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Experimental Gravel-rolls with Back-sloping and Vegetation Establishment 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 they can use to address existing erosion issues and protect their property from further erosion. The 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 the use of a gravel-roll with back-sloping and vegetation establishment as a potential technique for controlling excessive streambank erosion. The gravel-roll approach is designed to reduce erosive forces acting on the eroding streambank by back-sloping the streambank which gives it a higher width-to-depth ratio, and establishing vegetation that will decrease velocities by adding roughness and stabilize the streambank with root systems over the long-term. In addition, a gravel-roll is built at the toe, which is intended to protect the streambank toe in the short-term, allowing vegetation to stabilize the streambank over the long-term. Back-sloping reduced the eroding streambank to a 3:1 horizontal to vertical slope. The exposed soil was then covered with erosion control fabric and planted with vegetation. A gravel-roll was constructed at the toe of the streambank to provide additional protection. The gravel-roll consisted of gravel wrapped in C2 erosion control fabric sewn together with nylon twine. Two projects were constructed at two separate MDC Conservation Areas in Missouri using gravel-rolls with back-sloping and vegetation establishment. The projects Mill Creek and Starks Creek were built between January 2007 and July 2007.

The technique failed at both sites during the first high flow event that occurred following construction. Reasons for failure were the same at both sites, the inability of the gravel-roll to adjust to areas of scour and because it was not large enough to protect a high enough percentage of the streambank (typically 1/3 of the streambank height is covered with other toe stabilizing techniques). The gravel-roll functioned as a large unit, and it could not adjust to fill in small areas of streambank scour as they occurred. Water scoured areas above and behind the gravel-roll, and streambank erosion continued while the roll itself stayed in place. The size (i.e., diameter) of a roll is controlled by the width of the erosion control fabric so it cannot be adjusted. To alleviate this problem multiple rolls could be stacked at the toe of the bank; however, this adds considerable time and expense to an already expensive technique and does not address the other reasons the project failed. The reasons for discontinuing this technique after just two projects focused on the inability to adapt the technique to address reasons for its failure. Thus, the gravel-roll with back-sloping and vegetation establishment technique will not be recommended because it has no utility 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. The 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.

Table 1. River and site details for the two gravel-roll projects. The watershed area is for the area located upstream of the site only and not the entire watershed.

	Mill Creek	Starks Creek
River Basin	Current	Little Niangua
Physiographic Region	Ozark Plateau	Salem Plateau
Stream Order	3	4
Reach Gradient	28 ft./mi	29 ft./mi
Watershed Area	14 mi^2	35 mi^2
Bank Height	6 ft.	10 ft.
Bank Length	125 ft.	183 ft.

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.

Back-sloping an eroding streambank is a commonly used supplement to other streambank stabilization techniques. Back-sloping a streambank involves using heavy equipment to reduce the slope of the eroding streambank to a slope of 1:1 or less, protecting it with erosion control fabric, and planting terrestrial bottomland vegetation. Typically it has been used to address the loss of riparian vegetation or improve the performance of other streambank stabilization techniques and not as a stand-alone technique on banks with toe erosion (Bowie 1982, FISRWG 1998, North Dakota Forest Service 1999, CPYRMA 2000, Tennessee Valley Authority 2003). The costs associated with this technique will depend on the type of heavy equipment and fabric used. Reducing the streambank to a slope of 1:1 is considered the absolute minimum and most authors recommend using a slope of 2:1 or 3:1 if possible.

This study tested gravel-rolls with back-sloping and vegetation establishment as a streambank stabilization technique. The gravel-roll with back-sloping and vegetation establishment technique was designed to be a cost-effective alternative to a traditional longitudinal rip rap toe protection streambank stabilization project. Instead of trying to armor the toe of the streambank by using rip rap from a quarry to protect it from erosion, the gravel-roll attempts to armor the toe of the streambank by using gravel available at or near the site in combination with back-sloping that reduces the forces acting upon the streambank by giving it a higher width to depth ratio. In addition as the erosion control fabric breaks down in the long-term the establishment of vegetation on the sloped streambank would decrease velocities by adding roughness and stabilization of the streambank via root systems. The gravel-roll was added to protect the toe of the streambank from erosion until the vegetation became established in the back-sloped area. The roll was intended to function in a manner similar to a gabion basket, in that it uses material ordinarily too small to protect the streambank by containing it into a larger structure. The reason we tested gravel-rolls and not gabion baskets were three fold. First, the erosion control fabric would biodegrade through time unlike the wire of the gabion baskets. Second, the gravel-roll allowed us to use smaller material than the mesh of a gabion basket. Finally, gabion projects have much higher associated cost, as much as $90 per linear foot than a gravel-roll (Freeman and Fischenich 2000,

