construction survey (6/4/2007), and four post-flow surveys (6/16/2008, 6/29/2009, 6/28/2010, and 6/13/2011).

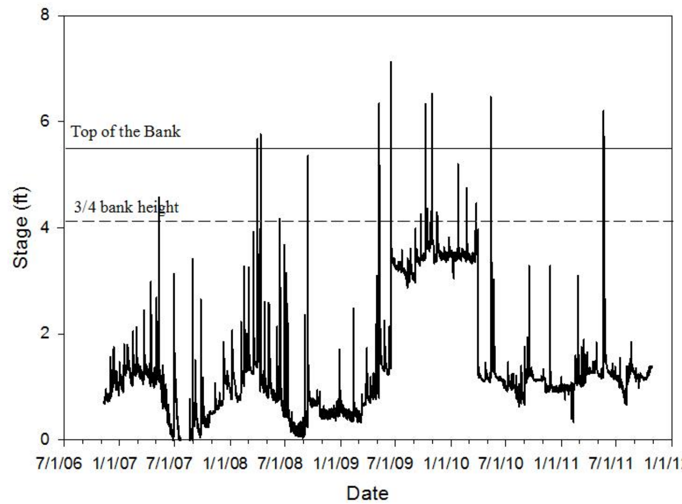

Figure 16. Levelogger® data from an unnamed tributary of Fiery Fork Creek for 2006 through 2011.

Fiery Fork Site 1

Fiery Fork Site 1 was tested by several flow events in 2007 and 2008 that reached a stage between ¾ the height of the streambank and the top of the streambank (Figure 16). The toe rock project held up during all of these flow events and appeared to be working. However, in May of 2009 the project was tested by the largest flow that occurred during the study, which caused the failure of the project. The failure started midway down the project causing the rock along the entire lower half of the project to dislodge (Figure 17). The project appears to have failed due to insufficient rock size. In the middle of the project at approximately the apex of the bend, the rock began to be lifted away from the streambank by the force of the flow. All the rock on the lower half of the project was carried away and deposited downstream in the next gravel bar. Once the rock was removed the streambank began to erode rapidly causing several trees to fall into the channel.

Once the failure process started on the downstream end of the project it continued during all the subsequent flow events. The physical surveys, which

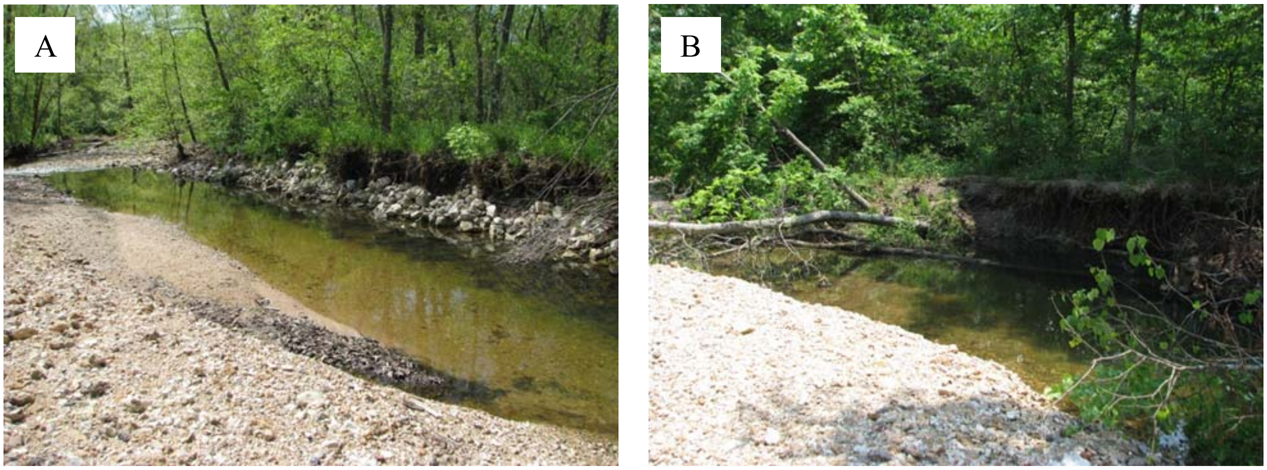

Figure 17. Fiery Fork 1 farm rock toe project. (A) Lower end of the project post-flow in May 2008. (B) Lower end of the project post-failure in June 2009.

