Impacts of Streambank Stabilization Structures
WRAP Report

Prepared by
J. Craig Fischenich, PhD, PE
Research Civil Engineer
ERDC Environmental Laboratory

Overview

The Omaha District (CENWO) requested that a report identifying impacts of streambank stabilization structures and measures be prepared under the Wetlands Regulatory Assistance Program. The report is to assist the CENWO in evaluating stabilization practices, with a focus on the Yellowstone River system. The CENWO requested that the report include the following:

1. Structure Impacts. The report should provide a discussion of the impacts various streambank stabilization structures have on the following parameters.

General concept and purpose of each structure type.
Impacts on water surface elevations.
Impacts on velocities, including secondary velocities.
Impacts on erosion/scour and deposition.
Impacts on sediment transport through the design reach.
Length of the river that is impacted by the specific structure type.

2. Bibliography. The report should include an annotated bibliography of the references relative to structure design, structure impacts, and geomorphological processes. The bibliography need not be exhaustive, but shall encompass the current state-of-the-art of the streambank stabilization design.

This report presents an overview of bank stabilization measures and their potential impacts. Bank stabilization activities alter the physical environment in ways that cause direct and indirect impacts to the character of the stream and riparian ecosystem and to the processes or functions of the systems. These impacts can often be viewed as either adverse of beneficial, depending upon the perspective of the individual assigning values to the system. For example, a particular stabilization structure may alter the environment in a way that benefits a particular species or life stage to the detriment of another. Impacts to various social uses are likewise often offsetting.

This report attempts to avoid value-based assessments by focusing on the affects of stabilization measures upon measurable aspects of a stream’s structure and function. The extent to which these impacts are viewed as adverse or beneficial are left to the reader. The prevailing philosophy in ecosystem management is that physical alterations of the structure and character of an ecosystem are most significant if they also impact process-based functions. For this reason, each of the stabilization measures described in this report is described in terms of its influence upon functions.

Streambank Stabilization Measures

Distinctions among various bank stabilization measures can be made on the basis of 1) how they work, 2) the materials used, 3) their geometry and position in the landscape, and (in some cases) 4) the character of stream system to which they are applied. Stabilization measures can be generally grouped into four broad categories based upon how they work or function:

1) Structures whose primary function is to prevent erosion by armoring the eroding bank
2) Structures that prevent erosion by deflecting the current away from the bank
3) Methods that reduce the erosive capability within the channel
4) Geotechnical methods of slope stabilization

Virtually every imaginable material has been used for bank stabilization. The most common materials include stone, vegetation, and concrete (typically formed into blocks or broken into graded riprap). A distinction among stabilization measures is often made on the basis of material use. Measures that rely upon inert materials (such as riprap) alone are often referred to as "conventional" treatments. Techniques that employ the use of vegetation independently or in combination with other natural materials, but as an integral component of the stabilization measure, are generally referred to as "soil bioengineering". A contingent of analysts regard conventional treatments as "bad" and soil bioengineering measures as "good", but the true impacts depend upon the other factors described in this report and upon the specific materials used within each of these categories.

The geometry and position of a structure can influence its function and impact. For this reason, otherwise similar structures are often given different names depending upon their size, shape, and orientation relative to the stream. For example, a low sill that extends across a channel and creates backwater can be called a weir, regardless of its size or material (riprap, concrete, sheet pile, boulder, log, etc.,). If the structure is designed to prevent the upstream migration of a nick point or headcut, it is also a grade control structure. If constructed to the floodplain elevation, it functions as, and is called a channel block. It can be oriented other than perpendicular to the flow to initiate a variety of affects in the velocity field and scour pattern, and will take on a name associated with its geometry (vortex weir, Reichmuth weir, W-weir, etc.,). Analogies can be made for virtually any other type of structure (armoring, deflecting, slope stabilizing), and the important point is that the impacts from a measure depend upon its specific geometry and landscape position.

The nature and extent of impact depends also upon the character of the stream and riparian system. Clear distinctions can be made on the basis of the stream type (meandering/braided, clay/silt/sand/gravel/cobble bed, riffle-pool/step-pool, etc.,) and dominant processes (snowmelt/ rainfall, bedload/suspended load, aggrading/degrading/stable, etc.,). Each of these systems behaves differently and, thus, affect and are affected by stabilization measures in different ways. Structures that merely deflect flows in a bedload-dominated cobble bed stream might function to trap sediments and build bars in a sand bed stream with a high suspended sediment load.

The following paragraphs provide a brief overview of common stabilization measures. They are arranged on the basis of function, because most measures are selected on this basis so as to address a particular problem on a stream. An infinite number of techniques could be identified in each category by altering the materials, dimensions, or considering their influence on different stream types, so this list of measures is not exhaustive. In most cases, bank stabilization projects will use combinations of the techniques described below in an integrated approach. Toe protection often will require the use of armoring techniques using stone, large logs, or other inert materials. Stone blankets may be placed on the bank face, perhaps supplemented with interstitial plantings, but most upper bank areas can usually be stabilized using vegetation alone, or any one of dozens of soil bioengineering techniques, particularly if slope stabilization is warranted. Deflection structures can eliminate the need for some armor structures, or can allow the use of different armor materials. Grade control or other energy reduction may be required to supplement a stabilization measure on a stream with systemic instabilities.

Armoring techniques

The armoring technique is the placement of a protective covering, usually consisting of stone, over part or all of the stream bank. Armoring techniques function by preventing the boundary shear induced by flowing water from contacting erodible bank material. These techniques affect the bank sediment input, roughness, and local shear. Material type and channel alignment determines the extent of the impacts. In general, armor structures cause a scour hole to develop at the toe of the structure and extend riverward for a limited distance. The depth of scour varies with alignment and material type. Velocity may increase in the scour region, but there is little or no change in the velocity at points further riverward. If the structure does not encroach appreciably on the channel, there should be no measurable change in river stage for a given discharge. Bed sediment movement may be affected. Properly constructed armor structures, particularly if they incorporate a vegetation component, provide a locally diverse aquatic environment without significant effect on the hydraulic conditions of the adjacent river reaches. Riparian disruption is generally the greatest environmental concern, and measures should be taken to minimize impacts.