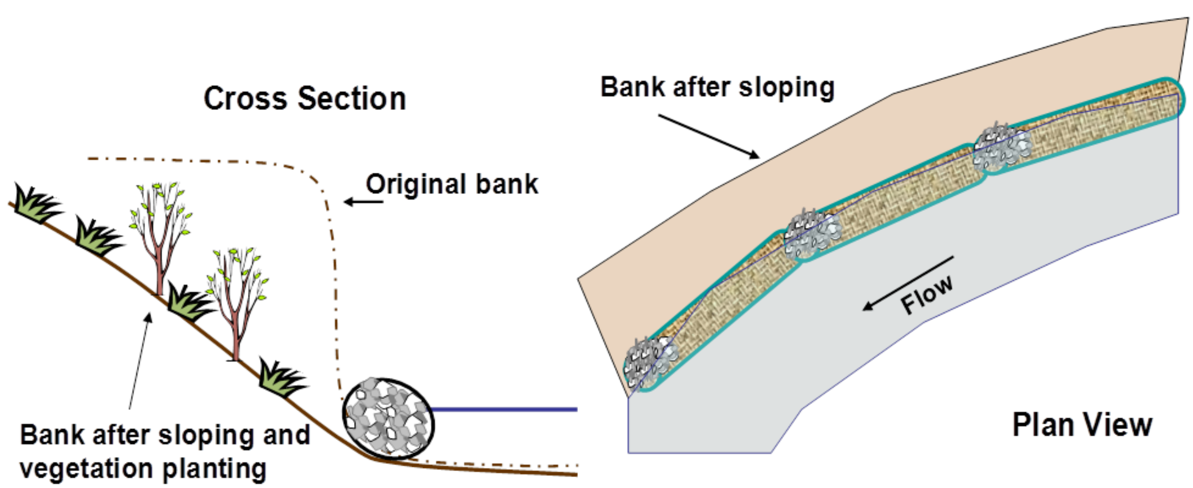

Figure 1. Cross sectional and plan view of a back-sloped streambank with a gravel-roll.

Maryland Department of the Environment 2000). Gabions have little potential for widespread use in Missouri because they can cost as much, if not more, than solutions that rely on rock alone (Fischenich and Allen 2000, Tennessee Valley Authority 2003).

The objectives of this study were to examine the performance of gravel-rolls with back-sloping and vegetation establishment and determine: 1) the extent of continued erosion or deposition at the toe of the bank, 2) if the streambank maintained its constructed slope, 3) if the gravel-roll would hold together and stay in position, and 4) if back-sloping and vegetation establishment was a cost effective alternative to longitudinal rip rap toe protection.

Figure 2. Starks Creek gravel-roll construction. (A) streambank prior to construction. (B) streambank sloping July 2007. (C) Gravel placement July 2007. (D) Sewing the gravel-roll closed July 2007.

STUDY SITES

The gravel-roll with back-sloping and vegetation establishment technique was evaluated at two 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. Selected stream segments were located on Starks Creek on Mule Shoe Conservation Area (MSCA) in Hickory County and Mill Creek on Peck Ranch Conservation Area (URCA) in Carter 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

Gravel-roll Design

The gravel-roll with back-sloping and vegetation establishment approach was designed to stop erosion by reducing erosive forces acting on the eroding streambank by providing a higher width to depth streambank ratio, establishing vegetation that would decrease velocities by adding roughness and stabilization of the streambank via root systems over the long-term, and armoring the streambank toe with the roll to protect it. An experimental gravel-roll project consisted of two parts; 1) sloping and planting vegetation on the streambank and 2) building a gravel-roll to protect the toe of the bank. The goal of the back-sloping and vegetation establishment was to reduce the slope of the eroding streambank to a 3:1 ratio (Figure 1). To accomplish slope reduction, all excess streambank material was removed from the site, loaded in a dump truck, and taken to an upland site. The exposed soil was then covered with C2 coconut fiber erosion control fabric and planted with perennial rye grass to provide a ground cover until trees could become established. C2 erosion control fabric comes in 7.5 ft. X 120 ft. rolls that were staked down with 6 inch x 1 inch x 6 inch staples to protect the bank. A total of 12 different tree species were then planted at a rate of more than 1500 per acre for all species combined at the two sites. Species planted were river birch, sandbar willow, buttonbush, false indigo, sycamore, cottonwood, roughleaf dogwood, gray dogwood, silky dogwood, deciduous holly, wild plum, and green ash.