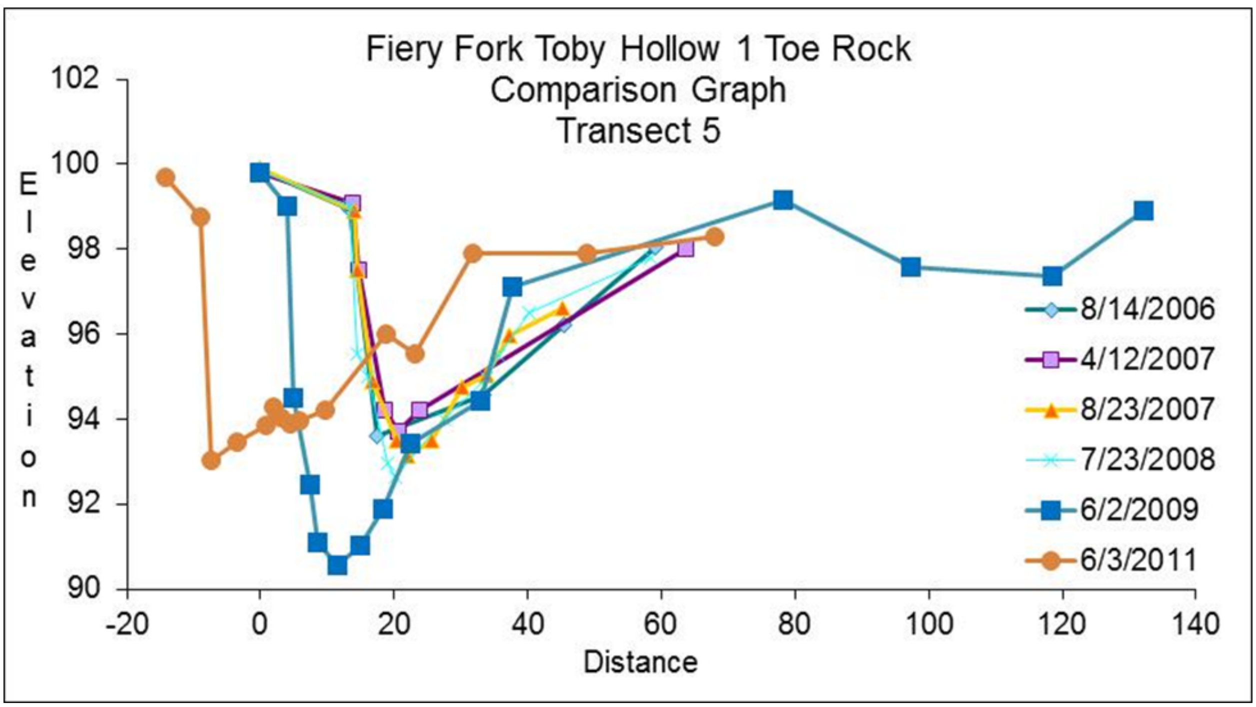

Figure 18. Physical survey data for transect five for the pre-construction survey (8/14/2006), post-construction survey (4/12/2007), two post-flow surveys (8/23/2007 and 7/23/2008), and two post-failure surveys (6/2/2009 and 6/3/2011).

were conducted post-construction and following flow events in 2008, the failure in 2009 and a final survey in 2011, provide evidence of the channel changes that resulted from the failure (Figure 18). There has been minimal streambank movement along the first three transects, where the rock stayed in place, and it has resulted in the streambank slope being reduced. Transects four through six show the dramatic changes caused by the project's failure. Transect four is located directly below the start of the failure and has seen a large increase in slope in addition to the erosion. Transects five and six have had a much higher erosion rate, over 20 ft. of erosion, than transect four and have also seen a dramatic increase in slope (Table 6).

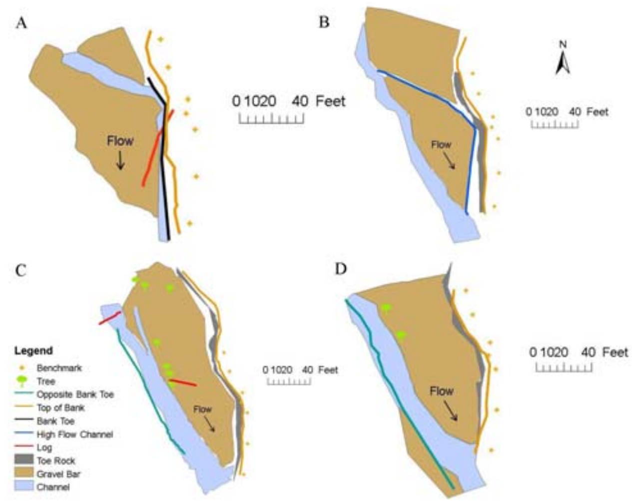

Figure 19. GPS maps of Fiery Fork 3 farm rock toe project. (A) Pre-construction August 2007. (B) Post-construction July 2008. (C) Post-flow May 2010. (D) Post-flow June 2011.

Fiery Fork Site 2

Immediately following project construction and prior to the post-construction survey, a high flow event occurred at this site and caused major changes to the channel. Although this event was less than a ¾ streambank full flow event, it was large enough to cause a shift in the channel (Figure 16). The thalweg switched from running against the toe of the streambank to a previous high flow area of the channel behind the gravel bar (Figure 19).

Post-construction monitoring did not occur until July 2008. The multiple high flow events that occurred throughout the rest of 2008, 2009, 2010, and 2011 worked to stabilize the stream in its new path. Initially the low flows continued to use the area along the project, but flow events in 2010 caused the original thalweg to fill in so much that it is almost nonexistent and is no longer even acting as a high flow channel. A comparison of the pre-construction survey data with the post-construction and post-flow survey data show the dramatic shift following the flow events. Transect one is located just downstream of where the shift occurred (Figure 20). The survey data show where the back side of the gravel washed out causing the thalweg to shift away from the bank. Transect three shows the distance the thalweg has moved away from the streambank and the deposition that has occurred (Figure 21).

Technique Performance

Six farm rock toe projects were installed between September 2006 and February 2008. The farm rock toe protection projects that were actually tested by flow events have resulted in only two outcomes. Three of the six farm rock projects worked as planned. The one complete failure and the one partial failure were caused by inadequate rock size. The sixth project was not a good test of the technique because the channel shifted away from this streambank immediately after project construction for reasons that had

Table 6. Streambank movement and changes in streambank slope due to erosion at the Fiery Fork farm rock toe project between the post-construction survey in April 2007 and the post-failure survey in June 2011. 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 Movement (ft.)	Toe of streambank Movement (ft.)	Bank Slope 4/2007	Bank Slope 6/2011
Transect 1	-0.07	-0.29	0.82	0.89
Transect 2	-1.36	0.64	0.92	0.73
Transect 3	-2.23	-0.60	1.42	0.98
Transect 4	-10.60	-14.22	1.16	11.48
Transect 5	-22.79	-26.05	1.02	3.71
Transect 6	-21.38	-24.88	1.13	6.18

