Arkansas River Corridor Projects
River Bank Stabilization and Concept Design

TO:	Tulsa County
COPIES:	File
PREPARED BY:	CH2M HILL
DATE:	March 26, 2010
PROJECT NUMBER:	386594

Introduction

Tulsa County, as part of the Arkansas River Corridor Master Plan (Carter & Burgess, 2004; C. H. Guernsey and Company et al., 2005), is undertaking an improvement project on the Arkansas River. The primary goals of the overall project are to improve least tern habitat, improve fish habitat and fish passage, improve the function of the river system itself, enhance economic development, increase recreational opportunities, and increase connectivity between the river and surrounding communities. The conceptual project components are described in detail in the Technical Memorandum (TM) entitled Baseline Project Summary for the Arkansas River Corridor Project (CH2M HILL, 2009a). Key components include:

- Design of habitat improvements along the corridor
- Design of bank stabilization in select areas
- Design of a new Sand Springs low-head dam, pedestrian bridge, and amenities
- Design of modifications to Zink Dam and lake with whitewater features
- Design of a new South Tulsa/Jenks low-head dam, pedestrian bridge, and amenities

This TM provides a qualitative overview of the range of river bank physical conditions observed throughout the project reach. A discussion of the dominant mode of river bank failure is presented. A table of pertinent variables to be used for prioritizing river bank reaches in need of repair is also presented. In addition, conceptual river bank stabilization alternatives are presented along with planning-level cost estimates. This information would provide the basis for more rigorous and quantitative design.

Objectives

The objectives of this evaluation are to:

- Identify the potential river bank stabilization techniques that are appropriate in the Arkansas River corridor.
- Develop planning-level cost estimates for stabilization alternatives.
- Prioritize alternative techniques based on local conditions, habitat value, constructability, and cost.

River Bank Erosion Principles

Three primary mechanisms are involved in river bank erosion: (1) mass failure (2) fluvial entrainment (hydraulic action), and (3) subaerial weakening and weathering. Interaction between these mechanisms is widely recognized (Couper and Maddock, 2001).

The removal of bank material by hydraulic action is closely related to near-bank velocity conditions, and in particular the velocity gradient close to the bank, which determines the magnitude of hydraulic shear (Knighton, 1998). Hydraulic action is probably the most dominant process eroding non-cohesive banks where individual grains are dislodged or shallow slips occur along almost planar surfaces, while its effectiveness against cohesive banks depends upon the moisture content and degree of preconditioning of the material (Knighton, 1998).

The susceptibility of river banks to mass failure depends on their geometry, structure, and material properties (Knighton, 1998). Processes of weakening and weathering related in particular to soil moisture conditions reduce the strength of intact bank material and decrease bank stability (Knighton, 1998). Cycles of wetting and drying are especially important, as they cause swelling and shrinkage of the soil, leading to the development of interpedal fissures and tension cracks, which encourage failure (Knighton, 1998). Shallow slips occur in cohesionless banks, while the dominant mechanisms in banks of high and low cohesivity seem to be deep-seated rotational slip and slab-type failure, respectively (Knighton, 1998).

Side slopes of deep channels may be high and steep enough to be geotechnically unstable and fail under the influence of gravity (Brookes and Shields, 1996). Fluvial processes in such a situation serve primarily to remove blocks of failed material from the bank toe, leading to a re-steepened bank profile and a new cycle of failure (Brookes and Shields, 1996). Figure 1 illustrates this process.

In composite river banks where cohesive material overlies non-cohesive sands or gravels, a relatively common condition is cantilever failure (Knighton, 1998). This process is a function of both fluvial scour and mass failure. When hydraulic action scours the toe and undermines the bank, a subsequent collapse of the overhanging bank material often results (Figure 1).

Subaerial processes, which include wetting and drying of the soil and freezing-thawing activity, are commonly thought of as 'preparatory' rather than 'erosive' processes; they weaken the surface of the bank prior to fluvial erosion, thus increasing the efficacy of the erosion (Couper and Maddock, 2001). Fluvial erosion, in turn, can lead to undercutting and subsequent mass failure. A mass failure event supplying sediment to the toe of the river bank tends to increase bank stability by decreasing the bank angle, unless fluvial conditions exceed the critical shear stress for removal of this material (Couper and Maddock, 2001).

Knighton (1998) summarized multiple factors influencing bank erosion, as shown in Table 1:

TABLE 1
Factors Influencing Bank Erosion (from: Knighton, 1998)

Factor	Relevant Characteristics
Flow properties	• Magnitude-frequency and variability of stream discharge • Magnitude and distribution of velocity and shear stress • Degree of turbulence
Bank material composition	Size, gradation, cohesivity, and stratification of bank sediments
Climate	• Amount, intensity, and duration of rainfall • Frequency and duration of freezing
Subsurface conditions	• Seepage forces, piping • Soil moisture levels, pore water pressures
Channel geometry	• Width, depth, and slope of channel • Height and angle of bank • Bend curvature
Biology	• Type, density, and root system of vegetation • Animal burrows, trampling
Man-induced factors	Urbanization, land drainage, reservoir development, boating, bank protection structures

The amount, periodicity, and distribution of river bank erosion are highly variable due to the many factors involved (Table 1). The amount of bank erosion is not solely a function of discharge magnitude or related shear stress conditions, so a threshold flow cannot reasonably be defined (Knighton, 1998).

Requirements for a Stable River Bank

Restoring a river bank to a stable condition requires protection against the three primary mechanisms involved in bank erosion (see preceding section). Protection must be provided from the toe of the slope to the top of the bank, and some distance beyond the top of the bank, depending primarily upon bank and overbank slopes, soil loads, and habitat requirements. A stable river bank exhibits the following characteristics:

- Stable bank geometry for the soil parameters onsite, including: texture, structure, fertility, erodability, chemistry, and depth. In composite banks, stability is governed by the strength of the weakest component, since its removal eventually leads to failure in the rest of the bank (Knighton, 1998).
- River bed stability adjacent to, and in the vicinity of, the river bank.
- A protective surface layer resistant to hydraulic scour at the toe and basal area of the river bank, as well as mid- and up-slope protection from weathering and erosion. Erosive forces above the normal water surface elevation include: fluctuating water

surface elevations (regulated and flood flows); wave action; raindrops; wind; and overland flow resulting in sheet, rill, and/or gulley erosion.

- Runoff control from upgradient sources to prevent sheet, rill, and gulley erosion of the bank face.
- Seepage control to prevent piping or internal erosion of the river bank.

These characteristics are incorporated into the stable river bank approaches presented below.

River Bank Erosion within the Project Corridor

Overview of Existing Conditions

Photographs of representative river bank conditions are included in Appendices A, B, and C. These photographs, taken March 30 through April 1, 2009, during a ground and helicopter reconnaissance, illustrate the range of bank stability and erosion conditions observed within the project reach:

- Appendix A – unstable and actively eroding banks
- Appendix B – moderately stable banks with moderately active erosion
- Appendix C – stable banks with low erosion rates

Figure 1 illustrates the two primary modes of mass failure observed during the field reconnaissance of March 30 through April 1, 2009: rotational slump and cantilever failure. The most prevalent mode of mass failure within the project corridor appears to be rotational slump. Examples of rotational slumps can be seen in Appendix A, Photos 184, 299, and 430. Photo 434 (also in Appendix A) shows an active rotational slump (slab failure) coupled with a flow slump caused by overland flow across the top of the unprotected, denuded bank.

Photo 185 (Appendix A) shows a combination of toe scour and cantilever failure. The right portion of the photograph shows a near vertical bank, with cantilevered material at the top. The cantilevered material is tenuously held in place, likely due to root density and perhaps slightly more cohesive soils in the upper layers. Previously failed bank material from this location has been entrained by the river, exposing the toe to another cycle of erosion. The bank on the left side of the photograph still has previously failed material at the toe, although the upper bank has retreated further inland than the adjacent bank.

Ultimately, the natural processes are seeking a more stable slope in equilibrium with the river hydrology and local hydraulics. Until a stable slope is attained, these exposed banks will not be able to support colonizing vegetation and reap the associated benefits, such as: improved soil tension and shear strength in the root zone; increased pore water uptake; and increased surface roughness, resulting in decreased near-bank velocity and scour.

Photo 173 (Appendix A) shows extensive bank erosion along a relatively high, steep bank. Given the relatively uniform slope of this denuded bank, it appears that this bank erosion has been taking place for a relatively long period of time. Some active erosion and shallow slips can be seen, so the bank slope is still attempting to develop stability in equilibrium with the local hydrology and fluctuating water surface elevations in the river. Without conducting a detailed geotechnical analysis of this bank, it is difficult to determine exactly what a stable bank slope would be for the local soil characteristics and hydraulic regime.

The river bank reaches shown in Appendix B are categorized as having moderate bank instability, with moderate rates of erosion, due primarily to bank slope and height. The shallower the bank slope and the lower the bank height, the more stable the bank becomes. Most of the river banks shown in Appendix B also exhibit dense stands of woody vegetation adjacent to the bank. Since the photographs were taken before the growing season, it is difficult to assess the extent of vegetation, if any, on the bank slopes.

Appendix C shows representative reaches of stable river banks. These include both engineered banks and natural banks. Stable natural banks can be seen in Photos 152 and 236. Stable engineered banks with riprap protection are shown in Photos 473 and 530. Banks with a combination of riprap and woody vegetation are shown in Photos 141, 144, 245, and 295. Banks with riprap on the lower bank with grass on the upper bank are shown in Photos 159 and 166.

Proposed Project Effects on Bank Stability

The two proposed dams and modified Zink Dam would generally increase the length of pool and decrease the length of free-flowing conditions within the project corridor. With the proposed project, flow magnitude, frequency, and duration would remain dynamic given: (1) the regulated (through the gates) and un-regulated (through the emergency spillway) flood flows from Keystone Dam; (2) the relatively low proposed dam heights; and (3) the proposed gate operations for sediment and fish passage. Generally, under existing conditions, there are approximately 2 river miles of pool conditions, created by Zink Dam, and approximately 22.5 river miles of free-flowing reach through the project corridor. Under the proposed project conditions, this would change to approximately 11.5 river miles of free-flowing reach and 13 miles of pool conditions.

The effects of the proposed project on bank stability are best described according to the three types of river reaches that would exist: free-flowing reaches, transition reaches, and pool reaches. Bank stability conditions in the free-flowing reaches should remain unchanged, as they would be subject to the same hydrologic and hydraulic regime, and therefore prone to the same types and degrees of bank erosion mechanisms.

The transition reaches would experience more frequently changing water surface elevations, velocities, and near-bank shear stress, so banks within these reaches would be subjected to shifting degrees of bank erosion mechanisms. Because hydraulic parameters that affect bank stability would be changing more frequently in these reaches, the overall effect would likely be a net increase in bank instability through the transition zones.

In the pool reaches, the net effect of the project would likely be a shift in the primary mechanism of bank erosion from fluvial entrainment to mass failure. The expanded pool conditions would expose significantly more river bank area to increased water depths, lower velocities, and less shear stress for longer periods of time. Compared to existing conditions, these changes would be more pronounced during low and mid-range flows as opposed to flood flows when the hydraulic effects of the proposed dams are dampened. During low and mid-range flows, the backwater effect from the low-head dams would decrease the near-bank velocities in the pool reaches, thereby decreasing fluvial entrainment of bank material. Increased water depths, however, would result in elevated pore water pressure in a greater extent of the banks, both laterally and vertically, for longer periods of time. Therefore, stabilizing and protecting banks from mass failure would be important. The influence of subaerial processes in the pool reaches would occur at the same frequency; however, their influence would shift up the bank vertically, above the new pool elevations where wet-dry and freezing-thawing cycles occur.

Prioritizing River Banks for Treatment

Given the significant total river bank length of approximately 41 miles from Keystone Dam to the proposed South Tulsa/Jenks low-head dam, reaches would need to be prioritized for treatment. In general, bank conditions such as those shown in Appendix A would be high priorities for stabilizing regardless of reach location. Banks such as those shown in Appendix C are stable now, and would likely remain stable under proposed project conditions; therefore, such areas would be monitored for any developing signs of instability and treated accordingly. Protection for river banks similar to those shown in Appendix B would be prioritized using qualitative guidelines such as those presented in Table 2.