The second part was the construction of the gravel-roll that consisted of creek gravel wrapped in C2 erosion control fabric and bound with nylon twine. After sloping the bank, a layer of erosion control fabric was placed at the toe of the new bank. Gravel was then taken from a nearby gravel bar (according to gravel mining guidelines) and piled on the erosion control fabric (Figure 2). The fabric was then wrapped around the gravel and sewn closed. Approximately 5 to 6 ft. of the upstream and downstream ends of the gravel-roll were keyed into the streambank and buried in order to keep flow from getting behind the roll. The same C2 erosion control fabric that was used to protect the sloped streambank was used to create the gravel-roll. Erosion control fabric was used to contain the gravel so that through time it would break down and slowly release the gravel back into the stream. Hopefully, prior to break down of the roll the

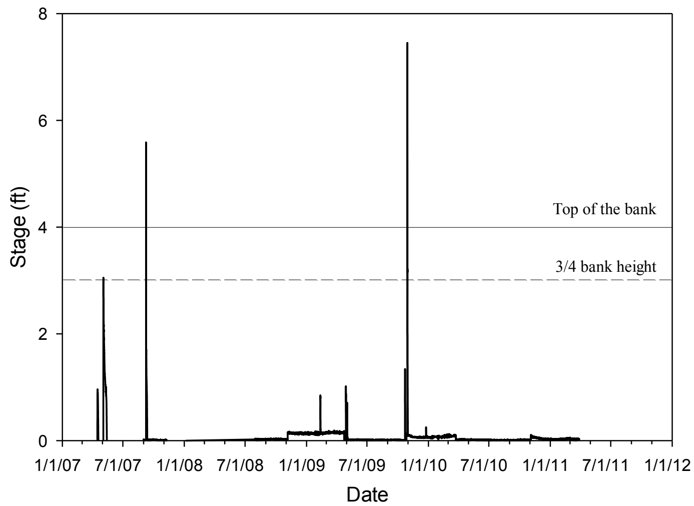

Figure 3. Levelogger® data from Mill Creek for January 2007 through March 2011. Flow data are missing for the period from 11/8/2007 through 7/30/2008 and after 3/28/2011 due to the loss of multiple Levelogger®s during high flow events.

planted trees would become established enough to protect the bank.

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 for the Mill Creek project ran from a benchmark on the eroding streambank to the top of the streambank across the channel, and transects at the Starks Creek project 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 of the bank, top of the sloped 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) 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-

Table 2. Streambank movement and changes in streambank slope due to erosion at the Mill Creek gravel-roll project between the post-construction survey in January 2007 and the post failure survey in July 2008. 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 1/2007	Bank Slope 7/2008
Transect 0	0.66	-6.24	0.28	0.52
Transect 1	0.97	-0.62	0.28	0.29
Transect 2	1.46	-4.54	0.30	0.38
Transect 3	1.35	-3.10	0.31	0.35
Transect 4	0.63	-8.31	0.35	0.92
Transect 5	3.30	-6.95	0.35	1.83
Transect 6	-0.56	-14.10	0.29	5.57

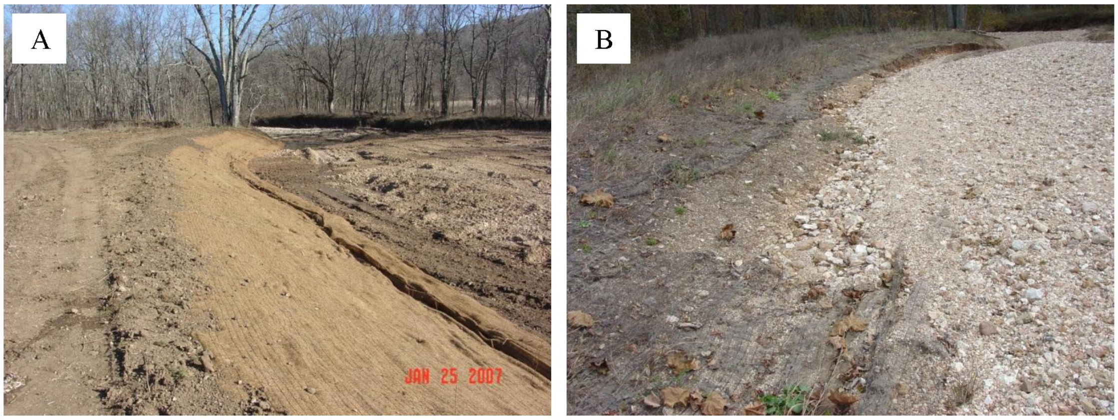

Figure 4. Looking downstream at the Mill Creek gravel-roll project. (A) Post-construction January 2007. (B) Post failure November 2007 showing bed aggradation.

round.