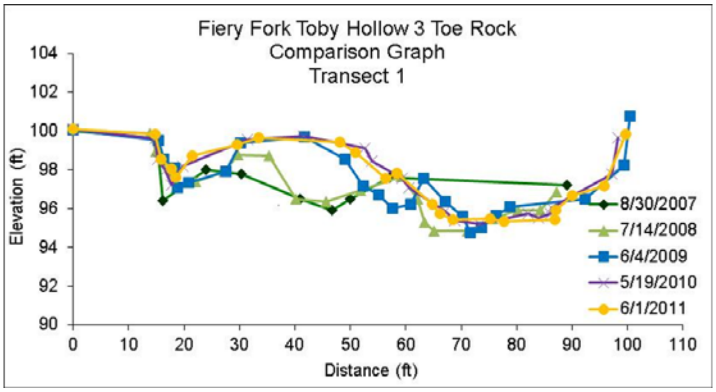

Figure 20. Physical survey data for transect one for the pre-construction survey (8/30/2007), post-construction survey (7/14/2008), and three post-flow surveys (6/4/2009, 5/19/2010, and 6/1/2011).

nothing to do with the project installation.

The first objective for monitoring the farm rock toe technique was to determine if the approach actually protected the toe from continued erosion and to determine the extent of any erosion or deposition that occurred. Success in this objective would be determined by whether or not the farm rock toe project protected the streambank toe from continued erosion. During the course of the study five of the six projects protected the toe from continued erosion; however, one of those lost all the rock in a portion of the bank, because it was undersized, and while no erosion has occurred to date it is no longer protecting the stream-

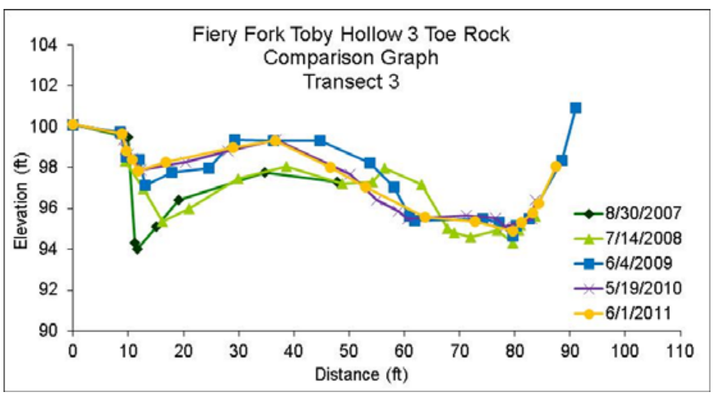

Figure 21. Physical survey data for transect three for the pre-construction survey (8/30/2007), post-construction survey (7/14/2008), and three post-flow surveys (6/4/2009, 5/19/2010, and 6/1/2011).

bank from erosion and at another site the thalweg moved away from the streambank immediately following construction so it was never tested. The only project that had any erosion, failed as a result of inadequately sized rock. All the farm rock toe projects that had rock large enough to stay in place protected the streambank from continued erosion. Weaubleau Creek and Sulphur Branch both had virtually no change in the location of the toe during the study. The Starks Creek and the Fiery Fork 2 project had a large amount of deposition due to the thalweg shifting away from the streambank and not as a result of the project; however at the Starks Creek project was tested by flow events for 2 ½ years prior to the thalweg shift unlike at the Fiery Fork 2 project. The Fiery Fork 1 project and the California Branch project both had no erosion upstream of the area that failed, which was more than half the length of the project at both sites. California Branch only had slight erosion due to the loss of the rock and not because the toe eroded. Only the failed area of the Fiery Fork 1 project had a large amount of erosion with the toe eroding more than 20 ft. from the time the failure started in 2009 until the final survey in 2011. The farm rock toe technique does appear to protect the toe of the streambank from erosion so long as the rock used to build the project is large enough to stay in place.

The second objective of the monitoring was to determine if the streambank would achieve a more stable slope through deposition at the toe or through erosion of the upper part of streambank while the toe remained stable. The four successful projects all showed a decrease in the slope of the bank. At Starks Creek limited erosion combined with the large amount of deposition at the toe of the streambank resulted in a reduction of streambank slope. For both the Weaubleau Creek and Sulphur Branch projects the slight reduction in slope was due to limited erosion at the top of the bank. At the Fiery Fork 2 project the streambank slope has either decreased due to deposition or remained virtually the same for all six transects. Overall there was only a slight change in the slope of the banks at these four sites as this decrease in slope was less than the decrease that was achieved by adding rock when the project was built when compared to the bare streambank prior to construction. The California Branch survey results showed a slight increase in the slope in the area where the toe rock washed away, but otherwise the slope remained virtually the same. At the Fiery Fork 1 project there was an increase in streambank slope for all three transects affected by the rock being washed away. The slope in this portion of the streambank is greater now than it was prior to project construction. The three transects located upstream of the failure have all maintained their slope. Although four of the projects were successful in slightly reducing the slope of the streambank it is obvious that this technique does not promote stability by causing a large reduction in streambank slope and instead relies completely on its ability to protect the toe from further erosion while vegetation becomes established.

The third objective was to determine if the farm rock toe stayed in place or started to wash away. There were two aspects to looking at this objective. The first aspect of this objective was to determine if by not keying the project into the streambank at the upstream and downstream ends and the bed throughout its length the project was more vulnerable to failure due to the possibility of water getting behind the project and washing it away. The lack of keys was not a problem at any of the six projects. At all six sites we made an effort to start and stop the project at a stable point and as a result not one of the projects failed due to this mechanism. Based on this result it appears that the farm rock toe approach could work without keys so long as the project starts and stops at stable points.