Stone-Fill Revetments - Stone-fill revetments are perhaps the most common of all streambank protection structures. Included within this group are several variations of the general theme of placing quarried stone, broken concrete, cobble, or soil cement parallel to the eroding bankline. The stone may be placed in a toe section with or without upper bank protection. A thin blanket may be used to armor the entire bank. The revetment may be windrowed, and allowed to launch as erosion undermines the structure. Revetments are often used in conjunction with other bank protection devices. A stone toe section with revegetation of the upper bank is one of the most cost-effective solutions to most erosion problems. Revetments are very successful in stopping erosion on streams where the major problem is bank undercutting from toe erosion or general erosion of the bank by shear velocities of the river. They provide only a limited amount of protection against erosion on streams subject to headcuts or general bed degradation. Revetments must be properly designed and constructed with suitable material to be effective.

Soil Bioengineering Techniques – Vegetation can serve as an effective interface between the soil and water and, in some circumstances, works well as an armor material. A number of soil bioengineering techniques employ vegetation as an armor (fascines, mattresses, etc.,) and even direct seeding is a form of armoring. The type of vegetation and its density are the primary determinants in establishing the effectiveness of a bioengineering measure as an armor. Dense herbaceous vegetation that "lays down" when overtopped by flowing water performs this function exceptionally well. Dense shrubs or ground cover can also be an effective armor, but some scour around the plants may occur. Woody vegetation is a rather poor armor material, and may increase surficial erosion when compared to other materials. Because few bioengineering techniques employ aquatic vegetation, the use of living vegetation as an armor material is generally limited to bank elevations above the baseflow level. Armor on the toe of the bank below this elevation is usually accomplished with inert materials such as riprap or logs. Likewise, the armoring benefits of vegetation are not immediate, so additional materials such as degradable fabrics are usually employed for temporary stabilization until the vegetation becomes well established.

Tree Revetments and Rootwads - Tree revetments are made from whole tree trunks laid parallel to the bank, and cabled to piles or deadman anchors. Eastern red-cedar (Juniperus virginiana) and other coniferous trees are used on small streams, where their springy branches provide interference to flow and sediment trapping. The principal objection to these systems is the use of large amounts of cable and the potential for trees to be dislodged and cause downstream damage. Some projects have successfully used large trees in conjunction with stone to provide bank protection as well as improved aquatic habitat. Tree revetments perform best on streams with a high suspended sediment load, trapping sediments within the voids of the branches. These sediments are ultimately colonized by pioneer vegetation species that stabilize the banks after the trees have rotted.

Rootwads consist of large logs with intact root wads are placed in trenches cut into the bank, such that the root wads extend beyond the bank face at the toe. The logs are overlapped and/or braced with stone to assure stability, and the protruding rootwads effectively reduce flow velocities at the toe and over a range of flow elevations. This approach replicates one of the natural roles of large woody debris in streams by creating a dynamic near-bank environment that traps organic material and provides colonization substrates for invertebrates and refuge habitats for fish. The logs eventually rot, resulting in a more natural bank. The revetment is intended to stabilize the bank until woody vegetation has matured, at which time the channel can return to a more natural pattern. In truth, rootwads function more as a habitat feature than as a stabilization device. They generate considerable local turbulence and scour, and are inherently unstable unless combined with other materials.

Soil-Covered Riprap - In urban areas or highly visible locations where it is advisable to keep banks mowed for aesthetic or safety purposes, riprap may be covered with soil and seeded to accelerate vegetation growth. This may also be done in areas where mowing is desired. Benefits of covering riprap with soil and seeding grass are largely aesthetic. Although access to the stream is improved, few aquatic or riparian habitat values are derived. Edaphic and climatic conditions are the major constraints to covering riprap with soil and seeding with vegetation, particularly grass. Covering riprap with soil and seeding is feasible only if climatic conditions are conducive to the growth of the plants or supplemental irrigation is practical. The practice has largely been confined to urban areas where aesthetics is a consideration, and where machine mowing can replace more expensive hand-mowing maintenance methods. Soil covered riprap seeded with grass performs well in situations where flow velocities in the vicinity of the bank do not exceed 4 to 6 ft/s. Critical velocities vary with the variety of grass used and soil conditions.

Cellular Blocks - Cellular blocks are designed to be placed on a prepared bank in a manner that leaves many openings. This method allows vegetation to grow from cavities in precast concrete blocks. Construction often involves the placement of a filter cloth between the soil and the cellular blocks if the soil is erodible. Specialized equipment can be used to install the blocks but hand placement will be required when bank access is inadequate. Vegetation can then be planted or allowed to invade naturally. Cellular blocks have been successfully used in stream flow up to 15 feet per second. The holes in the blocks limit the potential of failure due to hydrostatic pressure, but turbulence may dislodge the blocks if they are not properly placed. Like riprap, cellular blocks conform to minor changes in the bank. However, it is not an economical alternative to riprap.

Geogrid - Non-woven polyester fabric shaped as hexagons, with sides approximately 8 inches and a depth of 4 to 8 inches, are stapled together to form a mat to the shape and area of the bank to be protected. The geogrid mat then is placed on the bank and filled with soil, sand, aggregate, or other native materials. The raised edges of the geogrid material provide the erosion protection until the vegetation becomes established within the cells. The geogrid provides virtually permanent erosion control due to the rot-proof nature of the materials used and the eventual establishment of vegetation, which further enhances its structural integrity. Geogrid revetments are inexpensive, quick and easy to build. Turbulent flows at the toe of the geogrid are the most frequent cause of revetment failure. For this reason, it should usually be coupled with a low stone toe structure. Flanking is also a problem, so stone refusals at the upstream and downstream limits of the geogrid are recommended.