RESULTS

Mill Creek

The Mill Creek gravel-roll with back-sloping and vegetation establishment project was built in January of 2007. Mill Creek is a losing stream in the reach where this project was built, so it only has flow immediately following rain events. The first flow event to test the project occurred in September 2007 (Figure 3). During this event, the stream went from no flow to a stage of approximately 5.5 ft. Flows must exceed a stage of 4 ft. to exceed the height of the top of the streambank at this site. The initial flow event caused the complete failure of the project (Figure 4).

The failure occurred because the gravel-roll

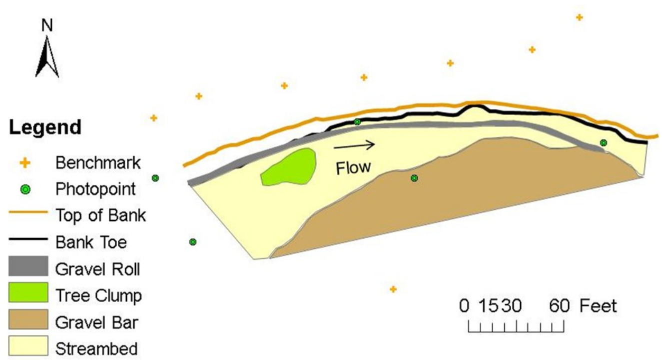

Figure 5. GPS map of Mill Creek gravel-roll project showing gravel-roll location and streambank toe location following project failure in July 2008.

functioned as a single long tube and did not adjust to scour in the way that rip rap does. The roll also did not protect a high enough percentage of the streambank so the water scoured the area above and behind the gravel-roll. Once this area started eroding, it continued until a large portion of the streambank in the bend was washed away. Even though the streambank eroded severely, the gravel-roll did not come apart or move but rather stayed in place and ended up buried in the streambed. A GPS map showing the location of the gravel-roll and the changes in the channel following project failure demonstrates how the roll stayed in place (Figure 5).

Following project failure, a post-flow survey

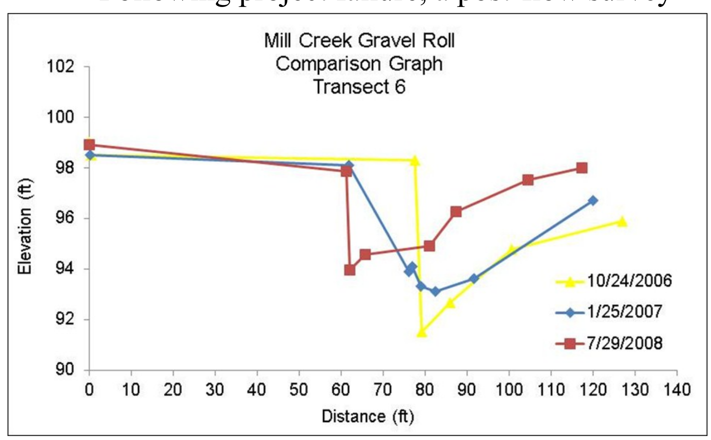

Figure 6. Physical survey data for transect six covering the pre-construction survey (10/24/2006), post-construction survey (1/25/2007), and post failure survey (7/29/2008).

was conducted. Survey data were collected from all seven transects and compared to the survey data collected during the post-construction survey (Table 2). Erosion occurred along all transects, particularly at the downstream end of the project. Erosion resulted in an increase in the slope of the bank. A complicating factor at this site was aggregation of the streambed; the bed actually rose due to aggradation and buried the gravel-roll along the section where failure occurred (Figure 6).

Starks Creek

The Starks Creek gravel-roll with back-sloping and vegetation establishment project was built in July of 2007. Following construction, this project was not tested by any high flow events until the spring of 2008. The first two flows greater than ¾ of the streambank height occurred in February and March of 2008. The project survived both of these flow events but failed during the first flow event that went over the top of the streambank on March 18th (Figure 7). This flow reached a stage of 12.6 ft., well over the top of the streambank and represented a 10 ft. rise over the average flow the previous week. The flow event caused the complete failure of the project.

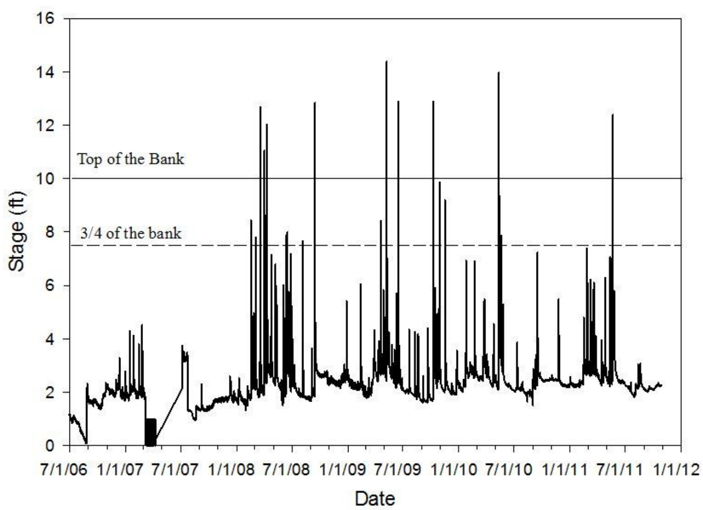

Figure 7. Levelogger® data from Starks Creek for June 2006 through October 2011. Flow data are missing for the period from 3/6/2007 through 7/5/2007 due to a Levelogger® malfunction.