The third objective was also used to evaluate whether or not 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 six projects and even between loads that were used at the same project. The project that failed and the partial failure were both the result of the use of inadequately sized shot rock. Prior to failure at the first Fiery Fork project, it was noted that the shot rock used to build this project was smaller than the rock used in any other farm rock toe projects. Given the failures at Fiery Fork and California Branch, 33% of the time the shot rock we got was not large enough to protect the bank. In addition the rock that was used at the second Fiery Fork project was also smaller than expected, however this project was never properly tested so it is unknown whether or not it would have stayed in place.

An unexpected result of this technique was how rapidly vegetation became established on the streambank and in the rock following construction. Four of the six sites had trees and other vegetation establish relatively quickly. At California Branch, Starks Creek, and Sulphur Branch the vegetation is so thick that you cannot see the project for the majority of its length. The only two sites where vegetation did not establish were the Fiery Fork project that failed and the other Fiery Fork project where deposition from the channel shift buried the rock prior to vegetation having an opportunity to establish. This rapid vegetation establishment is an excellent sign for long-term stability at these sites.

Technique Costs

The farm rock toe protection technique was intended to be a less expensive alternative to the traditional longitudinal rip rap toe approach. 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 rip rap 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; the 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 $18.03 or 54% per foot over a traditional rip rap toe project.

It's important to note however, that repair costs could 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. Additional rock purchases and equipment time that could have occurred had we decided to repair the

Table 7. Project costs (cost per linear foot) for an experimental farm rock toe project using shot rock and rip rap or a traditional longitudinal rip rap toe protection project using shot rock or rip rap at each site and the average costs for each.

Site	Experimental Shot Rock	Experimental Rip Rap	Traditional Shot Rock	Traditional Rip Rap
Starks Creek	$22.17/ft.	$31.76/ft.	$32.29/ft.	$45.09/ft.
Weaubleau Creek	$14.31/ft.	$26.02/ft.	$28.94/ft.	$43.58/ft.
Sulphur Branch	$12.81/ft.	$16.99/ft.	$18.70/ft.	$24.77/ft.
California Branch	$11.98/ft.	$14.83/ft.	$22.05/ft.	$27.03/ft.
Fiery Fork site 1	$13.19/ft.	$15.91/ft.	$21.07/ft.	$25.03/ft.
Fiery Fork site 2	$15.94/ft.	$19.22/ft.	$28.56/ft.	$33.07/ft.
Average Costs	$15.07/ft.	$20.79/ft.	$25.27/ft.	$33.10/ft.

first Fiery Fork project, would quickly override any of the potential cost savings gained from using the experimental approach. The cost of repair makes it critical that the rock used is of adequate size and that the stopping and starting points of the project are located at stable points.

The alternate approaches of building the farm rock toe with rip rap or using the traditional longitudinal rip rap toe protection design with shot rock would have saved approximately $12 or 37% and $8 or 24% per foot of streambank respectively when compared to the traditional approach. However neither of these approaches was tested and the second approach does not address 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 toe technique as an approach for stabilizing streambanks. The results indicate that the farm rock toe approach has potential; however the failures that occurred were related to the steps we took to reduce costs. The two failures were caused by rock that was too small to stay in place. The decision to use shot rock was made in order to reduce the costs associated with a rip rap blanket approach while hopefully stabilizing the streambank. While the decision to go without keys appears to be a good way to save money, the decision to use shot rock ultimately caused problems and would have limited cost savings at two sites if needed repairs had been made.

To save money, the farm rock toe approach does not use rip rap, which is graded out to a certain size, but instead uses shot rock which is made from rock of a variety of sizes. The large variation we saw will make it impossible to be certain that the shot rock will be adequate to protect the streambank until it is on site. This is a strong indication that if given the financial option of purchasing rip rap instead of shot rock it would be worth it to spend the extra money to get rip rap even if using the farm rock toe approach. Otherwise it is critical to the success of the project that the largest shot rock possible is used. When using shot rock to build a farm rock toe project the majority of rock needs to be at least as large as the median rip rap rock size (200-230 lbs. or 1.3-1.5 ft. in diameter) or larger because of the smaller sized rock that is mixed into shot rock.

Another consideration with this technique is that contractors tend to overbuild these projects. The design called for toe rock to cover ⅓ to ½ the streambank height; however, half the projects covered more than ½ of the streambank height after construction, which increases the costs associated with the technique and does not appear necessary to be successful. This conclusion is based on the fact that the two projects that were most closely built to covering only ⅓ of the streambank height were the most successful. However one of the projects that was overbuilt and covered more than ¾ of the streambank still resulted in a complete failure, because the rock used was not of adequate size. Steps should be taken by the project coordinator to ensure the proper amount of rock is used in order to keep the cost associated with this project down and to make sure the project is built as designed.

MANAGEMENT IMPLICATIONS

Application of the lessons learned from studying these six projects could result in further modifications to the farm rock toe technique that could result in cost reductions over the traditional approach, and perhaps better success. Building a farm rock toe project using rip rap instead of shot rock, under the current design, would save approximately $12 or 37% per foot of streambank when compared to the traditional approach. The cost is approximately $6 or 38% per foot more than the experimental approach we used, but the extra $6 would minimize, any risk of getting undersized rock that would not stay in place. This approach would also address the cause for failure of two of our projects. Another modification to our design would be the potential use of the traditional design with shot rock instead of rip rap. This approach would save approximately $8 or 24% per foot versus the traditional approach. The extra $10 or 68% over the approach we used would buy some margin of error in the project design because keys would protect against water getting behind the toe rock at the upper and lower end of the project, but it would not address the reason our projects failed which was due to inadequately sized rock. These additional approaches might be useful if you are unsure about the source and type of shot rock you can get, and to protect against project design issues, but neither has been tested so their limitations are unknown.