Gabions - Gabions are rock-filled wire or synthetic baskets that are wired together to form continuous structures. The mesh is typically galvanized or coated with polyvinyl chloride to reduce corrosion. Gabions can use lower quality stone than riprap structures and can be placed on steeper slopes. Gabion structures are flexible enough not to be vulnerable to minor bank shifts but need to be placed on a firm foundation. Gabions may also be used to construct deflective structures, and would have the same impacts as jetties or hardpoints when constructed as such. Sediment is usually deposited among the rocks in gabion structures, and vegetation often becomes established so that the structure is obscured and the stream has a natural appearance. Unvegetated gabions are similar in appearance to masonry work, which may be visually pleasing in some settings. The steep slopes on which gabions are sometimes placed may hinder wildlife access. Gabion structures can be designed with artificial overhangs, flow deflectors, and other features to enhance fish habitat. Failed baskets may be hazardous to recreationists, especially canoeists. Gabions have been widely used for streambank protection on streams located in a variety of environments in the U.S. and Europe. They are most frequently used in urban areas, particularly on small watersheds where high flood conveyance is desired. Gabion streambank protection structures have performed very well in some settings. The major problem is basket failure, a problem that is aggravated by ice and other debris, gravel bedload movement, vandalism, and corrosive streamflows. Gabions are usually cost prohibitive when compared to riprap structures, but instances may occur when they are a preferred alternative.

Geotextile fabrics - On small streams, a good vegetative cover of grass or shrubs may be sufficient to protect streambanks from scour. But if the soils consist of easily erodible material such as sand or gravel, it is often necessary to provide temporary cover until the vegetation has become established. Various natural and synthetic fibers have been developed for use in erosion prevention. Many different applications may employ specific fabrics that are available. In most cases involving flowing water, fabrics used alone do not provide sufficient protection due to their buoyancy and their tendency to be moved by currents. Fabric used in conjunction with vegetation is often an effective solution. Fabrics are also used frequently as a bedding for revetments to prevent leaching of fine bank materials. Geotextiles used with vegetation produce the same environmental benefits as vegetation used alone. The major benefit is aesthetic, but when woody vegetation is used, riparian benefits can be significant, and there may be some aquatic benefits from shade and organic debris falling into the stream. The benefit of using fabrics with riprap is entirely structural. Fabrics have been used on streams in many locations. In areas without sufficient rainfall to support dense plant cover, supplemental irrigation is usually required if vegetation is used. Geotextiles work well in providing temporary protection until vegetation can become established at sites where they are not exposed to swift currents for prolonged periods of time. Natural geotextiles tend to function better than synthetics due to their ability to breakdown, to absorb moisture, and to create favorable growing environments.

Soil Cement - Primarily used on the upper bank, soil cement forms a protective layer over the bank. Mixed with 15% portland concrete, bank soil is compacted to provide a stable surface. To prevent structural damage, hydrostatic pressure should be reduced by adequate drainage. In areas devoid of quarried stone, soil cement is often economically effective due the availability and low cost of materials, and ease to apply. Soil cement is recommended if vegetation is difficult to establish. It should be noted that this method should not be used where traffic is expected due to the fact that soil cement is not flexible. Effectiveness of soil cement on existing projects has not been adequately evaluated.

Bulkheads - Bulkheads, or other vertical wall structures, are used on vertical or near vertical bank slopes to prevent a bank from sliding into the river. A variety of materials, such as gabions, stone, sheet metal, and timber to name a few, can be used to construct bulkheads. For timber bulkheads, it is wise to place riprap at the toe of the structure for scour protection and to tie the ends of the bulkhead into the bank to prevent severe erosion and flanking where the flow re-attaches to a natural, sloping bank. This usually requires some form of transitional protection using a sloping revetment. Bulkheads must be designed to prevent hydrostatic pressure from damaging the structure. Also, care must be taken to prevent soil loss between the piles and a geotextile filter may be necessary to prevent soil loss. Bulkheads can be harmful to the environment by elimination of riparian habitat, or abrupt land water transitions. Vertical walls provide little or no valuable habitat. Their poor aesthetics also count heavily against them to the extent that local planning permission may well be denied in areas. Exposed piling is ideal when the bank is used intensively for boat operations, mooring and maneuvering, such as around locks and marinas. It will withstand high current velocities and wave attack, and if properly designed will be stable against severe toe scour. Submerged piling may produce adequate toe protection, but can be a serious hazard to boats. Since the bankline is vertical, piling is useful in confined sites with restricted space for a sloping bank. Conversely, a vertical piled wall on one bank may promote erosion opposite due to wave and current reflection.

Flow deflection techniques

Flow deflection techniques are based upon the principle that by redirecting higher velocity flows away from the bank, erosion can be reduced or eliminated in areas between structures. This procedure usually results in a lower cost than continuous armoring of the bank. Deflective structures are constructed approximately perpendicular to the flow, and therefore reduce the effective width of the river. Locally, a scour pocket develops off the end of the structure and continues downstream in a teardrop pattern. There is usually an increase in the velocity adjacent to the structure. Average cross-channel velocity may increase, decrease, or be unaffected. Generally, there is an increase in stage and/or depth for a given flow in the channel adjacent to the structure, particularly if the structure length exceeds 1/6 of the channel width. Material type, length, height, location, and orientation of the structure will affect the degree of impact. These structures are usually constructed with less disruption to the riparian community than other erosion control techniques. Effects on wildlife species are usually insignificant. Sediment accretion behind the structures may provide additional access to the river for some species, and provides good substrate for benthic organisms. Recreational benefits increase if access is provided to the structures. The primary environmental benefit of deflective structures is the creation of additional habitat for fish species. The cross sectional changes provide diversity and, by using proper materials, suitable cover and substrate increase.