TABLE 2
Prioritization of River Bank Conditions by Reach

Bank Condition	Pool Reach	Transition Reach	Free-flowing Reach
Failing under existing conditions	High	High	High
Steep side slope	High	High	Moderate
Moderate side slope	Moderate	Moderate	Low
Gentle side slope	Low	Low	Low
High bank height	High	High	Moderate
Moderate bank height	Moderate	Moderate	Low
Low bank height	Low	Low	Low
Infrastructure on the bank slope or overbank	High	High	Moderate
Infrastructure near the bank slope or overbank	Moderate	Moderate	Low

Habitat value would also influence the prioritization of banks needing treatment. Unstable banks located within reaches that provide important riparian habitat would be prioritized over those with only marginal habitat value, unless infrastructure protection is required. In particular, habitat requirements would be considered when designing treatments for unstable banks near least tern nesting sites. For example, least terns tend to avoid nesting in close proximity to gallery forest and other structures rising above the water line (CH2M HILL, 2009b). Crowding by Canada geese can also be detrimental to least tern nesting (CH2M HILL, 2009b). Therefore, bank stabilization near least tern nesting sites would have to account for these habitat preferences to avoid unwanted ecological impacts. This would be achieved by selecting appropriate vegetation species, density, and distribution for planting the river banks. Bank geometry would also be important near least tern nesting habitat.

Quantification of Existing River Bank Conditions Using the Helicopter Reconnaissance Video

The project corridor was videotaped using a low-elevation helicopter reconnaissance flight in March 2009. The flight video was produced by Immersive Media Corporation under a contract with Tulsa County. Flying each bank of the river and the centerline, the 11 lenses capture a 360-degree image on each frame. Using a computer and the Immersive Media content viewer or the Geographic Information System (GIS) compatible viewer, the users navigate a virtual video of the corridor. To quantify the longitudinal extent of existing river bank conditions within the project corridor based on stability, five categories of relative bank stability were defined as follows: stable, stable to moderately stable, moderately stable, moderately stable to unstable, and unstable. These categories were defined solely on the basis of visual, physical evidence as observed in the helicopter video. The photographs included in Appendices A, B, and C provided a sort of calibration for the video desktop analysis. The software used to view the video includes spatial data, so the distances, or extent of river bank categories, were quantified. The results of this analysis are included in Table 3 and depicted graphically in Appendix D.

TABLE 3
River Bank Stability Summary Based on Immersive Media Video Analysis

	Pooled/Impounded Areas Only (mi)			
River Bank Stability Category	Sand Springs	Zink	South Tulsa/Jenks	Total
Stable	7.3	3.7	1.8	12.7
Stable to Moderately Stable	0.3	0.3	0.7	1.3
Moderately Stable	7.1	3.4	1.6	12.1
Moderately Stable to Unstable	2.1	1.1	1.4	4.5
Unstable	1.3	0.2	1.3	2.8
Total	18.0	8.7	6.7	33.4

River Bank Stability Category	Entire Project Corridor (mi)
Stable	31.6
Stable to Moderately Stable	6.4
Moderately Stable	27.2
Moderately Stable to Unstable	8.7
Unstable	8.0
Total	81.9

Recommended Stabilization Techniques

For structural purposes and habitat and aesthetic values, the recommended bank stabilization technique for the project corridor is a reinforced toe coupled with bioengineering techniques above the toe. Riprap revetment from the toe to the top of the bank, without any bioengineering methods, is recommended only where banks would be stabilized in the immediate vicinity of infrastructure and where the use of vegetation may be prohibited.

Allen and Leech (1997) presented a schematic of river bank zones that is useful in identifying appropriate bank stability treatments. Using this approach, the bank is divided into four zones (Figure 2): toe, splash, bank, and terrace. The zones are defined by Allen and Leech (1997) as follows:

- ***Toe zone*** *– that portion of the bank between the bed and average normal stage. This is a zone of high stress and can often be undercut by currents. Undercutting here will likely result in bank failure unless preventative or corrective measures are taken. This zone is often flooded greater than 6 months of the year.*
- ***Splash zone*** *– that portion of the bank between normal high-water and normal low-water flow rates. This and the toe zones are the zones of highest stress. The splash zone is exposed frequently to wave wash, erosive river currents, ice and debris movement, wet-dry cycles, and freezing-thawing cycles. This section of the bank would be inundated throughout most of the year (at least 6 months/year), but note that a large part of this inundation may occur in the dormant season of plants. The water depths fluctuate daily, seasonally, and by location within the splash zone.*
- ***Bank zone*** *– that portion of the bank usually above the normal high-water level; yet, this zone is exposed periodically to wave wash, erosive river currents, ice and debris movement, and traffic by animals or man. The zone is inundated for at least a 60-day duration once every 2 to 3 years. The water table in this zone frequently is close to the soil surface due to it closeness to the normal river level.*
- ***Terrace zone*** *– that portion of the bank inland from the bank zone; it is usually not subjected to erosive action of the river except during occasional flooding. This zone may include only the level area near the crest of the unaltered "high bank" or may include sharply sloping banks on high hills bordering the stream.*

It would be important to spatially define these zones through the project reach under the proposed conditions. This would require knowledge of the proposed operating rules for the low-head dams, as well as the frequency, duration, and magnitude of river flows through the reach based on historical conditions and operations at Keystone Dam.

For this concept level-of-effort, recommended bank stabilization methods for the project corridor are summarized in Table 4. Table 4 indicates the bank zones to which each method applies. Illustrations of many of the proposed stabilization methods are included in Figures 3 through 12.

Bank shaping, though not explicitly included in Table 4, is a treatment that would be considered and evaluated at each stabilization site. The need to regrade river banks to a stable slope would involve the evaluation of bank soils, probable groundwater fluctuation, and bank loading conditions. Potential impacts to existing riparian habitat that may result from bank shaping would be evaluated as well. For example, at some locations the benefits of bank shaping may be outweighed by the disturbances associated with land clearing for equipment access. Slope stability analyses are recommended to ensure that stable bank configurations are designed based on local soil characteristics and hydrology.

A wealth of information exists in the literature pertaining to all of the recommended stabilization methods listed in Table 4. An overview of key concepts and definitions associated with the methods listed in Table 4 is presented below.

TABLE 4
Recommended Bank Stabilization Methods by River Bank Zone

Stabilization Method	Toe Zone	Splash Zone	Bank Zone	Terrace Zone	Comments
1) Rock toe:					
a) Extended to maximum scour depth	√				See Figure 3, Method A.
b) Launchable stone:					
i) Windrow		√	√	√	Riprap placed above the toe
ii) Trench-fill	√				Riprap placed at low water level
iii) Weighted riprap toes	√				Riprap placed at intersection of channel bed and side slope. See Figure 3, Methods C and D.
2) Longitudinal Peaked Stone Toe Protection (LPSTP)	√	√			A launchable, weighted stone toe method coupled with live branch cuttings to promote siltation. See Figure 4.
3) Joint planted riprap	√	√	√	√	Temporary irrigation may be required in bank and terrace zones until roots can reach the water table. See Figures 5 and 12.
4) Live staking	√	√	√	√	Live stakes can be used alone, or in combination with other bioengineering methods. Temporary irrigation may be required in bank and terrace zones until roots can reach the water table. See Figures 5, 6, and 7.
5) Live fascine		√	√	√	Used primarily for surface erosion control; not to be used on banks experiencing mass movement or other slope instability. See Figure 6.
6) Brush mattress		√	√	√	Application in the splash zone must be used in association with a hard toe; not to be used on banks experiencing mass movement or other slope instability; provides excellent habitat. See Figure 7.
7) Branchpacking		√	√	√	Application in the splash zone must be used in association with a hard toe; used to restore small holes in banks; not effective in slump areas greater than 4 feet deep or 4 feet wide, or on slopes steeper than 2:1 (H:V). See Figure 8.
8) Brush layering		√	√	√	Application in the splash zone must be used in association with a hard toe; works better on fill rather than cut slopes. See Figure 9.

TABLE 4
Recommended Bank Stabilization Methods by River Bank Zone

Stabilization Method	Toe Zone	Splash Zone	Bank Zone	Terrace Zone	Comments
9) Vegetated geogrids (also called fabric encapsulated soil lifts)		√	√	√	Application in the splash zone must be used in association with a hard toe; useful for rebuilding very steep eroded banks. See Figure 10.
10) Live slope grating			√	√	Useful for establishing vegetation on slopes steeper than 1.5:1 (H:V). See Figure 11.
11) Woody vegetative planting			√	√	Combination of trees and shrubs planted to create wildlife habitat, increase surface roughness and improve soil strength.
12) Sod mattress			√	√	Use of sod in the bank zone requires staking sod to the bank; used to prevent soil erosion and improve soil moisture retention on high banks above the water table
13) Riprap with soil and grass or ground cover	√	√	√	√	Similar to joint planted riprap, except that the voids amongst the riprap revetment are backfilled with soil to more rapidly establish a more dense vegetated cover amongst the rock. This is particularly useful on banks that tend not to silt-in naturally over time, perhaps due to drought periods, lack of interface with flood flows, or low suspended solids concentrations in the river. See Figure 12.

Rock (Stone) Toe

Toe protection may be provided by two methods: extend to maximum scour depth or place launchable stone. The U.S. Army Corps of Engineers (USACE, 1991) detailed both methods and provided recommendations for each. USACE's recommended methods are described briefly here and illustrated on Figure 3. The original "method" designations used by USACE are retained and labeled accordingly on Figure 3.

Rock placement to the maximum scour depth, or founded on nonerodible material, is shown on Figure 3, Method A. This is the preferred method of rock toe protection; however, it can be difficult and expensive when underwater excavation is required. Given the significant length of bank treatment areas anticipated for this project, it is likely this method would be considered only for areas that involve significant infrastructure value and high costs associated with failure. If toe excavation can be made in the dry, Method A becomes more feasible.

Launchable stone is placed in sufficient quantity to stabilize erosion that may occur below the stone. USACE (1991) defines launchable stone as stone that is placed along expected erosion areas at an elevation above the zone of attack. As the attack and resulting erosion occur below the stone, the stone is undermined and rolls/slides down the slope, stopping the erosion. This method has been widely used on sand bed streams.

USACE (1991) outlines three successful applications of launchable stone:

- Windrow revetments: riprap placed at the top of the bank
- Trench-fill revetments: riprap placed at the low water level
- Weighted riprap toes: riprap placed at the intersection of the channel bottom and side slope

Method C on Figure 3 is applicable when the riprap is to be placed underwater and little toe scour is expected, such as in straight reaches that are not downstream of bends (USACE, 1991).

Method D on Figure 3 is extremely useful where water levels prevent excavation for a toe section. Method D illustrates a launchable, weighted riprap toe that is highly applicable to the project corridor given the significant lengths of potential treatment areas. Even if excavation is practical, this method may be preferred for cost savings if the cost of extra stone required to produce a launchable thickness equal to or greater than 1.5 times the overlying revetment thickness, T, shown on Figure 3, is exceeded by the cost of excavation required to carry the design thickness, T, down the slope (USACE, 1991). This method also provides a "built-in" scour gage, allowing easy monitoring of high-flow scour and the need for additional stone reinforcement by visual inspection of the remaining toe stone after the high flow subsides, or by surveyed cross-sections if the toe stone is underwater (USACE, 1991).

Another launchable, weighted stone toe method is referred to as a "longitudinal peaked stone toe protection" (LPSTP) (USACE, 2009). This method is illustrated on Figure 4. Live branch cuttings are placed immediately above the stone toe, and dense vegetation becomes established at the waterline. This is an excellent means of promoting natural siltation, creating and diversifying shoreline habitat, and improving aesthetics. Bank shaping and any number of bioengineering methods described below can be used in concert with this toe protection method to stabilize the bank and terrace zones.

Bioengineering Methods

Inherent in all the soil bioengineering methods described below is the need to develop an appropriate vegetation strategy. The vegetation strategy for this project would be based on site-specific goals and hydrology data. Goals would include factors such as bank stability, habitat, erosion control, and aesthetics. Pertinent hydrology data include:

- Stage-discharge
- Depth to summer water table
- Timing of peak discharge
- Magnitude, frequency, and duration of flood flows
- Magnitude of baseflow during the growing and dormant seasons

Joint Planted Riprap and Live Staking

Joint planting (JP) and live staking (LS) soil bioengineering systems are units fabricated from live, woody plant material branches (Sotir and Fischenich, 2007). When LSs are planted in joints between stones, the process is referred to as “joint planting.” “Pole planting” is another term associated with JP, although pole planting usually refers to much larger LSs that can be mechanically driven into rock joints. The larger “poles” are less susceptible to damage during installation, and they can be driven deeper into the bank. This is useful for reaching a relatively deep water table, and for mechanically driving the poles through a thick layer of rock revetment (Figure 5).

The term “live staking" is used when the live woody stakes are planted in the absence of rock revetment. LS can be done in a dense grid pattern to cover a significant amount of bank area; or, LSs can be used to help secure other soil bioengineering materials such as fascines (Figure 6) or brush mattresses (Figure 7).