Overall the farm rock toe results indicate that this approach does have potential for use as a streambank stabilization technique; however, proper site selection, project design, and construction are essential to using this technique appropriately. The most important factors in the success of the farm rock toe projects appear to be the stability of your starting and stopping points and the size of shot rock used. In the six sites we selected we were able to have stable starting and stopping points and as a result we did not suffer any failures as a result of saving money by not keying the project into the bed or bank. Two of the sites were negatively impacted by using shot rock instead of rip rap as the undersized rock we received resulted in the failure and partial failure of those projects. An additional modification to the farm rock toe approach of using rip rap 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 potentially making it the better option. The farm rock toe approach should not be attempted by a landowner without the assistance of an experienced professional.

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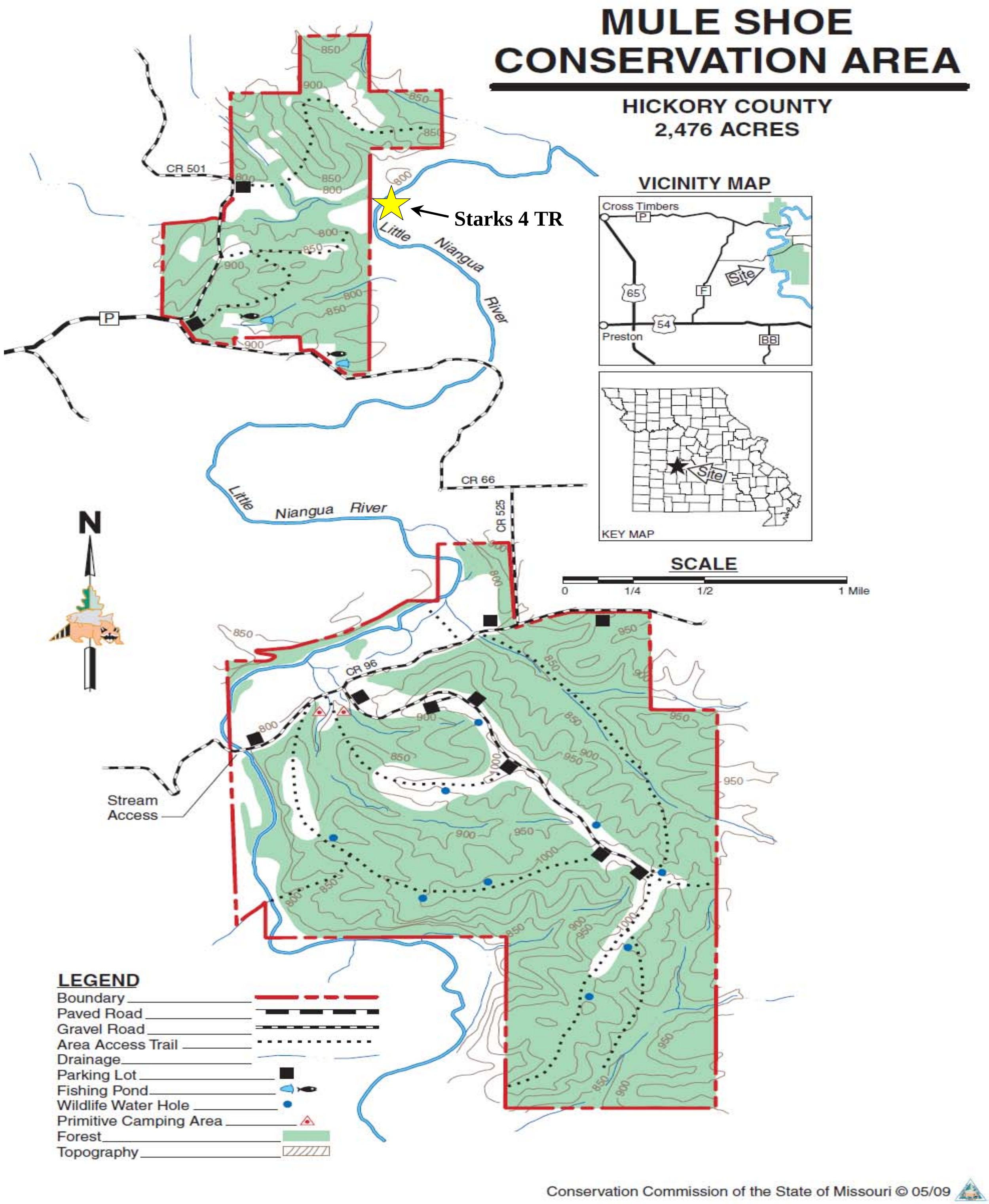
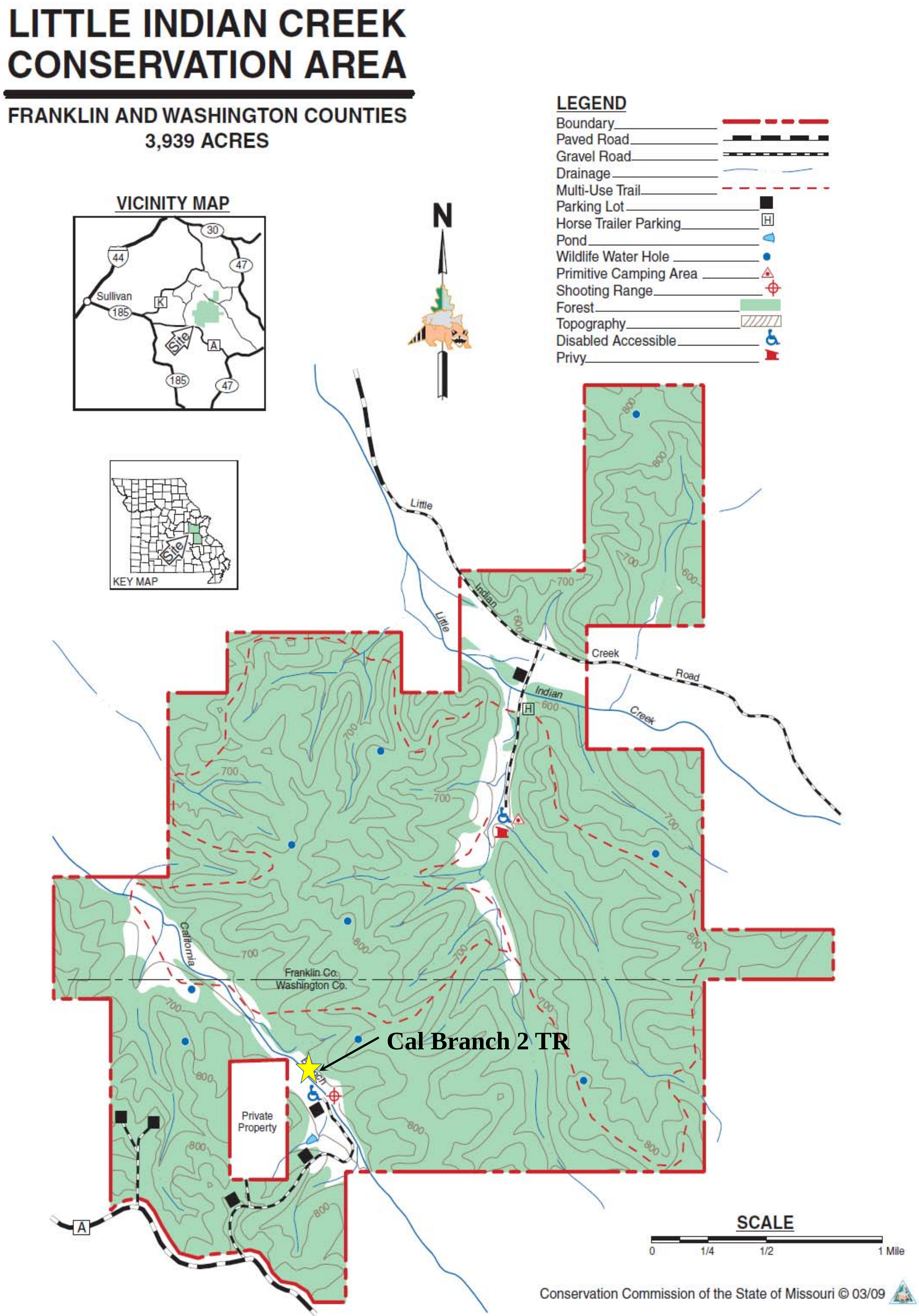
Appendices