Figure 8. Looking downstream at Starks Creek gravel-roll project. (A) Post-construction October 2007. (B) Post failure April 2008. (C) October 2008. (D) October 2011.

The failure occurred for the same reasons as the Mill Creek project. The water scoured the area above and behind the gravel-roll, and once this area started eroding, it continued until a large portion of the streambank in the bend was washed away (Figure 8). Even though the streambank eroded severely, the gravel-roll did not come apart or move but rather stayed in place and ended up buried in the gravel bar that built up on the opposite side of the channel. The gravel-roll was placed at the toe of the streambank during construction. However, following the failure, the gravel-roll was located in the center of the channel due to toe erosion and not because it moved (Figure 9).

A post-flow survey was conducted in June 2008 and was compared to the survey data collected during the post-construction survey. The data show that in the area where flow is parallel to the project (transects 0-3) the streambank held and maintained its sloped angle. However, the lower end of the project (transects 4-6) failed to protect the toe from erosion and the streambank did not maintain its location or angle. Toe erosion occurred within the final three

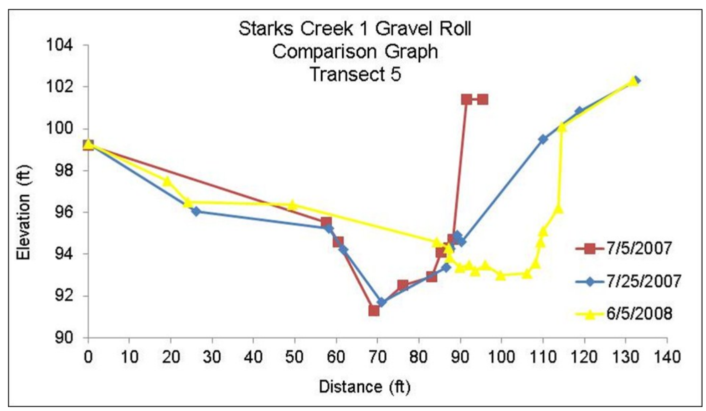

Figure 9. Physical survey data for transect five covering the pre-construction survey (7/5/2007), post-construction survey (7/25/2007), and post failure survey (6/5/2008).

transects and slope increased as well (Table 3).

Technique Performance

Two gravel-roll with back-sloping and vegetation establishment projects were installed between January 2007 and July 2007. Both projects failed the first time they were tested by a flow event that topped project banks. The two complete failures are due to an inherent flaw in the approach of this stabilization technique.

The first objective for monitoring the gravel-roll with back-sloping and vegetation establishment technique was to determine the extent of continued

Table 3. Streambank movement and changes in streambank slope due to erosion at the Starks Creek gravel-roll project between the post-construction survey in July 2007 and the post failure survey in June 2008. 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 7/2007	Bank Slope 6/2008
Transect 0	-0.68	3.27	0.20	0.25
Transect 1	-0.20	5.05	0.21	0.20
Transect 2	-0.65	9.15	0.19	0.16
Transect 3	0.74	1.09	0.25	0.27
Transect 4	-1.96	-4.46	0.30	0.40
Transect 5	4.35	-23.35	0.22	4.33
Transect 6	0.58	-16.40	0.25	1.05

erosion or new deposition of sediment along the toe of the bank. To successfully achieve this objective the gravel-roll needed to protect the toe from erosion until the vegetation was well established on the bank. At both projects there was erosion at the toe following the first high flow event. There was erosion along all seven transects at Mill Creek. Erosion was most extensive at the downstream end where the last transect eroded more than 14 ft. The Starks Creek project also had extensive erosion at the downstream end of the project. Erosion was most extensive at transects five and six with erosion of more than 23 ft. and 16 ft., respectively Water scoured the area above and behind the gravel-roll at both projects, continuing streambank erosion while the roll itself stayed in place. The roll did not protect a high enough percentage of the streambank in order to keep the toe from continuing to erode. A complicating factor at the Mill Creek project was the aggregation of the streambed that occurred. The streambed rose due to aggregation and buried the gravel-roll along the section where the failure occurred. Aggregation might have contributed to the failure at that site. However, this did not occur at Starks Creek, which also failed.