Hardpoints and Jetties - The terms hardpoint and jetty are generally regarded as being synonymous. However, for this manual, the terms are used to differentiate between differing degrees of the same basic structures. Both structures consist of a stone or soil spur that extends riverward of and perpendicular to the bank, and a stone root to prevent flanking of the structure. Hardpoints are low stubby structures that are frequently overtopped and extend riverward less than 15 or 20 feet. Jetties are generally constructed to the height of the high bank, and extend riverward more than 20 feet. Hardpoints deflect the current away from the eroding bank for only a short distance, with no attempt to change the general alignment of the river. By contrast, jetties deflect current for a considerable distance, and are often intended to alter the main flow of the river. Hardpoints and jetties are best suited to long straight reaches of river, or on the convex bankline of meanders. Structures placed on the concave bank can fail from excessive scour between structures. The main advantage of hardpoints and jetties is the low quantity of material needed to protect a given bank relative to other structural alternatives. The environmental benefits of this structure type are primarily related to fisheries and recreation. Hardpoints and jetties create habitat diversity not found with most other structure types. Scour off the end of the structure creates deep pools and high velocity flows. Scallop areas of shallow, relatively slow-moving water provide additional habitat diversity downstream of the structures.

Cribs - Used on smaller streams on a limited basis, cribs, or log cribs, deflect erosive currents away from the bank and induce sediment deposits behind the structure. Cribs are constructed during low flow in the shape of a 30-60-90 triangle. The long side of the triangle should be towards the bank while the short end should be facing downstream so the flow will be deflected towards the center of the channel. Log used in the construction should be a minimum of 6 inches in diameter and the stone should be angular in shape and keyed into the bank 12-24 inches. The crib height should be small enough to allow floodwaters to pass over the top. Crib deflectors deepen channels, create meanders, remove silt, and enhance aquatic habitat, but may cause bank erosion on the opposite side of the crib if not properly constructed. Cribs do not require any special construction skills and are generally economical if materials are located nearby. Cribs exposed above the water may be aesthetically displeasing and the logs will need replacement due to rotting.

Dikes - Dikes are useful for bank protection where the water depth adjacent to the bank is greater than 4 feet, and the stream velocity is too high for other techniques. There are two types of dikes, permeable and impermeable. Permeable dikes allow water and sediment to flow through with reduced velocity while impermeable dikes are used to reduce river width. While both types of dikes are constructed perpendicular to the stream bank, permeable dikes uses timber piles as the main ingredient for construction while impermeable dikes use stone. Permeable dikes design criteria depend on sediment load and most have horizontal bracing throughout the structure. Factors that affect the design of the impermeable dikes are severity of expected flows, method of construction, and maintenance requirements. Regardless of the type of dike used the design length of the structure should be at least one-third the length of the desired protection. Since eroding bankline can be great in length, multiple dikes will be needed to produce the desired effect. Dikes can also be useful in a variety of rivers ranging from high or low gradient tributaries and secondary alluvial streams. Permeable dikes require flows with high sediment loads to be fully effective whereas impermeable dikes do not require a high concentration of sediment to protect the bankline. Dikes become more economical than riprap as the depth of the water increases but, it is safer than a continuous form of bank protection such as revetments on bank curves greater than thirty degrees. Dikes produce deep and narrow stream channels but become ineffective when overtopped with high water.

Fence Dikes - Fence dikes are very similar in design to hardpoints and jetties. The difference lies in the materials used. Fence dikes consist of wood planks or wire mesh attached to timber piles extending riverward of the eroding bank. Stone is often used as a foundation, or is placed at the end of the structure to reduce scour. When wire mesh is used, it is typically backfilled with another material such as brush or hay. The impact to the channel from this type of structure is somewhat different than for stone-fill jetties or hardpoints. Since fence dikes are relatively permeable, less scour occurs riverward of the structure's end. Sediment accretion behind the structure is often more extensive than for less permeable structures. Environmental benefits and considerations for this structure type are the same as for hardpoints and jetties. Recreational benefits are less for fence dikes than for hardpoints or jetties because they do not improve access to the river. Fence dikes have been used extensively on rivers throughout the US with mixed success. They are more prone to damage than hardened structures, particularly from ice or debris. Fence dikes require more maintenance than hardpoints or jetties.

Fences - Used in small low gradient streams, fences are constructed parallel to the bank line to promote sedimentation. Fences are made of a variety of materials but the prime materials used are wood and wire. On sandy bottoms, fence posts should be spaced 6 to 10 feet apart and driven 15 feet into the ground if stream velocities over 15 feet per second are expected. To provide extra protection, brush, hay bales, used tires, or rock can be placed between the fence and the stream bank. Fences can be designed to deflect stream low or to trap debris. Eliminating the problem of constructing a stable foundation, fences are more economical than riprap or matting methods. Since fences are constructed away from the bank, they promote sedimentation but are vulnerable for damage due to ice flows or large debris from heavy floods.