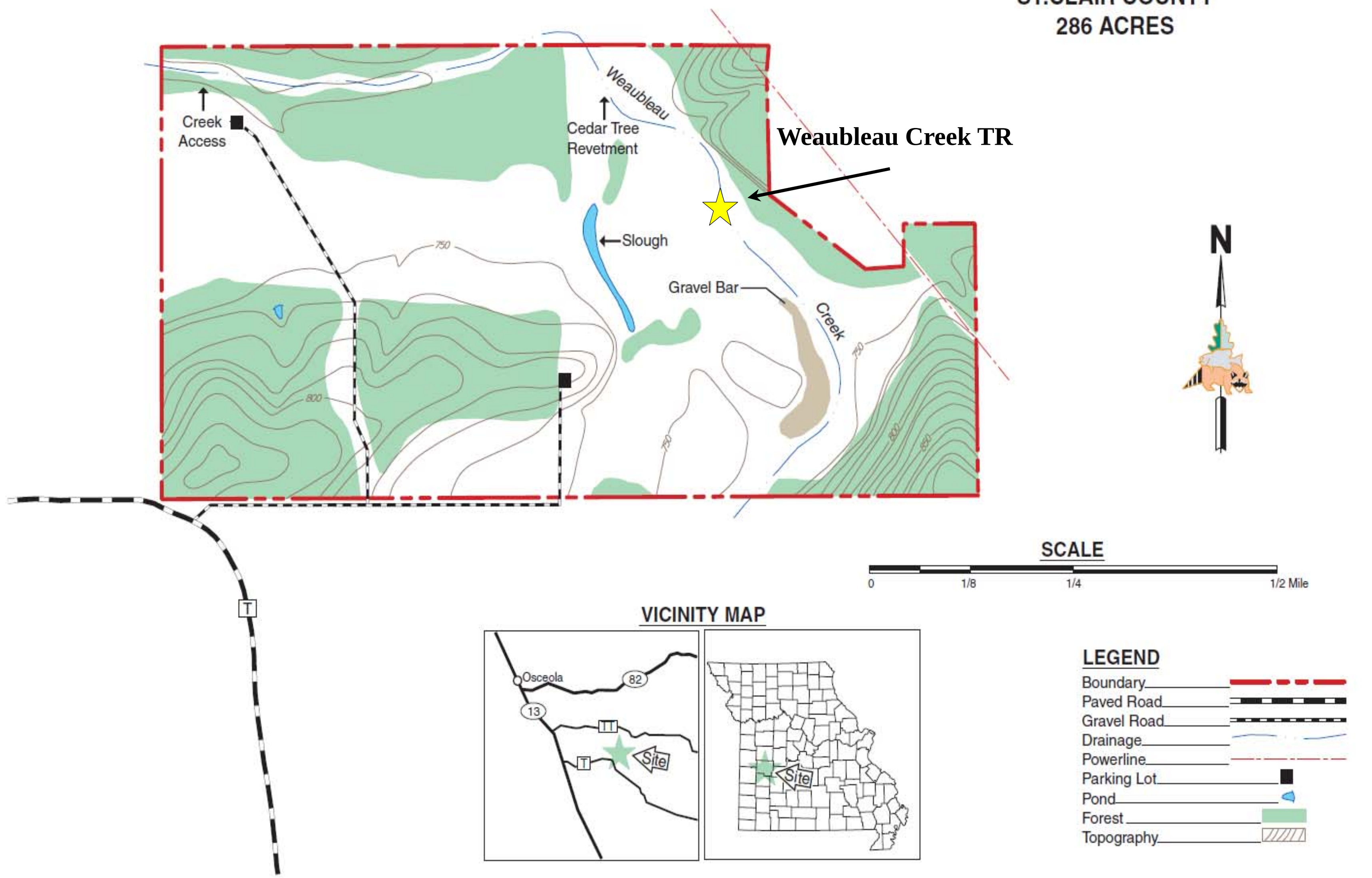
Appendix 1: Area Maps

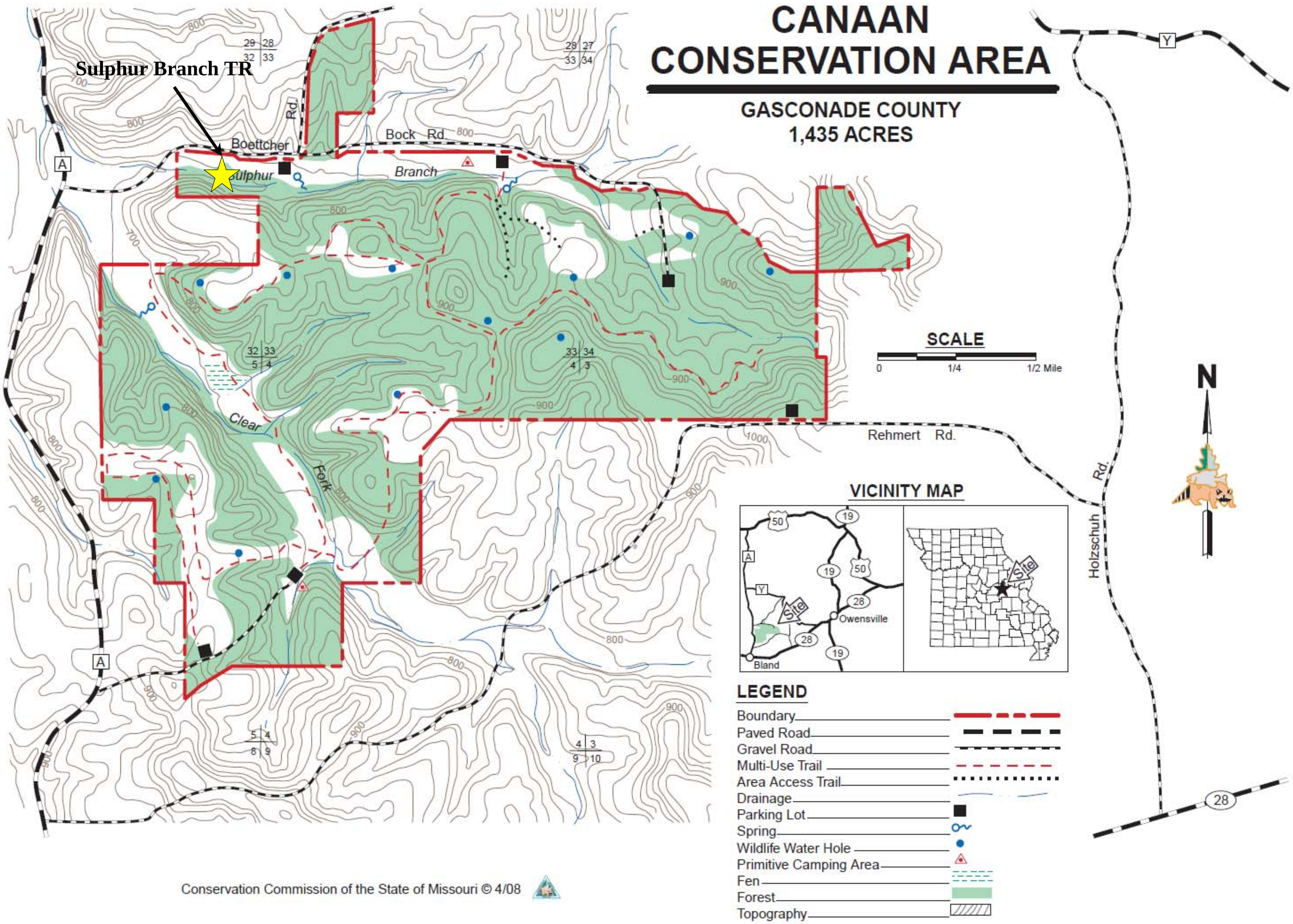



LITTLE INDIAN CREEK
CONSERVATION AREA
FRANKLIN AND WASHINGTON COUNTIES
3,939 ACRES
VICINITY MAP
Sullivan
Site
KEY MAP
LEGEND
Boundary
Paved Road
Gravel Road
Drainage
Multi-Use Trail
Parking Lot
Horse Trailer Parking
Pond
Wildlife Water Hole
Primitive Camping Area
Shooting Range
Forest
Topography
Disabled Accessible
Privy
N
Little Indian Creek Road
Indian Creek
California
Franklin Co.
Washington Co.
Private Property
Cal Branch 2 TR
SCALE
0 1/4 1/2 1 Mile
Conservation Commission of the State of Missouri © 03/09