The second objective for monitoring the gravel-roll with back-sloping and vegetation establishment technique was to determine if the streambank maintained a stable slope or if it returned to an unstable angle. The failure at both sites resulted in the streambank returning to an unstable slope. The Mill Creek project had a slight increase in slope at the four upstream transects, while the three downstream transects all had a dramatic increase in streambank slope. The Starks Creek project maintained a relatively stable slope at the five upstream transects, but the two downstream transects, where the failure occurred, showed a dramatic increase in streambank slope.

The third objective for monitoring the gravel-roll with back-sloping and vegetation establishment technique was to determine if the gravel-roll held together and maintained position. When the streambank started to erode at Mill Creek the gravel-roll stayed in place, because it functioned as a single long tube and did not shift to protect the areas of scour in the way that toe rock does. The roll did not adjust to areas of scour as we anticipated. This same result was seen at Starks Creek, where after the failure of the project the roll actually ended up positioned in the middle of the channel at the downstream end of the project due to the extensive erosion and not because it moved. The failure of both projects appears to be due to the failings of the approach. The roll did not adjust to scour and did not protect a high enough percentage of the bank. Water scoured the area above and behind the gravel-roll, allowing continued streambank erosion while the roll itself stayed in place.

Technique Costs

The gravel-roll with back-sloping and vegetation establishment approach was intended to be a less expensive alternative to a longitudinal rip rap toe protection project that would still stabilize the streambank. In addition to examining how well the technique performed, it was also vital to determine the costs associated with the technique and what the 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 three different ways at each site: the experimental gravel-roll with back-sloping design, a traditional longitudinal rip rap toe protection design, and an experimental farm rock toe design using rip rap (Table 4). On average the gravel-roll only saved $2.58 or 3% per foot when compared to a traditional longitudinal rip rap toe project and cost $6.06 23% per foot more than the experimental farm

Table 4. Project costs based on three different approaches to stabilizing the streambank at each site and the average costs for each approach.

Site	Experimental Back-sloping Project	Traditional Longitudinal Toe Protection	Experimental Farm Rock Toe (Rip Rap)
Mill Creek	$16.21/ft.	$19.20/ft.	$14.08/ft.
Starks Creek	$48.35/ft.	$50.51/ft.	$38.36/ft.
Average Costs	$32.28/ft.	$34.86/ft.	$26.22/ft.

rock toe approach using rip rap. The lack of savings with this approach coupled with the concurrent failures that occurred makes this technique an unusable alternative for landowners.

DISCUSSION

The results from the two gravel-rolls with back-sloping and vegetation establishment projects established that this technique has no potential as a stabilization technique. Despite the failure of the initial project at Mill Creek during the first high flow event to test the project, we were unwilling to abandon the technique without further testing because the results at the Mill Creek project were complicated by the bed aggradation that occurred during the high flow. However, the second failure at the Starks Creek, again during the first flow event to test the project, made it clear that the technique was failing because of its own flaws and not due to bed aggradation. Following the second failure, the technique was given up on, and no more gravel-roll projects were installed. Both projects failed for exactly the same reasons. The main reason for discontinuing the technique focused on the inability to adjust this technique to deal with the reasons it failed. Project failure centered on the inability of the gravel-roll to adjust to areas of scour and that it did not protect a high enough percentage of the bank. Gravel within in a stream channel is easily transported by the stream, otherwise it would not be in the channel; therefore, gravel is too small to pile at the toe of a streambank like rip rap. The experiments tested if the gravel could be held together in a larger structure, the gravel-roll, and still protect the toe of the bank. The gravel-roll did not work because it actually formed too large a structure that was not capable of adjusting to small areas of scour. Rip rap has the advantage of being able to adjust to the same small scours to prevent project failure. In addition, the gravel-roll does not cover a large enough area of the bank. The size (i.e., diameter) of a roll is controlled by the width of the erosion control fabric so it cannot be adjusted. We could deal with this problem by stacking multiple rolls at the toe of the bank; however this adds considerable time and expense to an already expensive technique and does not address the other reasons for project failure.

MANAGEMENT IMPLICATIONS

The goal of the gravel-roll with back-sloping and vegetation establishment technique was to potentially develop an affordable and effective alternative to a traditional rip rap toe protection technique using gravel that was available at the site of the erosion problem. The technique failed to accomplish any of this at the two sites where it was tested. The results at these two project locations have established that this technique is not an appropriate solution for stabilizing eroding streambanks. The gravel-roll was abandoned so quickly because there was no way to deal with the inherit flaws in the technique. Without being able to alter the technique to deal with its problems, no further action was needed. As a result, the decision was made not to move forward with this technique. The gravel-roll with back-sloping and vegetation establishment technique will not be recommended in the future because it has no utility to landowners.