Over time, the LSs are effective for erosion control and the JP system provides reinforcement to slopes where rock has been placed (Sotir and Fischenich, 2007). The LS and JP live cut branches are expected to grow roots and top growth, with the roots providing additional soil reinforcement and surface cover providing protection from runoff and river flow (Sotir and Fischenich, 2007).

Live Fascines

Live fascines are bundles of dormant, live cutting bound together into a long, cylindrical form. Their primary use is to minimize bank erosion above the toe. Additional uses include improving habitat for aquatic plants and animals, contributing to food web dynamics, and enhancing aesthetics through the establishment of vegetation.

The Federal Interagency Stream Restoration Working Group (FISRWG, 1998) summarized the applications and effectiveness of live fascines (Figure 6) as follows:

- Can trap and hold soil on streambank by creating small dam-like structures and reducing the slope length into a series of shorter slopes.

- Facilitate drainage when installed at an angle on the slope.
- Enhance conditions for colonization of native vegetation.
- Should, where appropriate, be used with other soil bioengineering systems and vegetative plantings.
- Require toe protection where toe scour is anticipated.
- Effective stabilization technique for streambank, requiring a minimum amount of site disturbance.
- Not appropriate for treatment of slopes undergoing mass movement.

Brush Mattress

A brush mattress is a thick layer of live branch-cuttings installed to cover and physically protect river banks (Figure 7). It is primarily used to minimize bank erosion on slopes no steeper than 2:1 (H:V), that are not experiencing mass movement. Brush mattresses provide excellent habitat for birds, small fur-bearing animals, and insects, as well as other organisms that are in turn fed upon by fish and other higher organisms (Allen and Fischenich, 2001).

The Federal Interagency Stream Restoration Working Group (FISRWG, 1998) summarized the applications and effectiveness of brush mattresses as follows:

- Form an immediate protective cover over the streambank.
- Capture sediment during flood flows.
- Provide opportunities for rooting of the cuttings over the streambank.
- Rapidly restore riparian vegetation and streamside habitat.
- Enhance conditions for colonization of native vegetation.
- Limited to the slope above base flow levels.
- Toe protection is required where toe scour is anticipated.
- Appropriate where exposed streambanks are threatened by high flows prior to vegetation establishment.
- Should not be used on slopes which are experiencing mass movement or other slope instability.

Branchpacking

In this technique, alternate layers of compacted backfill and live branches are used to restore voids, slumps, and holes in river banks (Figure 8).

The FISRWG (1998) summarized the applications and effectiveness of branchpacking as follows:

- Commonly used where patches of streambank have been scoured out or have slumped, leaving a void.

- Appropriate after stresses causing the slump have been removed.
- Less commonly used on eroded slopes where excavation is required to install the branches.
- Produces a filter barrier that prevents erosion and scouring from streambank or overbank flows.
- Enhances conditions for colonization of native vegetation.
- Provides immediate soil reinforcement.
- Live branches serve as tensile inclusions for reinforcement once installed.
- Typically not effective in slump areas greater than 4 feet deep or 4 feet wide.

Brush Layering

In brush layering, live, cut branches are interspersed between layers of soil, preferably on fill slopes (Figure 9). This technique is very similar to branch packing, except that it is used over longer bank lengths rather than just filling voids or small slumps. It is more effective on fill slopes because longer stems can be used in fills. This method is used to stabilize a slope against shallow sliding or mass wasting, in addition to providing erosion protection.

Vegetated Geogrids or Fabric Encapsulated Soil Lifts

As illustrated on Figure 10, vegetated geogrids, or fabric-encapsulated soil lifts, are earthen structures made from living, rootable, live-cut, woody plant material in conjunction with rocks and natural or synthetic geotextile material (Sotir and Fischenich, 2003). This method is useful for rebuilding very steep eroded streambanks with slopes too steep for normal brush layering. These systems can be constructed on slopes ranging from 2:1 (H:V) to 0.5:1 (Sotir and Fischenich, 2003).

The FISRWG (1998) summarized the applications and effectiveness of vegetated geogrids as follows:

- Quickly establish riparian vegetation if properly designed and installed.
- Can be installed on a steeper and higher slope and have a higher initial tolerance of flow velocity than brush layering.
- Can be complex and expensive.
- Produce a newly constructed, well-reinforced streambank.
- Useful in restoring outside bends where erosion is a problem.
- Capture sediment and enhance conditions for colonization of native species.
- Slope stability analyses are recommended.
- Require a stable foundation.

Live Slope Grating

Live slope grating is shown in Figure 11 and described as follows (Mississippi State University, 2008):

A live slope grating is a lattice-like array of vertical and horizontal untreated timbers that are fastened or anchored to a steep slope. It is constructed to be self-supporting. The openings in the structure are filled with suitable backfill material and layers of live branch cuttings which are placed in a manner similar to brush layering. The purpose of the grating structure itself is not revetment for the slope, but rather to provide a means to make establishment of vegetation possible.

This technique is used because it allows vegetation to be established on very steep slopes (steeper than 1.5H:1V) without requiring extensive excavation and clearance at the foot of the slope or extensive importation of select backfill and cribfill.

Its primary use is to minimize bank erosion and enhance aesthetics through the establishment of vegetation.

Woody Vegetative Planting

Although most soil bioengineering methods involve the use of woody vegetative plantings, this technique is included here as a separate method to emphasize that numerous trees and shrubs can be planted in the bank and terrace zones using methods other than LS. For example, larger balled-and-burlapped saplings and shrubs can be planted in and among LSs and seeded areas to develop a multi-stage canopy and thus diversify habitat and improve aesthetics. Desirable tree and shrub species would be important in areas that are near public access points and parks. Trees and shrubs not only provide habitat and aesthetic benefits—their root structure significantly enhances bank stability.

Sod Mattress

Sod mattresses are useful for establishing immediate ground cover to prevent soil erosion. On steep banks where seed can be washed away from raindrop erosion and sheet flow, sod mats can be secured to the bank. Deep rooting grasses such as bermudagrass, buffalo grass, and switchgrass are good candidates. As these grasses establish, other plants can colonize the stable bank.

Riprap with Soil and Grass or Ground Cover

Where riprap revetments are required, backfilling voids in the riprap with soil is useful for more rapidly establishing a dense vegetated cover among the rock (Figure 12) (USACE, 2009). This technique should be coupled with JP and seeding to prevent erosion of the soil before vegetation colonizes the treatment area. This is particularly useful on banks that tend not to silt-in naturally over time, perhaps due to drought, lack of interface with flood flows, or low suspended solids concentrations in the river.

Planning-Level Costs

The highest cost item associated with stabilizing the river banks would be stabilizing the toe zone. The toe is the most critical zone of the bank in terms of long-term bank stability. Because rock would be required to stabilize this zone, equipment access would be a significant factor in dictating construction methods and costs. It is anticipated that the majority of construction access would be over land; however, access to the river banks using a barge may also be considered.

Another influence on cost associated with bank toe stabilization is whether or not in-river turbidity control would be required during construction. If so, this would likely be accomplished using in-river turbidity screens. A determination with the regulating agencies would need to be made as to how the turbid water would be managed. This could range from no controls at all, given the dilution effect of the river, to pumping from within the turbidity screen into some form of passive or active treatment. Prescribing a launchable stone toe protection method, such as a weighted riprap toe, may preclude the need for any turbidity control.

Other factors that would influence the cost of stabilizing the bank toe zone include the anticipated depth of river bed scour, bank slope, local shear stress and velocity, and water surface elevation and flow duration. The anticipated scour depth would influence the volume of rock required to protect against future bed scour, if any. The bank slope would determine whether or not excavation would be required to reshape the bank into a more stable slope, which would affect the volume of rock required. The hydraulic shear stress and velocity associated with the design flows would dictate the size of rock required to stabilize the bank. The water surface elevation and associated flow duration would dictate the vertical extent of the toe zone (see Figure 2), and thus the extent of rock required up the bank face. The water depth at the treatment site would also indicate the most cost-effective and feasible method of toe protection, whether that be excavating for scour protection (Method A, Figure 3) or designing a launchable stone toe (Methods C and D, Figure 3).

Above the toe zone, a variety of bioengineering methods are anticipated to be feasible and appropriate for the range of conditions observed in the project corridor. Table 5 lists some unit costs for some common bioengineering techniques. These costs were obtained from published literature and adjusted to current prices.

To develop a planning-level cost estimate for the typical range of bank conditions observed in the project corridor (see Table 3), a number of assumptions were required. The bank geometry assumptions are summarized in Table 6.

Using the bank geometries defined in Table 6, a range of planning-level costs were developed based on estimated material costs, profit, and contingencies. Costs associated with turbidity control and land clearing for access or barge work are not included. For the rock toe protection, a gravel filter thickness of 0.5 foot, a rock revetment thickness of 1.5 feet, and a geotextile fabric were assumed, as appropriate, for the various methods of toe protection illustrated in Figure 3. A simple prescription of live staking, 3 feet on center, was used for the bioengineering costs above the toe zone.

The resultant planning-level costs range from $275 to $770 per linear foot of bank using Method D (Figure 3) for toe protection. Using a longitudinal peaked stone toe protection method (Figure 4), the costs ranged from $550 to $1,250 per linear foot of bank. The low end of the cost estimate is associated with a stable to moderately stable bank, and the high end is associated with an unstable bank. These estimated costs are based on the simplest bioengineering techniques, so cost adjustments upward would be expected if more labor-intensive methods such as brush mattressing were prescribed. The calculations of total costs

TABLE 5
Unit Costs (in dollars) of Representative Bioengineering Methods

		USACE Cost and Year of Development				Cost for December 2009			Use Average
Item	Unit	Year	Low Cost	High Cost	ENR	ENR[a] December 2009	Low Cost	High Cost	Cost (Rounded)
Live Staking[b]	Each	2001	3.00	10.00	6318.20	8641.45	4.10	13.68	9.00
Joint Planting[b]	Each	2001	6.00	15.00	6318.20	8641.45	8.21	20.52	15.00
Live Fascine - 6" to 8" Bundles[c]	Each	2000	10.00	30.00	6238.10	8641.45	13.85	41.56	28.00
Inert Fascine - 12" Bundles[c]	Each	2000	10.00	26.00	6238.10	8641.45	13.85	36.02	25.00
Inert Fascine - 18" Bundles[c]	Each	2000	14.00	30.00	6238.10	8641.45	19.39	41.56	31.00
Brush Mattress[d]	Square Feet	2000	2.32	5.11	6238.10	8641.45	3.21	7.08	6.00
Vegetated Geogrids[e]	Square Feet	2001	15.00	35.00	6318.20	8641.45	20.52	47.87	35.00

Notes:
Costs are complete and include 5% Profit and 10% Contingency.
[a] The costs presented in Table 5 have been adjusted from the cost resource that the unit costs came from to the current date to which these costs have been escalated (December 2009) using the Engineering News-Record Construction Cost Index (ENR CCI) for the 20-City National Average index.
[b] Costs include harvesting, transportation, handling, fabrication, and storage of the live cut branch materials. Costs for other system elements (e.g. riprap) and bank reshaping are not included. Source of USACE cost data is Sotir and Fischenich (2007).
[c] Costs include securing devices for installation, twine (for fabrication), harvesting, transportation, handling, fabrication, storage of the live cut branch materials, excavation, backfill, and compaction. Structures are normally 20- to 30-ft long each. Inert fascines, as opposed to live fascines, are not intended to grow. Source of USACE cost data is Sotir and Fischenich (2001).
[d] Costs include live fascince installation along with the brush mattress. Source of USACE cost data is Allen and Fischenich, 2001.
[e] Costs are based on contractor bid projects on sites 10 to 60 ft in height and include: harvesting, transportation, handling, and storage of the live cut branch materials or rooted plants. Source of USACE cost data is Sotir and Fischenich (2003).

TABLE 6
Assumed River Bank Geometries for Planning-Level Cost Estimate

River Bank Condition	Scour Protection Depth (ft)	Toe Zone Vertical Dimension (ft)	Vertical Dimension above Toe Zone (ft)	Existing Toe Zone Side Slope (xH:1V)	Existing Side Slope above Toe Zone (xH:1V)
Stable	0	8	5	2	2
Stable to Moderately Stable	0	8	8	2	2
Moderately Stable	3	8	10	2	1.5
Moderately Stable to Unstable	6	10	13	2	1
Unstable	6	12	15	2	0.5

for repair/stabilization based on the River Bank Stability Categories presented in Table 3 and the planning-level costs per linear foot presented in this paragraph are contained in the *Preliminary Cost Estimate* TM (CH2M HILL, 2010).

A definition of the planning-level cost estimate used for this analysis is included in Appendix E.