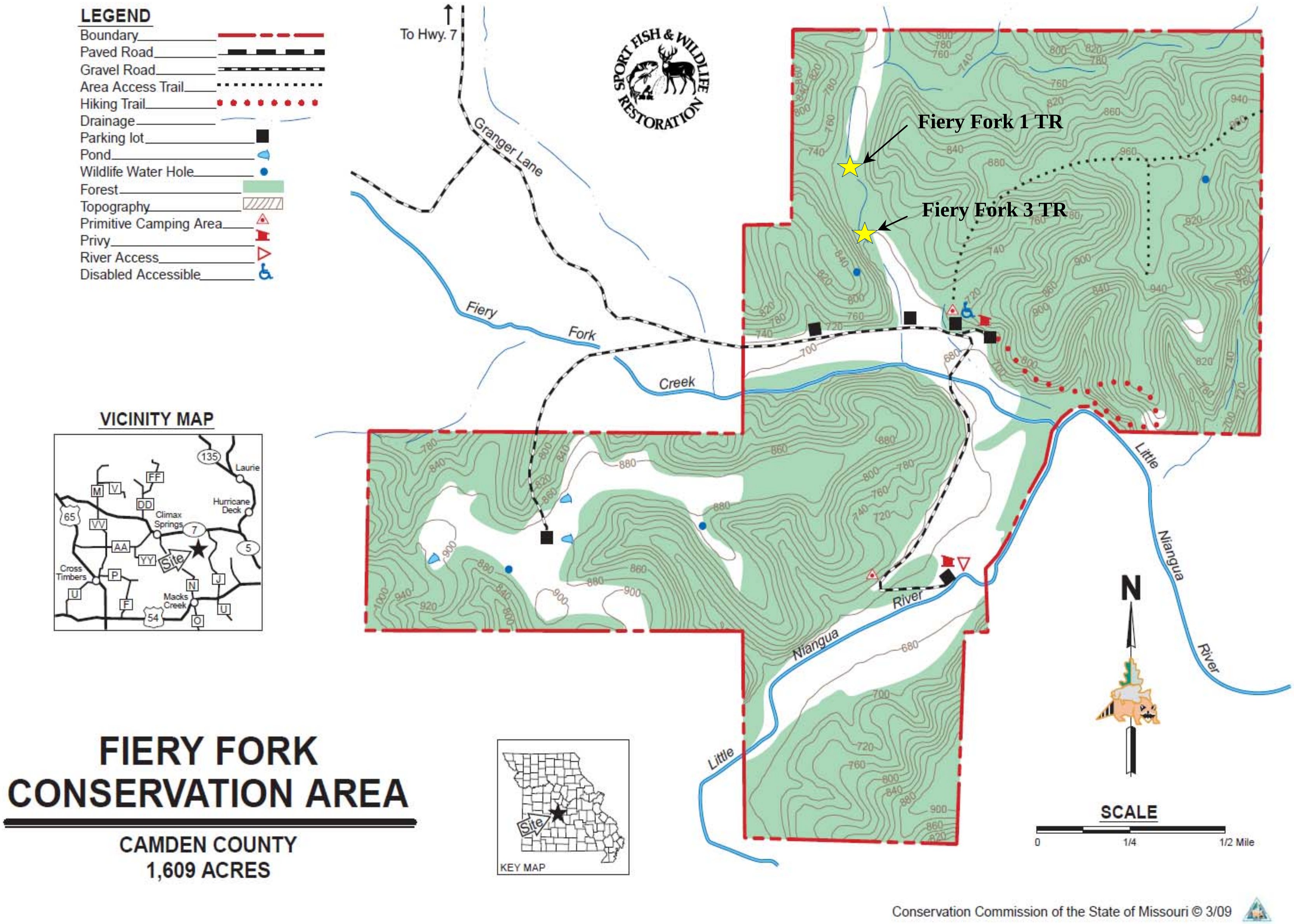
KINGS PRAIRIE ACCESS

ST.CLAIR COUNTY
286 ACRES





CANAAN
CONSERVATION AREA
GASCONADE COUNTY
1,435 ACRES
Sulphur Branch TR
Boettcher
Rd.
Bock Rd.
Sulphur
Branch
Clear
Fork
Rehmert Rd.
Holzschuh Rd.
SCALE
0
1/4
1/2 Mile
N
VICINITY MAP
Owensville
Bland
Site
LEGEND
Boundary
Paved Road
Gravel Road
Multi-Use Trail
Area Access Trail
Drainage
Parking Lot
Spring
Wildlife Water Hole
Primitive Camping Area
Fen
Forest
Topography
Conservation Commission of the State of Missouri © 4/08



LEGEND
Boundary
Paved Road
Gravel Road
Area Access Trail
Hiking Trail
Drainage
Parking lot
Pond
Wildlife Water Hole
Forest
Topography
Primitive Camping Area
Privy
River Access
Disabled Accessible
To Hwy. 7
Granger Lane
SPORT FISH & WILDLIFE RESTORATION
Fiery Fork 1 TR
Fiery Fork 3 TR
Fiery
Fork
Creek
Little
Niangua
River
VICINITY MAP
Laurie
Hurricane Deck
Climax Springs
Site
Cross Timbers
Macks Creek
N
SCALE
0
1/4
1/2 Mile
FIERY FORK
CONSERVATION AREA
CAMDEN COUNTY
1,609 ACRES
KEY MAP
Conservation Commission of the State of Missouri © 3/09

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