Energy reduction methods

Energy reduction methods function by reducing the ability of the river to erode bed and bank material. In the case of vanes and fence revetments, this is accomplished by reducing boundary shear and secondary helical currents. Selective clearing and snagging and chute closures both function by reducing the most severe flows along eroding banks. Vanes and fences have little effect upon the morphology of the river. Sediment transport may be slightly reduced in the immediate vicinity of the structures, but this is of little consequence. They are intended to have minimal impact upon the channel geometry. On the other hand, clearing and snagging and chute closures can both have a dramatic effect upon the morphology of the river. Clearing and snagging reduces stages, changes the velocity distribution at a section, and can increase sediment transport through the reach. Selective clearing of bars and islands can cause realignment of the main channel of the river. Chute closures or channel blocks increase the flow in the main channel and reduce or deplete flows in the chute. The stage of the river will increase upstream of the structure, particularly during high flows. Both velocity and sediment movement may increase slightly in the channel. If flow is eliminated in the chute, sediment deposition will eventually fill it. Vegetation encroachment will occur in the chute, further reducing the flood capacity of the section. Most of these methods cause sediment accretion, which improves substrate for boring macroinvertibrates. The sediment may cover other more-desirable habitat such as cobbles. The associated hydraulic changes may adversely affect other aquatic species due to a loss of higher velocity habitat and the potential for elevated water temperature. These methods generally have very little impact upon riparian habitat. They may positively or adversely affect recreation and aesthetics.

Vanes - Vanes are structures placed within the channel at an angle to the normal flow so that they reduce the secondary currents and thus reduce the erosive capacity of the river. The most common types of vanes are Iowa Vanes, baffle vanes, and stone vanes. Iowa vanes are small flow-training structures (foils), designed to modify the near-bed flow pattern and redistribute flow and sediment transport within the channel cross-section. The structures are typically installed at an angle of 15 - 20^{o} to the flow, with a height of 0.2 - 0.4 times local water depth at designed stage. The vanes function by generating secondary circulation in the flow. The circulation alters magnitude and direction of the bed shear stresses and causes a change in the distributions of velocity, depth, and sediment transport in the area affected by the vanes. As a result, the river bed topography may be altered by selective layout of the structures. Baffle-type vanes are structures consisting of boards attached to piles that are placed in series in the stream to disrupt the secondary currents that cause erosion on the outside of meander bends. The number, locations, spacing, orientation, size, and height of the vanes are critical to success and must be determined from careful analysis. Stone vanes are low stone structures angled upstream with an acute angle of 25 - 40^{o} from the bank. They are overtopped by all but the lowest flows. There are a number of variants of this structure depending on the slope, length, relative height, and materials. Bendway weirs are an example of this type of structure.

Because vanes stop erosion by modifying secondary circulation, no bank sloping or treatment is necessary. Aquatic benefits are not destroyed, and once vegetation becomes re-established on the eroding bank, riparian habitat and aesthetic benefits are improved. During low water, the vanes are not very appealing visually, and there may be some hazard to navigation and to recreationists using the stream. Vanes have not been used extensively. Prototype vane systems have been installed in a couple of midwestern streams, including the East Nishnabotna River in Iowa. It is too soon to evaluate the success of the prototype demonstration at this site, but sedimentation was induced between the structures and the bank in model studies. The sediment deposition may reduce the effectiveness of the structures, and could induce additional erosion along the bank due to the reduction in channel capacity. Vanes have been used successfully to ameliorate shoaling problems at water intakes and bridge crossings.

Clearing and Snagging – For flood control on small streams, conventional clearing and snagging has been used to remove all obstructions from the channel and to clear all significant vegetation within a specific width on both sides of the channel. Key aspects of selective clearing and snagging involve selective removal of vegetation based on size, condition, species, or location; removal of only those snags that are major flow obstructions; use of hand labor and small equipment when feasible, and rigid access controls when heavy equipment must be used; protection of existing vegetation of disturbed areas; and greater reliance on multidisciplinary teams in all phases of project planning and management. Disturbed areas should be restored to natural contours, and preserved trees should be spaced at irregular intervals. Natural sloughs, drains, and flood-plain depressions should be left in their original condition. Because of the limited improvement in flow hydraulics (upper flow capacity limit roughly equivalent to bankfull discharge), selective clearing and snagging is most often used to provide relief from high frequency nuisance flooding, for drainage improvement in agricultural areas, and recreational benefits. Increased hydraulic conveyance results from changes in the resistance to flow values in uniform flow equations. Vegetation, channel irregularity, obstruction to flow, and design flow conditions should be considered in estimating improvements in resistance coefficients.

Channel Blocks - Used in small to medium streams or on side chutes of larger streams, channel blocks are used to prevent stream flow from forming a new channel by keeping the flow in the desired channel. They are generally constructing during low to normal stream flows, and can be formed from riprap, soil, a rectangular framework of logs, or a variety of other materials. Channel block structures are usually placed in pairs, and must be designed for stability when overtopped. These structures often utilize riprap on the downstream side to prevent scour and are generally lower than the existing bankline to permit floodwater to pass through the secondary channel. Channel blocks effectively divert streamflow but are ineffective on large streams with large side channels. If the material is economically available, unskilled workers can be used in the construction of channel blocks to cut costs. Aquatic habitat is modified by the use of these structures. Active secondary channels may become backwater zones or wetlands. Flows in the main channel may deepen, with a corresponding coarsening of the bed material.

Fence Revetments – Fence revetments are used to solve a variety of bank protection problems. They are constructed parallel to the bank and to the flow at, or riverward of, the toe of the bank slope. Fences are constructed of wood or wire and are pervious. Stream velocity behind the structure is significantly reduced, thereby reducing erosion. Because fences stop erosion by reducing secondary currents and circulation, no bank sloping or treatment is necessary. Aquatic features are not destroyed, and once vegetation becomes re-established on the eroding bank, riparian habitat and aesthetic benefits are improved. Fences have been used successfully on many rivers. They are prone to damage from ice and debris, and must be regularly maintained. Fences can also limit access to and from the high bank.