References

Allen, H.H. and Craig Fischenich. 2001. Brush Mattresses for Streambank Erosion Control. EMRRP Technical Notes Collection. ERDC TN-EMRRP-SR-23. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Allen, H. H. and James R. Leech. 1997. *Bioengineering for Streambank Erosion Control, Report 1 – Guidelines*. Technical Report EL-97-8. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Brookes, A. and D. Shields Jr., editors. 1996. River Channel Restoration: Guiding Principles for Sustainable Projects. John Wiley & Sons, New York.

Carter & Burgess. 2004. Final Arkansas River Corridor Master Plan, Phase I Vision Plan. Prepared for the Indian Nations Council of Governments.

CH2M HILL. 2009a. *Baseline Project Summary for the Arkansas River Corridor Project.* Technical Memorandum prepared for Tulsa County – AR River Projects.

CH2M HILL. 2009b. *Arkansas River Corridor Projects Least Tern Data Review and Analysis*. Technical Memorandum to Tulsa County. July 2, 2009.

CH2M HILL. 2010. *Arkansas River Corridor Projects, Preliminary Cost Estimate*. Technical Memorandum to Tulsa County.

Couper, Pauline R., and Ian P. Maddock. 2001. *Subaerial River Bank Erosion Processes and Their Interaction with Other Bank Erosion Mechanisms on the River Arrow, Warwickshire, UK*. Earth Surface Processes and Landforms **26**, 631-646.

Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653. ISBN-0-934213-59-3.

Guernsey, C.H. and Company, EDAW, Inc., Hisinc, LLC, Alaback Design and Associates, Adaptive Ecosystems, Inc., Schnake Turnbo Frank, Inc. 2005. Final Arkansas River Corridor Master Plan, Phase II Master Plan and Pre-Reconnaissance Study. Prepared for the U.S. Army Corps of Engineers.

Knighton, David, 1998. Fluvial Forms and Processes – A New Perspective. Oxford University Press Inc., New York, New York.

Mississippi State University. 2008. *Live Slope Grating*. http://www.abe.msstate.edu/csd/NRCS-BMPs/pdf/streams/bank/liveslopegrating.pdf. Accessed October 29, 2009.

Sotir, R. B. and J. Craig Fischenich. 2001. *Live and Inert Fascine Streambank Erosion Control.* EMRRP Technical Notes Collection. ERDC TN-EMRRP-SR-31. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Sotir, R. B. and J. Craig Fischenich. 2003. *Vegetated Reinforced Soil Slope Streambank Erosion Control.* EMRRP Technical Notes Collection. ERDC TN-EMRRP-SR-30. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Sotir, R. B. and J. Craig Fischenich. 2007. *Live Stake and Joint Planting for Streambank Erosion Control*. EMRRP Technical Notes Collection. ERDC TN-EMRRP-SR-35. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

U.S. Army Corps of Engineers (USACE). 1991. *Hydraulic Design of Flood Control Channels.* Engineer Manual 1110-2-1601. Washington, DC.

U.S. Army Corps of Engineers (USACE). 2009. Ecosystem restoration plan in conjunction with proposed low water dams. Vision 2025 Arkansas River Corridor. Prepared for Tulsa County, Oklahoma. February 13, 2009.

Waters, T.F. 1995. *Sediment in streams: sources, biological effects, and control*. American Fisheries Society Monograph 7.

Figures

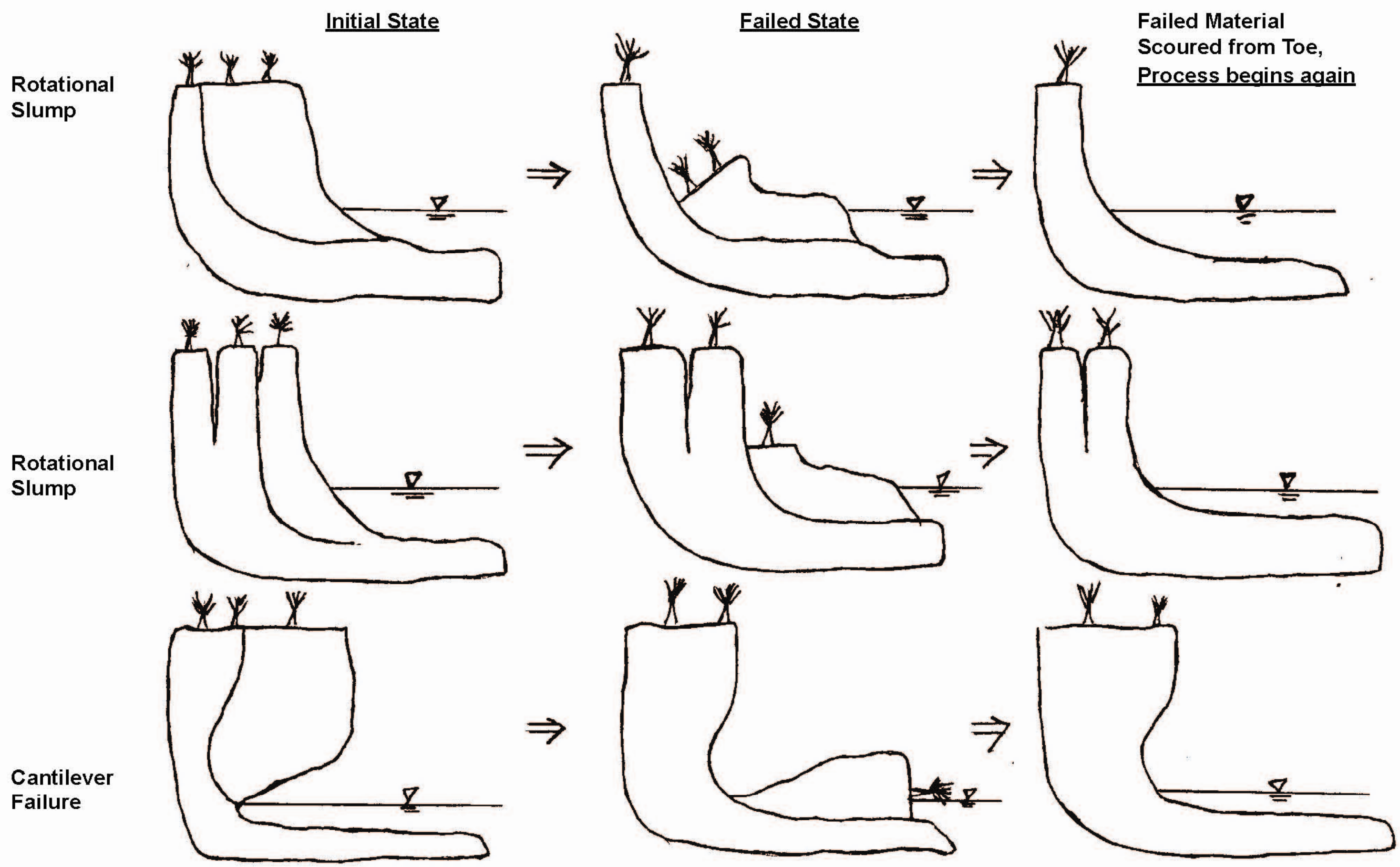
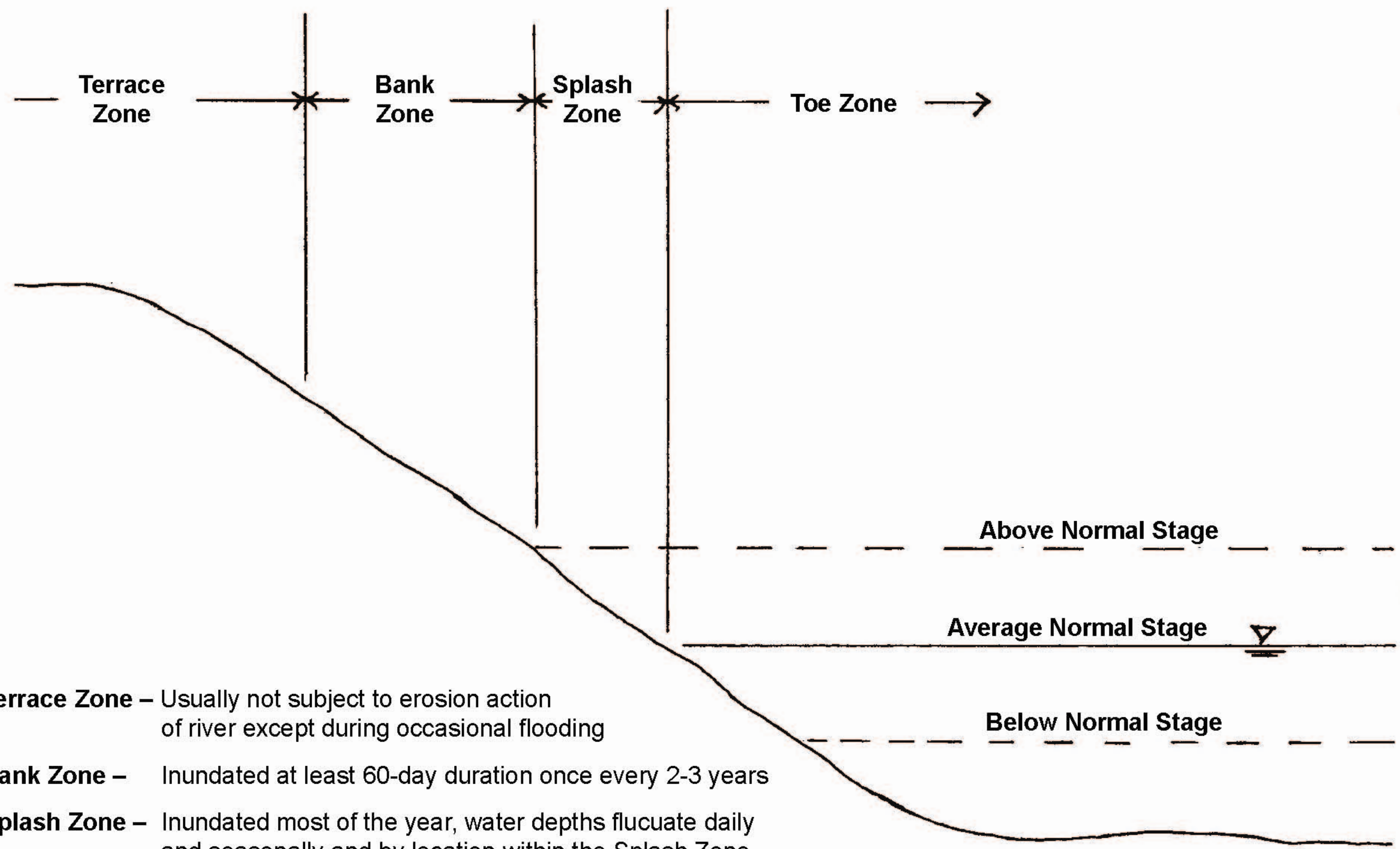


Figure 1
Modes of River Bank Failure
(from Waters, 1995)



Terrace Zone – Usually not subject to erosion action of river except during occasional flooding

Bank Zone – Inundated at least 60-day duration once every 2-3 years

Splash Zone – Inundated most of the year, water depths flucuate daily and seasonally and by location within the Splash Zone

Toe Zone – Inundated > 6 months per year

Figure 2
River Bank Zones
(adapted from Allen & Leech, 1997)