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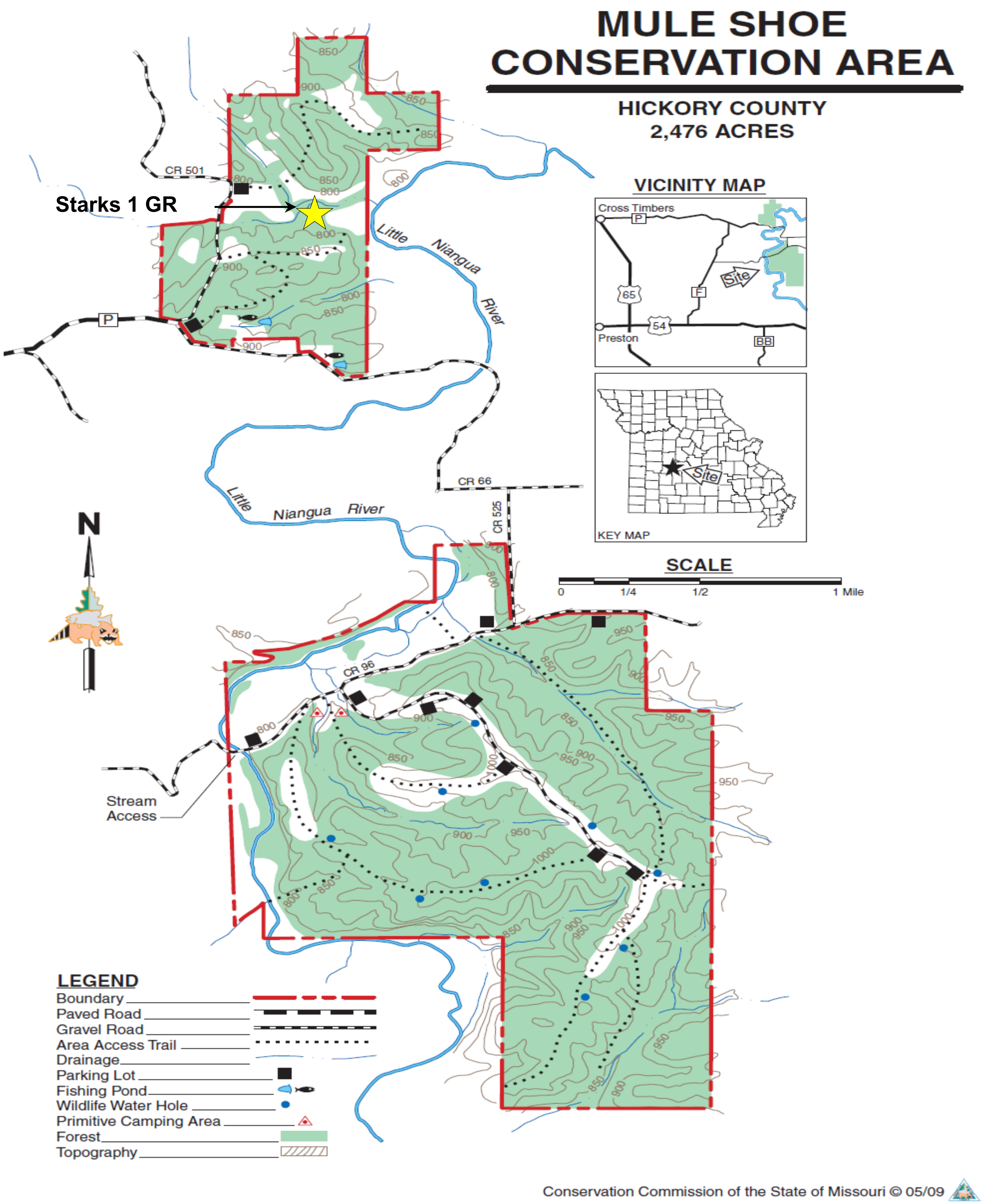
Appendices