Grade Control Structures and Low-Head Weirs- These are structures designed to reduce channel grade in natural or constructed watercourses to prevent erosion of a channel that results from excessive grade in the channel bed or artificially increased channel flows. This practice is used to stop headcut erosion or stabilize gully erosion. Grade stabilization structures may be vertical drop structures, concrete or riprap chutes, gabions, or pipe drop structures. Permanent ponds or lakes may be part of a grade stabilization system. Concrete chutes are often used as outlets for large water impoundments where flows exceed 100 cfs and the drop is greater than 10 ft. Where flows exceed 100 cfs but the drop is less than 10 ft., a vertical drop weir constructed of reinforced concrete or sheet piling with concrete aprons is generally recommended. Small flows allow the use of prefabricated metal drop spillways or pipe overfall structures. Designs can be complex and usually require detailed site investigations. Design of large structures (100 cfs) requires a qualified engineer. The National Engineering Handbook (Drop Spillways, Section 11, and Chute Spillways, Section 14) prepared by the USDA Natural Resources Conservation Service gives detailed information useful in the design of grade stabilization structures.

Low-head weirs are essentially the same type of construction as grade control structures, but the head loss over the structures is usually 2 feet or less. Built from rocks, logs, or other material, low-head weirs are usually intended for use in lower order perennial streams for water quality improvement and habitat enhancement. They can be designed to arrest bed degradation, and can be configured in a variety of ways to modify the flow field to achieve changes in channel geometry. Weirs are most successful in smaller streams with relatively coarse substrates.

Grade control and weir structures have a wide array of impacts. They create backwater in upstream reaches – increasing depth and reducing velocity. These upstream impacts reduce sediment transport capacity and stream reaches immediately upstream of these structures often have deposited sediments on the bed that are finer than those found in adjacent reaches. The extent of the upstream impacts depend upon the height of the structure and the streambed slope. Downstream of the structure, a scour pool is generally formed with a bed material composition more coarse than adjacent reaches. The size of the pool is dependant on the relative height of the structure and its geometric configuration. Grade control structures can become barriers to fish migration, but can be designed to accommodate this concern by employing a low-flow channel or chute. If they pool a significant amount of water, grade control devices may contribute to elevated stream temperatures. Benefits cited for these devices include formation of pool habitat, collection and holding of spawning gravels, promotion of gravel bar/riffle formation, trapping suspended sediments, reoxygenating water, allowing organic debris deposition, and promotion of invertebrate production.

Slope stabilization methods

If failure is due mainly to geotechnical factors like drawdown or seepage, protection against hydraulic erosion may not be the best treatment. On the other hand, geotechnical failure may represent a delayed response to continuing scour at the bank toe, in which case toe protection against hydraulic erosion is essential. When geotechnical factors alone are involved, this usually results in mass failure of the embankment material. Several different types of mass failure can occur in banks. These include sliding along a deep failure surface, shallow slips, and lock failures. Many factors affect mass failures. They include soil type, bank slope geometry, surface and ground water flow regime, infiltration, surcharge loading, tension cracking, and vegetation. Each factor's contribution to the failure must be identified before an appropriate solution can be selected. Slope stabilization techniques typically involve large-scale modification to the bank. This can seriously disrupt the riparian environment, and may affect aesthetics and recreation. Impacts to the aquatic community are generally slight, but reductions in sediment supply and the value of existing bank cover should be addressed.

Grading – The best structural solution to most geotechnical failures is to regrade the bank to a lower angle and to protect the toe and lower bank from further erosion that might otherwise over-steepen the slope. If weakening of the bank is also a factor, steps must be taken to prevent damage by limiting access or modifying the activities responsible. Shallow slips and dry granular flows are generally addressed with minor bank modifications. Deep-seated rotational slips are a severe form of bank instability and, because the failure surface is located deep inside the bank, surficial or shallow treatments are inadequate to deal with this type of failure. Major regrading of the bank coupled with toe protection and improved drainage may be needed to achieve stability. If space limitations preclude complete regrading, a structural retaining wall must be incorporated into the design. In the field, a geotechnical site survey must be performed to identify and quantify all the relevant factors and bank parameters before any firm conclusions can be drawn regarding the cause of failure and detailed design for stabilization. Impacts from grading are primarily related to the destruction of existing riparian habitat. There are also cases where relatively steep eroding banks provide habitat for burrowing or nesting fauna and this habitat is directly impacted from regrading activities. Some short-term impacts associated with sediment yield from a regraded site can be a concern for very large projects. Benefits include a reduction in sediment yield and any improvements associated with the relative values of the existing and replaced vegetation.

Geogrids and Geotextiles - As a surface failure, dry granular flow is easily dealt with using soil reinforcement by geogrid, geotextile or suitable living vegetation coupled with lower bank armoring to prevent undercutting. If weakening is a factor due to trampling or mechanical damage to the upper bank, then either active bank management should be employed to reduce or eliminate the activity responsible, or surface protection must be extended up the bank to prevent significant impacts on bank stability. The placement of a geogrid or geotextile over the soil surface can reduce the use of the site by some organisms as habitat. Some products utilizing a web or mesh of synthetic materials have also been known to trap small birds and mammals. Bio- or photo-degradable products are usually preferred when the intended use of the material is to provide temporary stabilization while a vegetation cover is established. If a non-degradable material is used to enhance soil strength, it is usually covered with soil and revegetated.

Retaining Walls – If regrading a shallow or rotational failure is precluded by lack of space, an over-steep bank can be stabilized using a vertical retaining wall. A wide variety of materials can be used for the construction of the walls and impacts, to some extent, depend on the type of material used. Retaining walls typically disrupt riparian/aquatic movement of organisms and provide an unnatural ecotone (though some retaining walls use natural materials and can accommodate vegetation plantings). Scour depths tend to be comparable to those found along natural banklines. Depending on the materials used, retaining walls can reduce the exchange of surface and ground water along a bank.