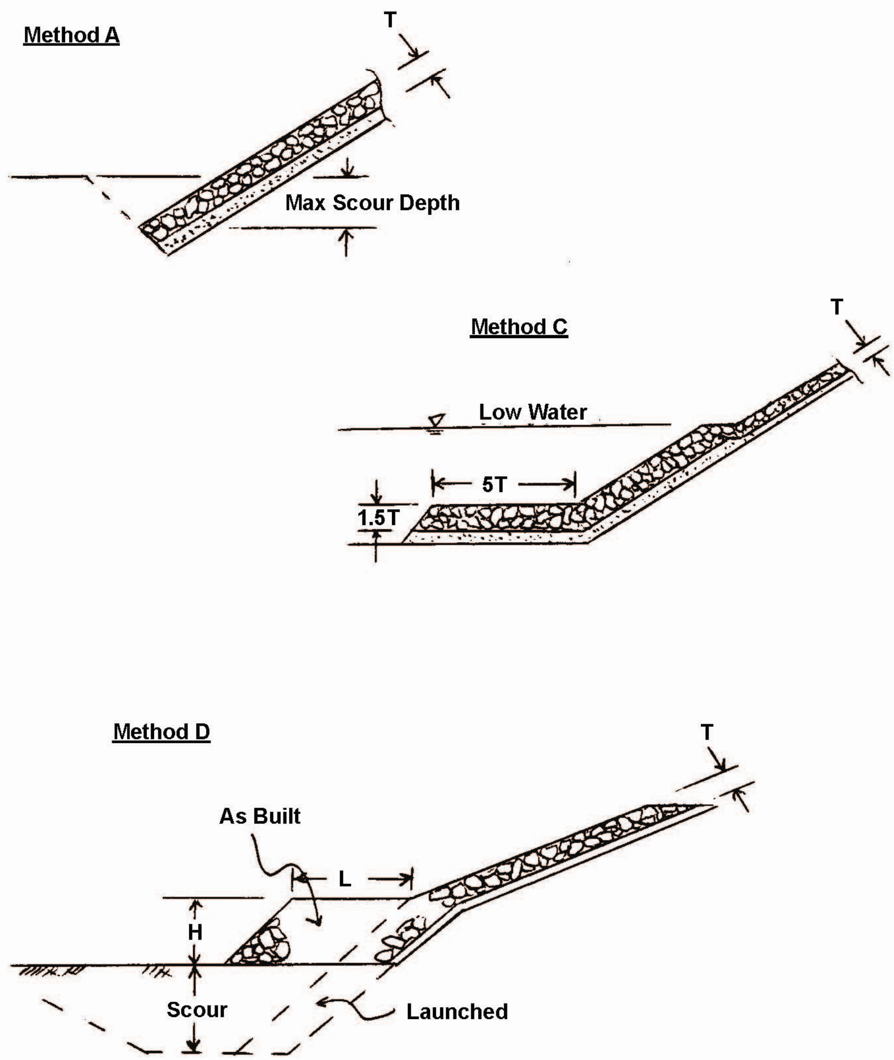
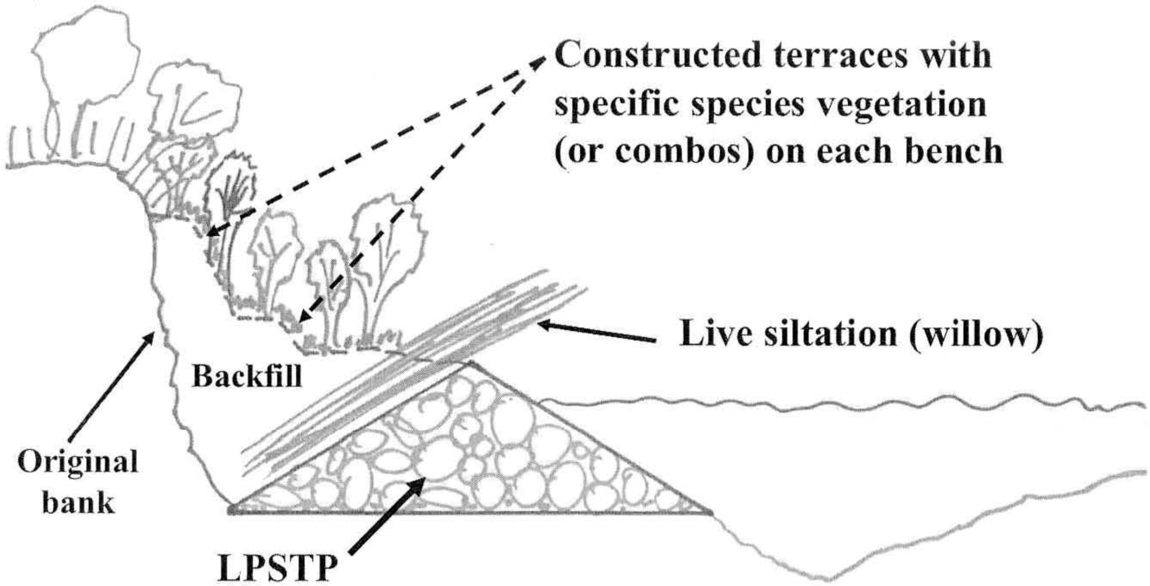


Figure 3
Rock Toe Protection
(from U.S. Army Corps of Engineers, 1991. Hydraulic design of flood control channels, EM 1110-2-1601, HQUSACE, Washington, DC)
NOTE: Method designations are consistent with the source document.



Longitudinal Peaked Stone Toe Protection (LPSTP)
Constructed of a well-graded, self-adjusting, self-filtering stone
(no filter fabric underlayment)

From: USACE, 2009

FIGURE 4

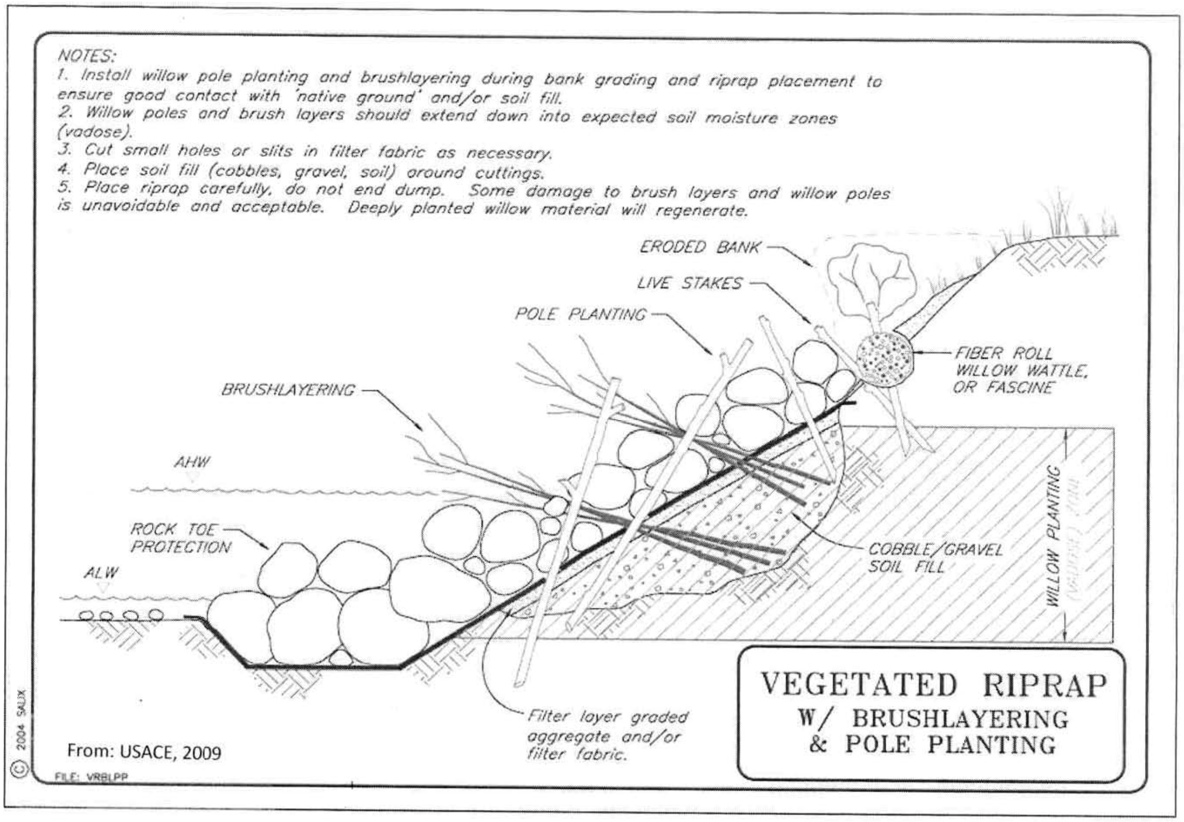

NOTES:
1. Install willow pole planting and brushlayering during bank grading and riprap placement to ensure good contact with 'native ground' and/or soil fill.
2. Willow poles and brush layers should extend down into expected soil moisture zones (vadose).
3. Cut small holes or slits in filter fabric as necessary.
4. Place soil fill (cobbles, gravel, soil) around cuttings.
5. Place riprap carefully, do not end dump. Some damage to brush layers and willow poles is unavoidable and acceptable. Deeply planted willow material will regenerate.
ERODED BANK
LIVE STAKES
POLE PLANTING
FIBER ROLL WILLOW WATTLE, OR FASCINE
BRUSHLAYERING
AHW
ROCK TOE PROTECTION
ALW
COBBLE/GRAVEL SOIL FILL
WILLOW PLANTING
Filter layer graded aggregate and/or filter fabric.
VEGETATED RIPRAP W/ BRUSHLAYERING & POLE PLANTING
© 2004 SALIX
From: USACE, 2009
FILE: VRBLPP

FIGURE 5

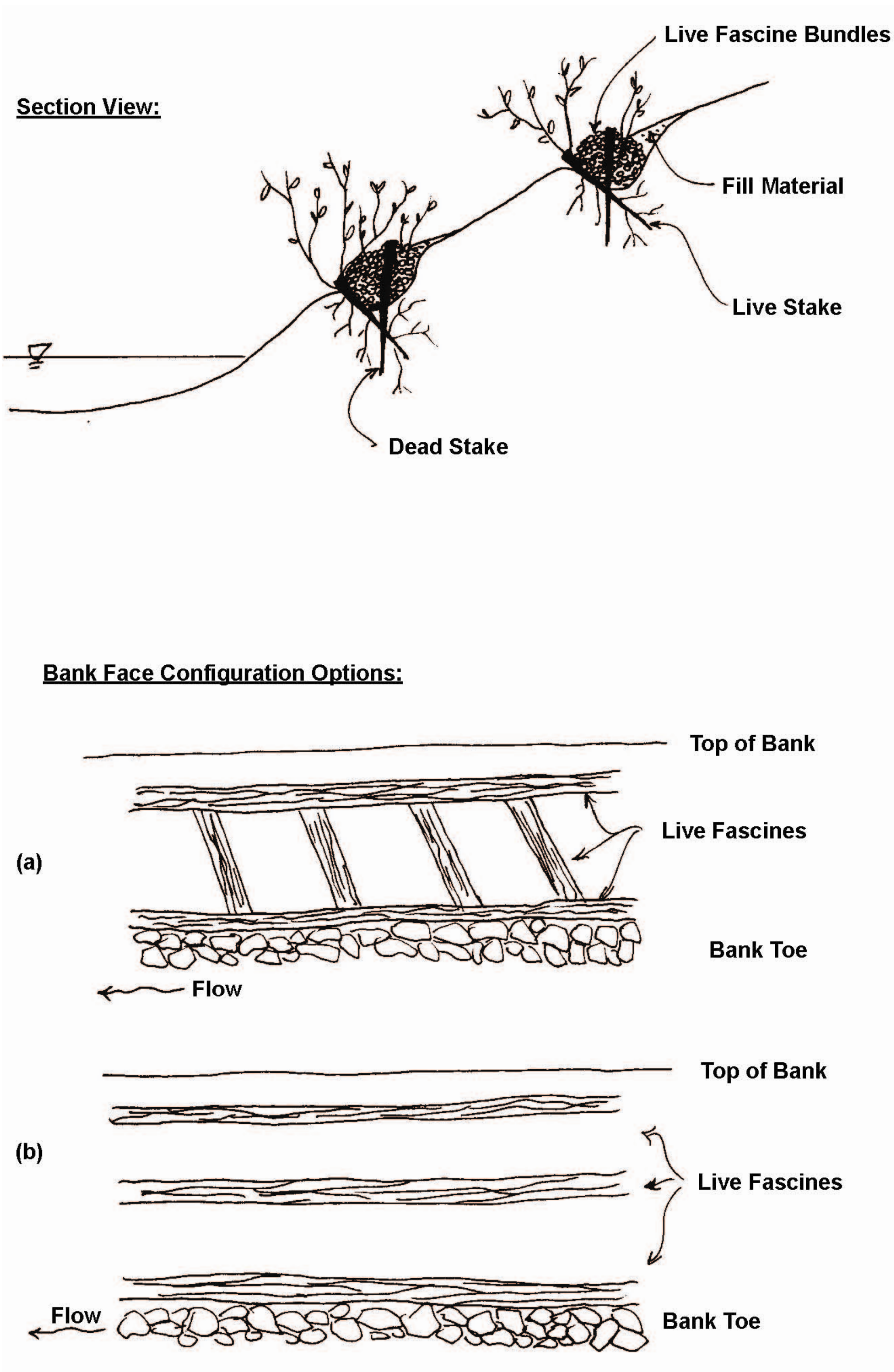
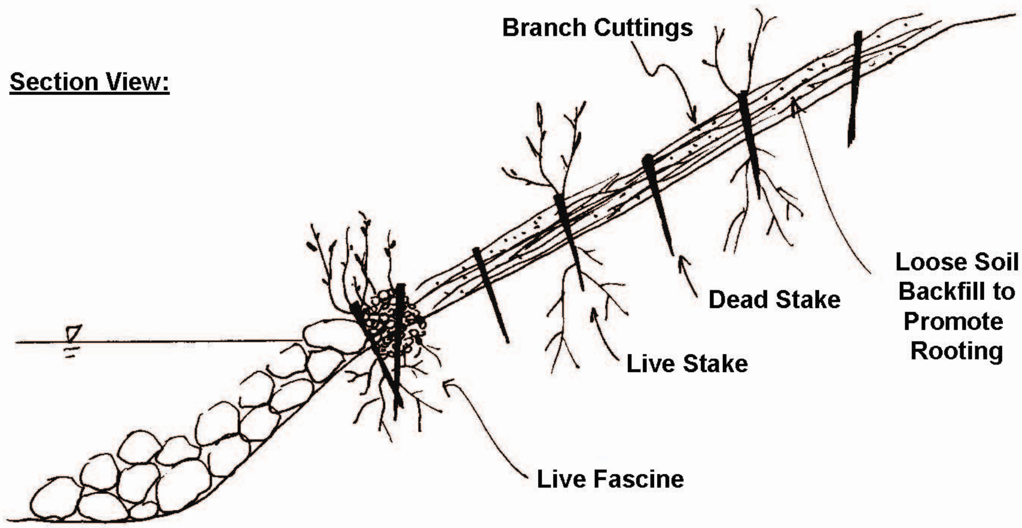