Appendix 1: Area Maps

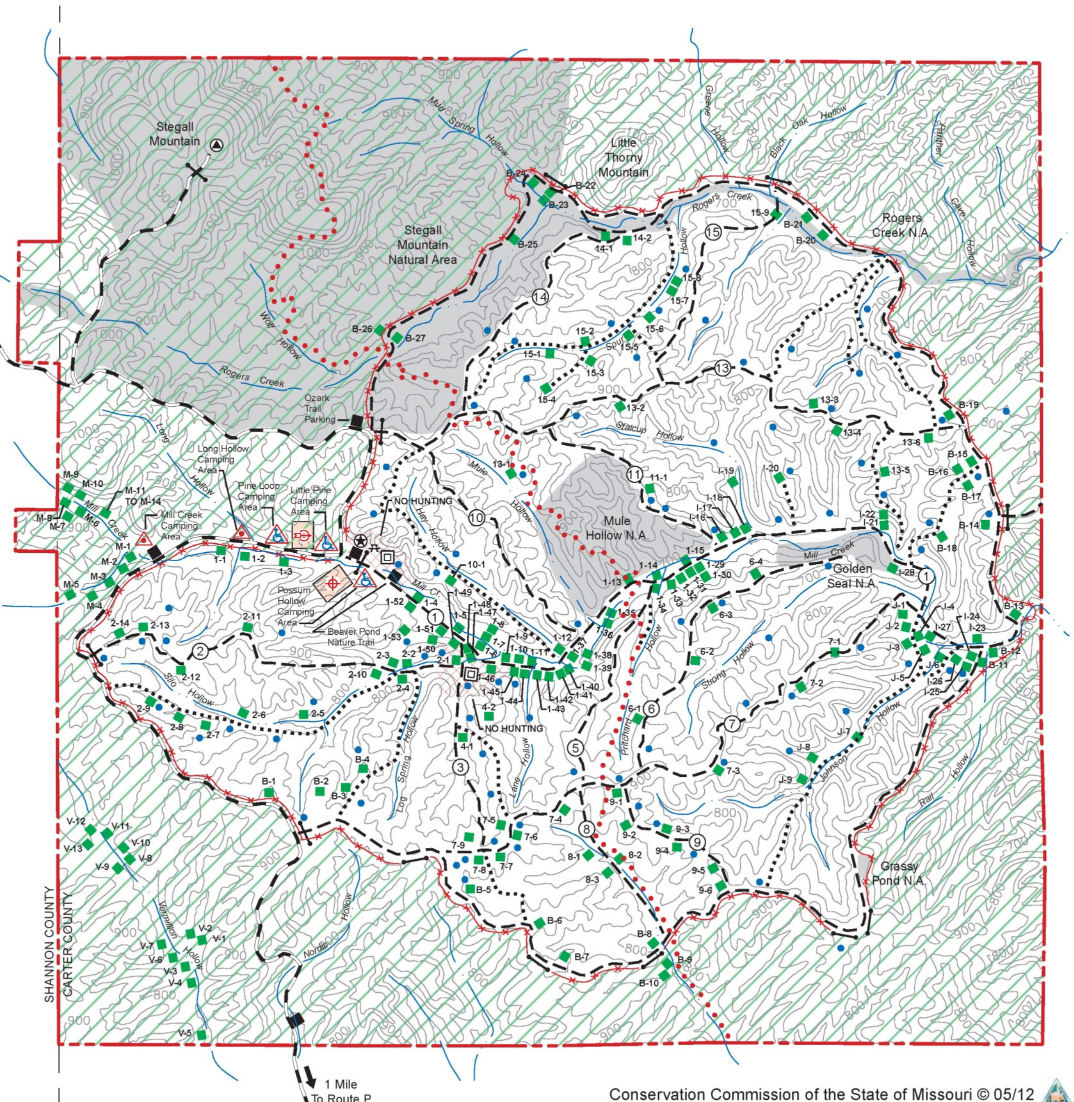


PECK RANCH CONSERVATION AREA

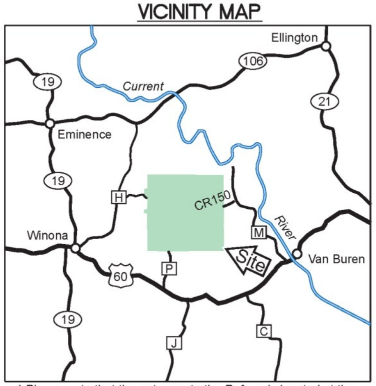
CARTER & SHANNON COUNTY
23,048 ACRES

LEGEND

- Boundary
- Gravel Road
- Service Road (6)
- Refuge Fence
- Ozark Trail
- Area Access Trail
- Drainage
- Parking Lot
- Pond
- Gate
- Food Plot (2-12)
- Topography
- Natural Area
- Public Hunting Area
- Primitive Camping Area
- Archery Range
- Shooting Range
- Fire Tower
- Buildings
- Area Headquarters
- Disabled Accessible
- Picnic Table
- Primitive Camping Area w/ Disabled Accessible Privy
- No Hunting Zone - Residential Area



VICINITY MAP



* Please note that the entrance to the Refuge is located at the Area Headquarters and is open during daylight hours only.

SCALE

0 — 1/2 — 1 Mile

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