Drains – Improvement of subsurface drainage is the key to preventing wet earth flow failures. Steps involved include the reduction of seepage pressures by encouraging free drainage, with a suitable filter installed to prevent piping erosion. Drainage may be achieved using perforated pipes or French drains. Filters may be granular, geotextile or vegetative. This is a serious form of instability that will require a geotechnical site survey to establish the details of the problem and a careful analysis of bank seepage to support the selection of an appropriate solution. Drains are usually below-ground and are covered and revegetated, so the impacts from their use are short-term and typically minimal.

Techniques that address bank weakening - Another category of bank stabilization addresses instabilities associated with weakening mechanisms. Weakening is caused by leaching, trampling, loss of riparian vegetation, ice scour, freeze-thaw, and a number of other factors that diminish bank strength. These can lead to slope failures, and a number of measures have been devised to address these problems. Fencing to restrict access to a trampled bank represents one end of the spectrum of possible impacts from measures intended to address bank weakening. Regrowth of riparian vegetation in these zones is the general consequence. On the other end of the spectrum are soil amendments that permanently alter soil structure and character. An example is the disking of cement or other binders into the soil and compaction of the bank to strengthen bank soils. These types of measures influence the composition of the riparian vegetation community.

Summary

The selection of an appropriate stabilization measure is usually based first and foremost on the cause of the problem. Armoring, deflecting, and energy reduction methods can be successfully employed to address erosion problems. Slope stabilization is usually required to address geotechnical instabilities in the bank and most weakening factors. Tables 1, 2, and 3 present a decision support matrix to aid in the selection of structural solutions for streambank restoration based upon the underlying problem. These tables are only a guide, because in practice each problem has individual elements that cannot be generalized, and every design is to some degree unique. At present there are no 'cook book' solutions to bank retreat problems and guiding principles must be applied in a flexible design strategy that ensures protection is adequate, cost-effective, safe, and environmentally acceptable**.**

Typically, more than one method or combination of methods can be used to address a particular problem. Selection of the “best” alternative, and refinement of that alternative, is generally based upon environmental considerations, material and equipment availability, cost, timing, and other factors. So it is at this stage in the selection process that the identification of impacts becomes most important. The following section discusses the nature of impacts that can be expected as a consequence of bank stabilization practice.

Table 1. Selection of Appropriate Structural Solutions for Erosion Processes

Failure Type	*Structural Considerations*	*Options for Structural Protection*
Parallel flow (fluvial entrainment)	Structures may either increase erosion resistance by armoring the bank with a non-erodible layer or reduce the intensity of attack by deflecting currents away from the bank. Flow attack is usually concentrated on the lower half of the bank	Revetments are used to provide surface armoring. Deflectors may be formed by dikes or groins. Soft systems use vegetation, hybrid systems use geogrids, geotextiles and cellular blocks with vegetation. Heavy protection uses riprap, armorstone and gabions at the toe, often with lighter protection on the upper bank.
Impinging flow (fluvial entrainment)	Impinging flow generates very high turbulence, secondary currents and elevated local velocities. Instantaneous shear stresses and near bank scour depths are large, but unpredictable.	Uncertainties associated with the intensity of attack by impinging prescribe the use of heavy protection. Use of soft or hybrid protection is inadvisable unless the channel is realigned to eliminate flow impingement. Realignment will have other benefits.
Boatwash	Chronic or severe boatwash erosion may persist at vulnerable places even in well-managed waterways. These locations may require structural protection.	Hard protection using a vertical wall protects the bank but may reflect wave energy against unprotected banks. Porous revetments and emergent vegetation are excellent energy dissipaters. In most cases there is scope for use of wet berms and soft engineering.
Wind-waves	Wind-waves have a wider wavelength than boat waves but are rarely a spectrum of heights and serious problem on British inland waterways.	Structural protection should be designed to absorb and dissipate wave energy without significant erosion and without reflecting it. A wet berm with emergent vegetation is recommended.
Rills and gullies (surface erosion)	Rills and gullies pose threats to the integrity of the bank surface including any surface protection.	Surface drainage may be controlled to prevent erosion using buffers, pipes, drop structures and lined channels.
Piping (seepage erosion)	Piping erosion is a common cause of failure of structural bank protection. A notch produced by piping is easily misinterpreted as due to boatwash.	A structural solution must allow free subsurface drainage while preventing loss of soil particles. This is best achieved by use of a granular, geotextile or vegetative filter.

Table 2. Selection of Appropriate Structural Solutions for Failure Mechanisms

Failure Type:	*Structural Considerations*	*Options For Structural Protection*
Shallow slide	Shallow slides occur because the bank angle exceeds the angle of repose. Surface armor installed to prevent erosion.	The best solution is to regrade the bank to an angle lower than the slides can disrupt angle of repose and protect the toe from further erosion. If space is limited a vertical wall can be used but deep toe scour will occur.
Rotational slip	This type of deep-seated failure threatens protection structures and surface treatments. It is not amenable to shallow solutions.	Major regrading coupled with toe protection and improved drainage will be necessary to achieve geotechnical stability. If limited space precludes regrading, a retaining wall must be constructed and protected against deep toe scour and positive pore water pressures
Slab-type failure	Slab-failure planes pass below the rooting layer and shallow stabilization measures or positive pore pressures may be critical.	Regrading to a lower bank angle will eliminate tension cracks. Tension cracks protection is installed to prevent further over-steepening. If limited space precludes this, a retaining wall must be constructed and protected against deep toe scour and positive pore water pressures.
Cantilever failure	Cantilevers are produced by erosion of a weak layer in the bank.	Measures that may be applied include armoring of the bank to prevent undermining of the weak layer, installation of a filter to prevent piping, and re-vegetation to increase soil tensile strength.
Soil fall	Soil fall occurs on steep, undercut banks of low cohesion. It adds to bank retreat due to flow, wave or piping erosion.	Soil fall may be eliminated by regrading the bank to a lower angle and protecting the surface with vegetation, a geotextile or a riprap. If lack of space precludes this, a vertical wall may stabilize the steep bank with suitable allowance for deep toe scour.
Dry granular flow	Dry granular flow is a surface failure that occurs on undercut banks, which have no effective cohesion.	Dry granular flow is dealt with by soil reinforcement using a geogrid, geotextile or vegetation coupled with toe protection to prevent further undercutting and active management to prevent trampling or mechanical damage to the upper bank.
Wet earth flow	Wet earth flow and liquefaction may pose a threat to bank protection and structural stabilization schemes.	Improvement of subsurface drainage is the key to prevention of wet earth flows. Steps involved include installation of pipes or drains to remove water and filters to retain soil particles.