Figure 6
Live Fascine

Section View:



Bank Face Plan View:

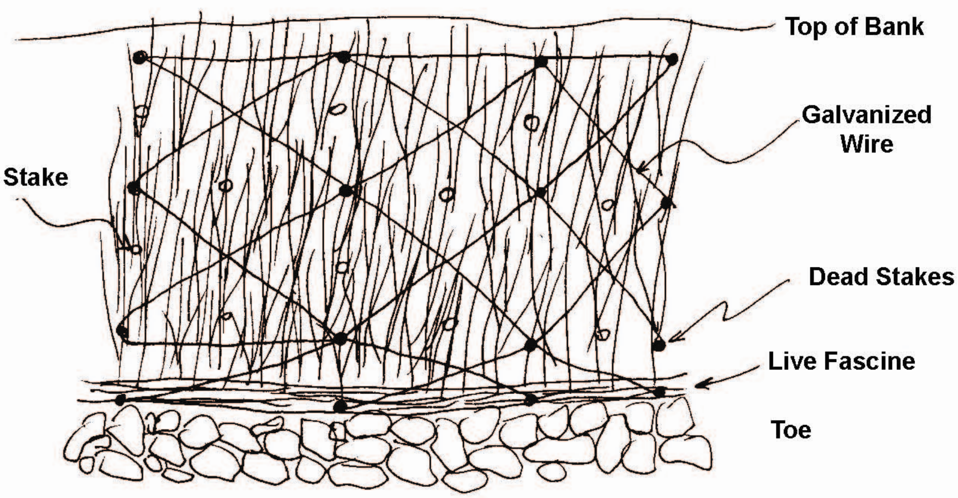


Figure 7
Brush Mattress

Section View:

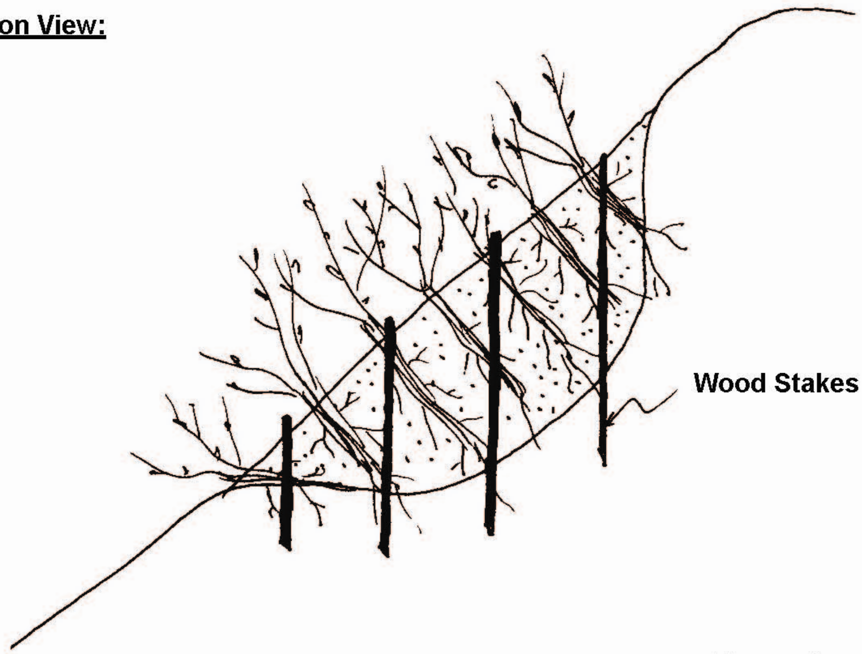


Figure 8
Branchpacking

Section View:

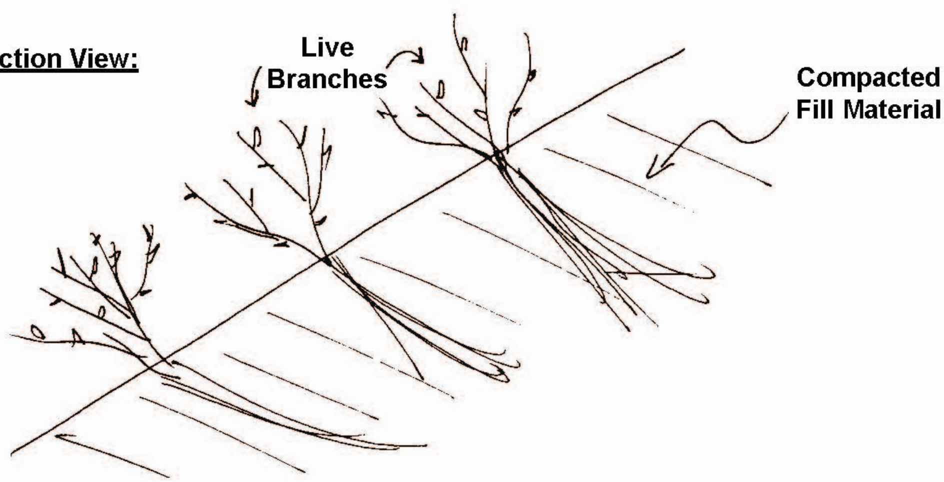


Figure 9
Brush Layering

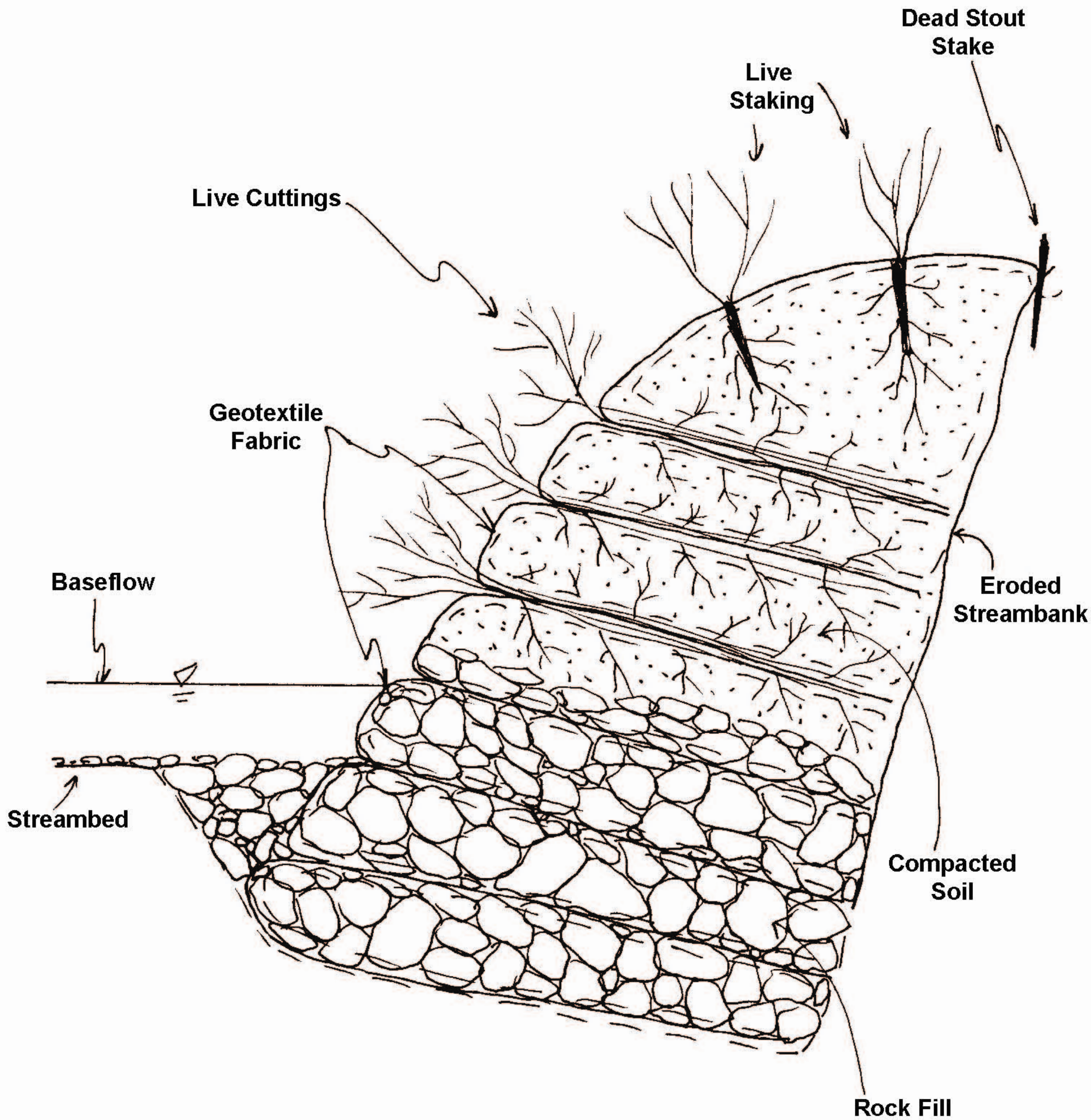


Figure 10
Vegetated Geogrids

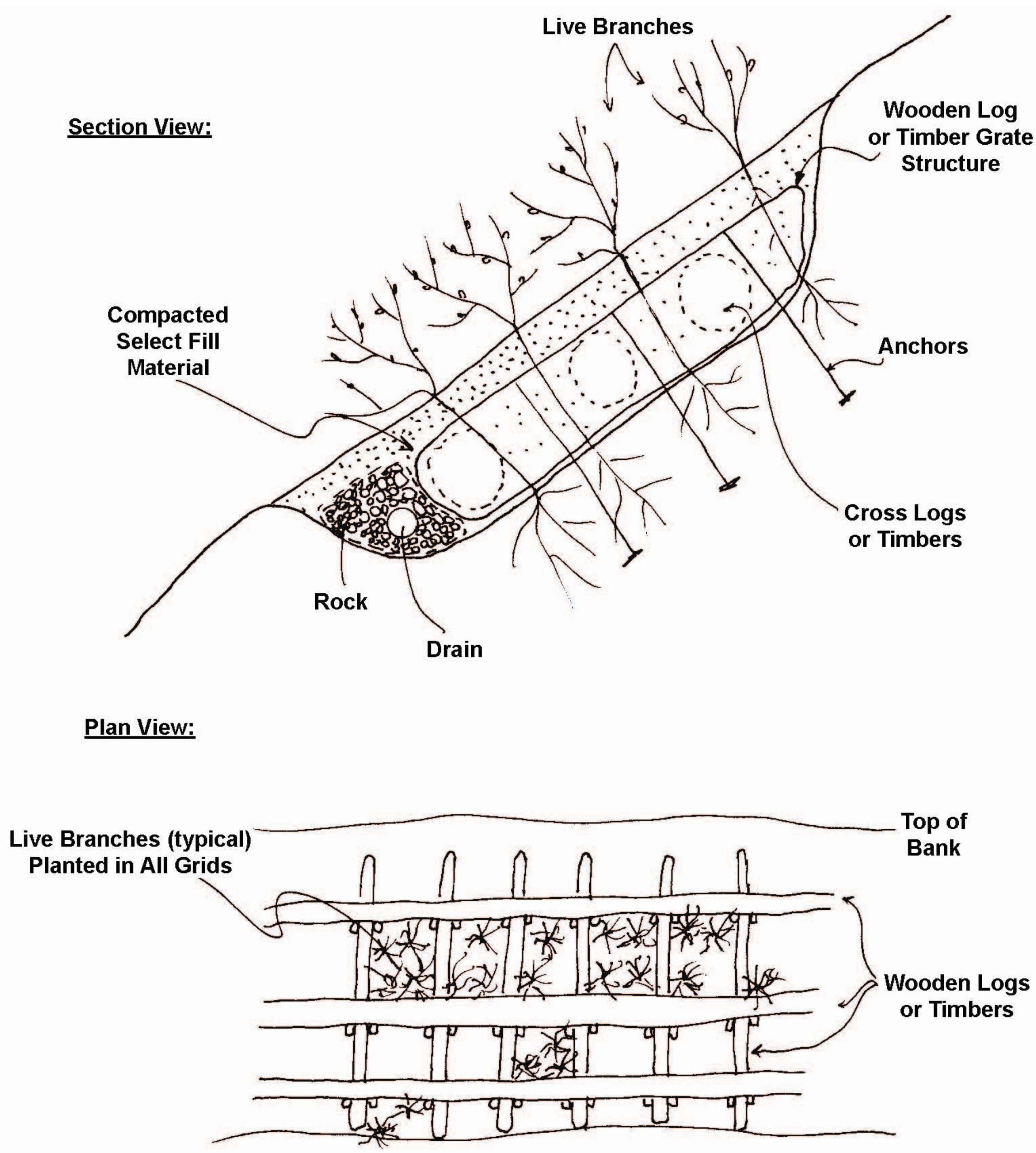
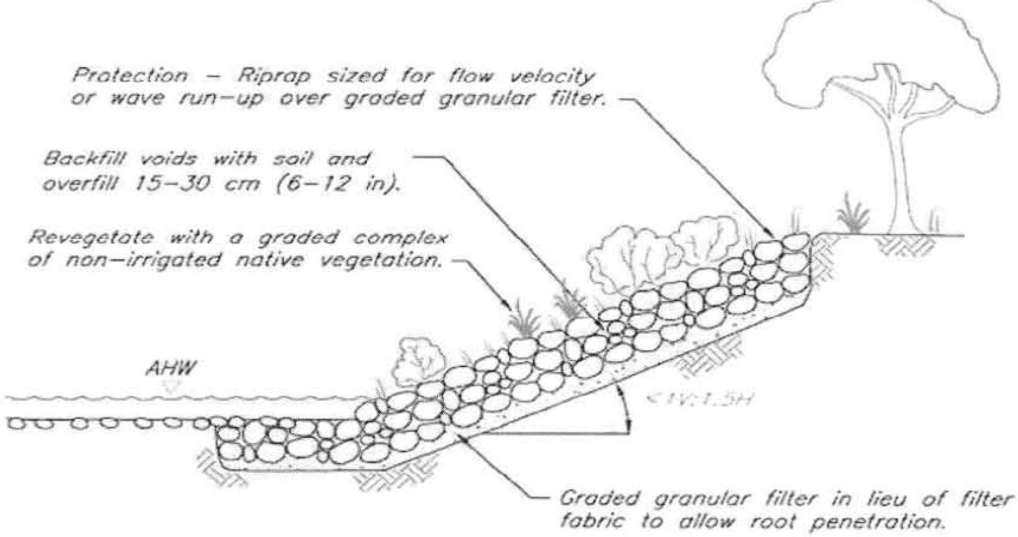


Figure 11
Live Slope Grating
(Source: Mississippi State University, 2008)



NOTES: CLASS 2 PERMEABLE MATERIAL

Permeable material for blankets or other subdrainage purposes shall consist of hard, durable, clean sand, gravel or crushed stone and shall be free from organic material, clay balls, or other deleterious substances.

Class 2 permeable material shall have a Durability Index of not less than 40 and a Sand Equivalent value of not less than 75.

SIEVE SIZES	PERCENTAGE PASSING
1-Inch	100
3/4-Inch	90–100
3/8-Inch	40–100
No. 4	25–40
No. 8	18–33
No. 30	5–15
No. 50	0–7
No. 200	0–3

RIPRAP
W/ SOIL AND GRASS OR GROUND COVER

From: USACE, 2009

FILE: RRSG

FIGURE 12

Appendix A
Photographs of Representative River Bank Conditions:
Unstable & Actively Eroding

PHOTO 173
Extensive unstable bank, high erosion rate: significant bank height with steep, denuded slope

PHOTO 184
Localized unstable bank, high erosion rate: significant bank height with steep to vertical, denuded slope

PHOTO 185
Extensive unstable bank, high erosion rate: significant bank height with steep to vertical, denuded slope

PHOTO 275
Localized unstable bank, high erosion rate: close to infrastructure (lower right corner of photo)

PHOTO 291
Unstable bank, high erosion rate: steep, high, denuded bank close to infrastructure; flanking and undercut potential

PHOTO 299
Local, active bank slumping, opportunity to stabilize prior to extensive lateral bank failure

PHOTO 430
Steep, high bank experiencing mass failure near infrastructure

PHOTO 431
Over-steepened, high bank, erosion, and mass failure associated with infrastructure (storm pipe outlet at lower left)

PHOTO 434
Unstable bank, high erosion rate: steep, high, denuded bank exhibiting overbank failure and rotational slumping

PHOTO 478
Unstable bank, high erosion rate: significant bank height with steep to vertical, denuded slope

Arkansas River Site Reconnaissance Photo Log

March 30 - April 1, 2009

Photo No.	Date	Location	Notes	River Flow
Arkansas River from Zink Pool to Sand Springs Approaching Hwy 97, Moving Upstream:				
173	3/31/2009	North shoreline, opposite side from Berryhill Creek confluence	Levee just beyond shoreline	17,500 cubic feet per second (cfs)
Arkansas River at Proposed Site of Sand Springs Low-head Dam at Hwy 97, Moving Upstream:				
184	3/31/2009	Tributary confluence on north shoreline at proposed Sand Springs dam site	Severe erosion along lower reach of tributary	17,500 cfs
185	3/31/2009	FFA hog farm next to tributary at proposed Sand Springs dam site	View of south shoreline	17,500 cfs
Arkansas River from Sand Springs just Downstream of Hwy 97 to Zink Dam, Moving Downstream:				
275	3/31/2009	Downstream view of Zink Dam and pedestrian bridge	River West Festival Park and PSO power plant on right; I-44 bridge beyond; 71st Street bridge in distance	17,500 cfs
Arkansas River from Zink Dam Tailwater to Creek Turnpike in Jenks, Moving Downstream:				
291	3/31/2009	East shoreline along Riverside Dr in Tulsa	Drainage culvert in foreground; River Parks trail and Riverside Dr. at top; between E 61st Street and E 66th Place	17,500 cfs
299	3/31/2009	Downstream view of west shoreline in Jenks	E 96th Street/E Main Street bridge downstream; Creek Turnpike and proposed Jenks low-head dam site beyond	17,500 cfs
Arkansas River in Jenks between Creek Turnpike and 71st Street Bridge, Moving Upstream:				
430	3/31/2009	Riverwalk Crossing shopping and restaurant development in Jenks	View of west shoreline	17,500 cfs
431	3/31/2009	Bank repair at Riverwalk Crossing in Jenks	View of west shoreline	17,500 cfs
434	3/31/2009	Bank repair at Riverwalk Crossing in Jenks	View of west shoreline	17,500 cfs
Arkansas River at Proposed Site of Sand Springs Low-head Dam, Just Downstream of Hwy 97:				
478	4/1/2009	Lower reach of tributary entering along south shoreline	Severe bank erosion	30,000 cfs

Appendix B
Photographs of Representative River Bank Conditions: Moderately Stable & Moderately Active Erosion

PHOTO 230
Moderately unstable bank, moderate erosion rate: flat (foreground) to moderate (background) bank slope, moderate bank height, woody riparian corridor of moderate width

PHOTO 233
Moderately unstable bank, moderate erosion rate: moderate bank slope, relatively high bank height, woody riparian corridor of substantial width

PHOTO 243
Localized bank failure with high erosion rate, but low bank height, no infrastructure in imminent danger, and low habitat value

PHOTO 289
Moderately unstable bank, moderate erosion rate: moderate bank slope and height, limited vegetation, partial existing revetment, close to park infrastructure, limited habitat value

Arkansas River Site Reconnaissance Photo Log

March 30 - April 1, 2009

Photo No.	Date	Location	Notes	River Flow
Arkansas River from Keystone Dam to Sand Springs at Hwy 97, Moving Downstream:				
230	3/31/2009	Downstream view of man-made ponds/lagoons on north shore	Just downstream of Sand Creek in Tanglewood area	17,500 cfs
233	3/31/2009	Downstream view of north shoreline at Wekiwa	Opposite side of river from Fisher Bottom	17,500 cfs
243	3/31/2009	Gravel operation on north shoreline in Sand Springs	S 129th West Ave; upstream of River City Park and Hwy 97	17,500 cfs
Arkansas River from Zink Dam Tailwater to Creek Turnpike in Jenks, Moving Downstream:				
289	3/31/2009	East shoreline at Johnson Park and E 60th Street S in Tulsa	River Parks trail in foreground; Riverside Dr in middle; Johnson Park at top	17,500 cfs

Appendix C
Photographs of Representative River Bank Conditions: Stable, Low Erosion Potential

PHOTO 141
Riprap with woody vegetation within the revetment

PHOTO 144
Stable riprap bank with naturally vegetated toe

PHOTO 152
Stable, shallow bank slope with woody vegetation

PHOTO 159
Terraced bank with riprap toe and grassed upper bank; and densely vegetated bank on inside river bend

PHOTO 166
Low bank height, shallow bank slope, riprap revetment

PHOTO 236
Stable, relatively shallow slope, densely vegetated bank with low erosion potential

PHOTO 245
Alternating riprap and woody vegetation banks

PHOTO 295
Shallow bank slope, rock toe with woody vegetation on the mid-bank, and grass on the upper bank

PHOTO 473
Riprap to top of bank

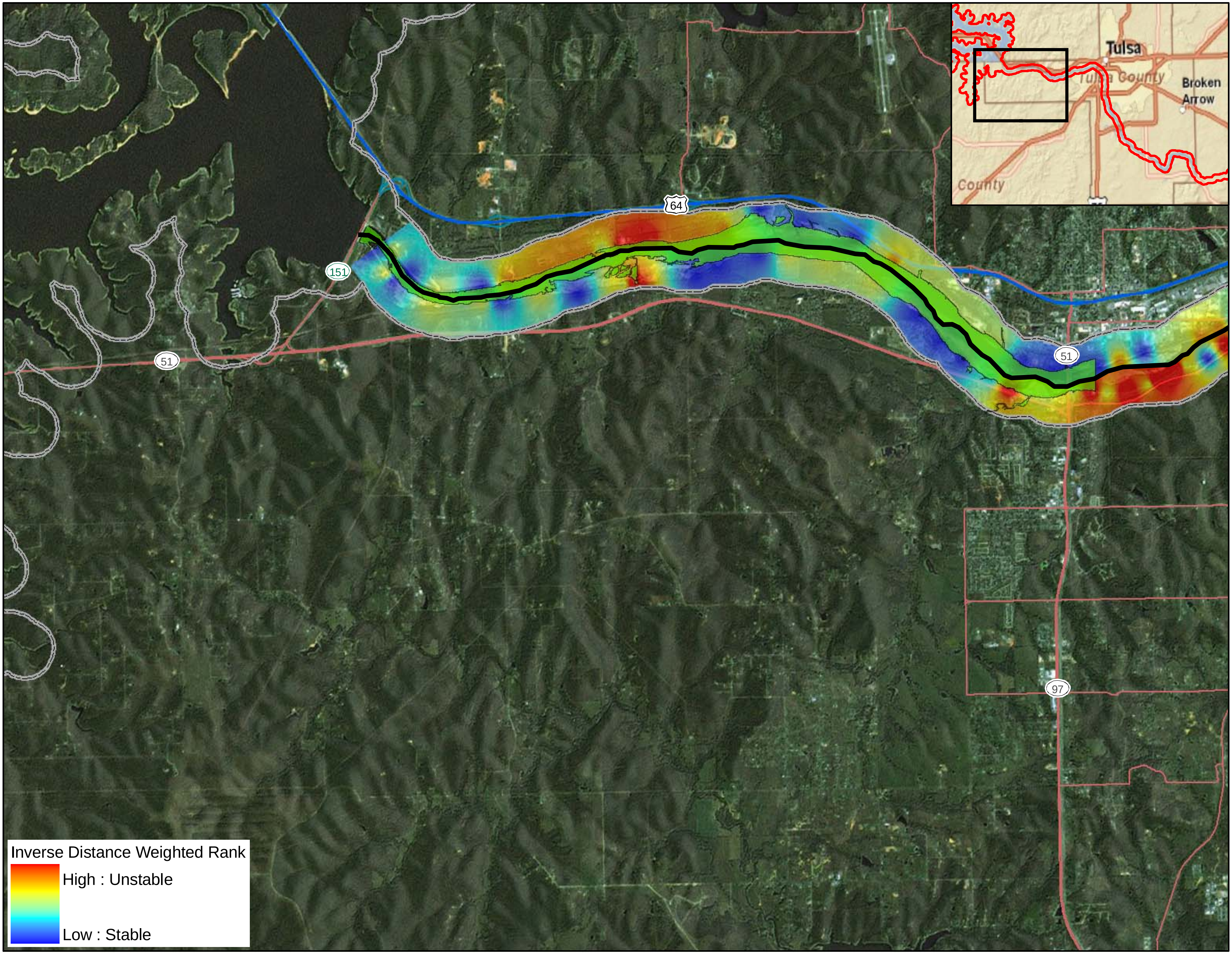
PHOTO 530
Riprap to top of bank

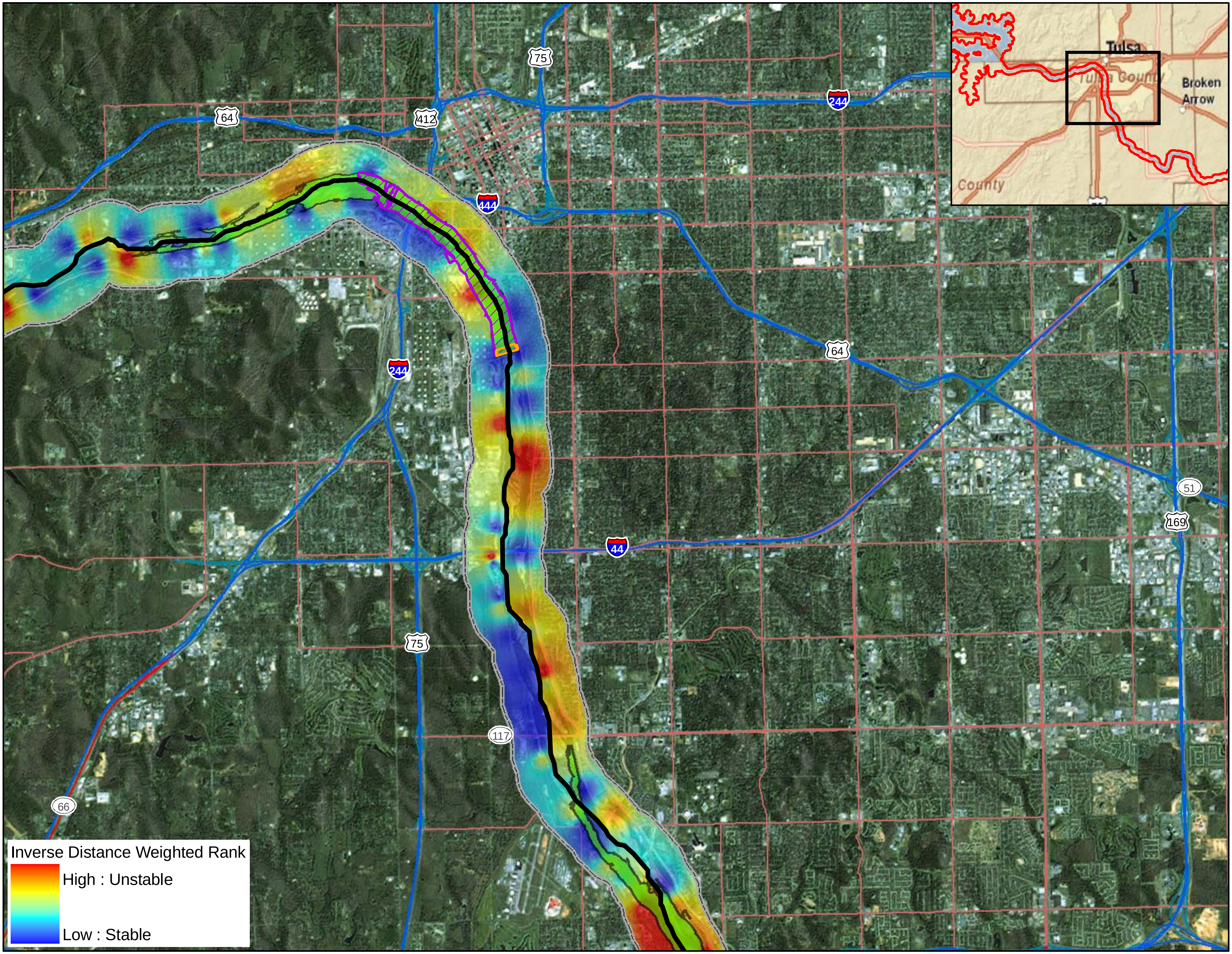
Arkansas River Site Reconnaissance Photo Log

March 30 - April 1, 2009

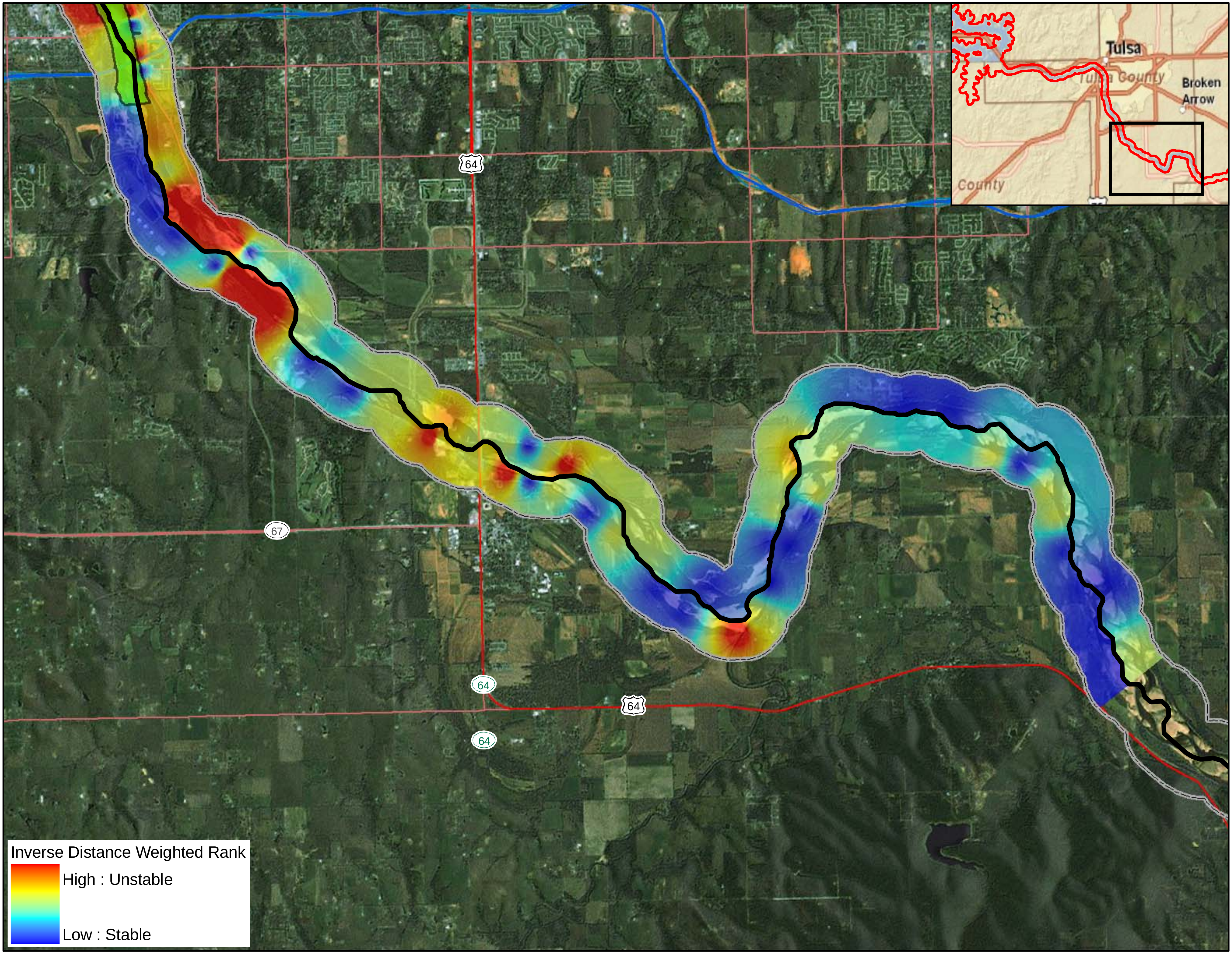
Photo No.	Date	Location	Notes	River Flow
Arkansas River from 71st Street Bridge (North of Jenks) to Zink Dam, Moving Upstream:				
141	3/31/2009	Southside WWTP	West shoreline downstream of I-44 bridge	17,500 cfs
144	3/31/2009	West shoreline just upstream of I-44 and Cherry Creek	S Elwood Ave on left	17,500 cfs
Arkansas River from Zink Pool to Sand Springs Approaching Hwy 97, Moving Upstream:				
152	3/31/2009	West shoreline between Zink Dam and W 23rd St bridge	Red Fork Industrial Area; Sunoco oil refinery beyond	17,500 cfs
159	3/31/2009	Sunoco oil refinery on west/south shoreline	River bend upstream of I-244/US75 bridge, next to downtown Tulsa	17,500 cfs
166	3/31/2009	Segment of riprap shoreline at Sunoco oil refinery	West/south shoreline	17,500 cfs
Arkansas River from Keystone Dam to Sand Springs at Hwy 97, Moving Downstream:				
236	3/31/2009	Downstream view of north shoreline toward Tulsa	US Hwy 64 crosses middle; Euchee Creek confluence near far right	17,500 cfs
Arkansas River at Proposed Site of Sand Springs Low-head Dam at Hwy 97, Moving Downstream:				
245	3/31/2009	Downstream view of proposed low-head dam site at Sand Springs	Hwy 97 bridge in middle; River City Park on left; FFA hog farm on right beyond bridge	17,500 cfs
Arkansas River from Zink Dam Tailwater to Creek Turnpike in Jenks, Moving Downstream:				
295	3/31/2009	Downstream view toward mouth of Joe Creek Channel and Creek Casino	Oral Roberts University on left	17,500 cfs
Arkansas River at Proposed Site of Sand Springs Low-head Dam, Just Downstream of Hwy 97:				
473	4/1/2009	South shoreline just upstream of tributary confluence	Next to FFA hog farm	30,000 cfs
Arkansas River East Shoreline (Tulsa) between Creek Turnpike and E 41st Street:				
530	4/1/2009	Construction of new River Parks "QT park" at E 41st Street	Along River Parks trail system and Riverside Dr on east side of river	30,000 cfs

Appendix D
Results of Video Desktop Analysis


Inverse Distance Weighted Rank
High : Unstable
Low : Stable
Tulsa
Tulsa County
Broken Arrow
County
64
151
51
51
97



Inverse Distance Weighted Rank
High : Unstable
Low : Stable
Tulsa
Tulsa County
Broken Arrow
County
64
412
75
244
444
44
117
66
51
169


Tulsa
Tulsa County
Broken Arrow
County
64
67
64
64
64
Inverse Distance Weighted Rank
High : Unstable
Low : Stable

Appendix E
Definition of Planning-Level Cost Estimate

Definition of Estimate

The estimate was prepared in accordance with the guidelines of AACE International, the Association for the Advancement of Cost Engineering. According to the definitions of AACE International, the Class 5 Estimate is defined as the following:

Class 5 Estimate. This estimate is prepared based on limited information, where little more than proposed plant type, its location, and the capacity are known, where preliminary engineering is from 0% to 2% complete. Strategic planning purposes include but are not limited to, market studies, assessment of viability, evaluation of alternate schemes, project screening, location and evaluation of resource needs and budgeting, and long-range capital planning. Examples of estimating methods used would include cost/capacity curves and factors, scale-up factors, and parametric and modeling techniques. Typically, little time is expended in the development of this estimate. The expected accuracy ranges for this class of estimate are –20% to –50% on the low range side and +30% to +100% on the high range side.

The cost estimates shown, which include any resulting conclusions on project financial or economic feasibility or funding requirements, have been prepared for guidance in project evaluation and implementation from the information available at the time of the estimate. The final costs of the project and resulting feasibility will depend on actual labor and material costs, competitive market conditions, actual site conditions, final project scope, implementation schedule, continuity of personnel and engineering, and other variable factors. Therefore, the final project costs will vary from the estimate presented here. Because of these factors, project feasibility, benefit/cost ratios, risks, and funding needs must be carefully reviewed prior to making specific financial decisions or establishing project budgets to help ensure proper project evaluation and adequate funding.