Table 3. Selection of Appropriate Structural Solutions for Weakening Factors

Weakening Factor:	Structural Considerations	Options for Structural Protection
Leaching	Leaching is difficult to detect and may seriously weaken the soil thereby threatening the integrity of the bank.	The structural solution is to strengthen the soil artificially by injecting grout or resin into the bank, but this will rarely be cost-effective.
Trampling	Trampling weakens the bank by destroying the soil fabric and it can also increase surface runoff.	Conventional structural treatments include concrete and bitumen to create footpaths and animal ramps. Modern alternatives use geogrids and cellular blocks that protect the surface while allowing vegetation to grow through them, producing a natural appearance.
Destruction of riparian vegetation	The structural role of vegetation in bank geotechnics is poorly understood but is often crucial to stability.	The best structural protection to prevent destruction of riparian vegetation is a fence. The creation of a fenced riparian buffer zone is highly beneficial when stabilizing, protecting and conserving a streambank. Destruction of bank vegetation can also be prevented structurally by using buttresses to stabilize the roots of undercut trees and geogrids and cellular blocks to promote riparian vegetation, and pocket fabrics for aquatic and emergent plants.
Mechanical damage	Mechanical damage may compromise the structural strength of the bank directly, or it may destabilize the bank indirectly by providing a foothold for a	The form of a structural solution depends on the activities responsible for mechanical damage. Heavy protection will be where activities such as boat mooring or angling impose intense stresses. Where activity is less severe, hybrid and soft protection may suffice.
Positive pore water	High pore water pressures may be disastrous to bank stability and are often responsible for the failure of bank stabilization schemes.	Structural solutions must dissipate pore pressures by allowing water pressures to drain through the bank while retaining soil particles. The detailed design is a topic in geotechnical engineering, but a variety of perforated pipes and filters are used to eliminate excess pressures.
Desiccation	Cracking and crumbling due to desiccation can lead to significant reduction in the operational strength of bank soils.	Structural solution through the installation of a light reinforcement system based on a geogrid, geotextile or suitable vegetation is an appropriate approach that retains a natural appearance to the bank.
Freeze/thaw (frost erosion)	In Britain erosion caused by freeze/thaw erosion alone does not merit a structural solution.	The intensity of freeze/thaw processes in Britain does not pose a hazard to soft or hard bank protection, which will be able to withstand the forces exerted without special design features.

Structure and Function of Stream and Riparian Ecosystems

Bank stabilization measures affect the hydraulics, sediment transport, and geometry of the adjacent channel, as well as many of the riparian/stream exchange processes. The local impacts from these activities and structures vary by function, materials, design, and construction methods, and can result in a wide range of positive and adverse environmental impacts. Through proper planning and design, negative impacts can be minimized and positive impacts maximized.

There is a set of complex relationships between numerous dependent variables that dictate the physical, biological and chemical character of stream and riparian ecosystems. Changes to any one variable, whether induced by nature or as a result of man's activities, cause the system to respond in ways that are not altogether predictable, and create changes in all other variables. Recognizing these relations and identifying the appropriate causes and effects is the basis for characterizing impacts. A basic understanding of fluvial processes, geomorphology, hydrology, hydraulics, stream ecology, and natural and anthropogenic impacts is needed to undertake these analyses.

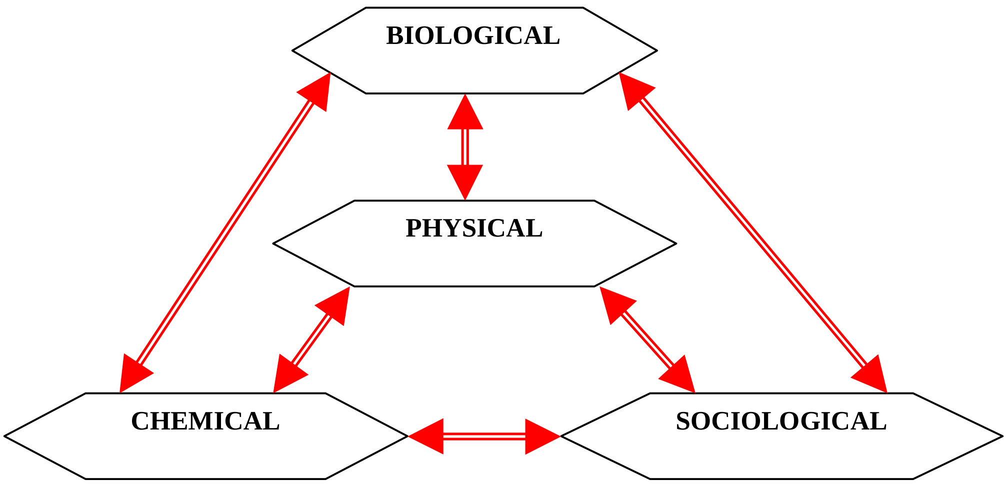

Figure 1 Ecosystem Relations. Items in the boxes define the structure of the system, and the arrows denote interactive processes or functions.

Streambank stabilization can directly affect each of the ecosystem components shown in Figure 1. But most of the direct affects are to the physical character of the system. The physical changes then affect the chemical, biotic, and social components of the ecosystem. The physical changes can also affect the processes, or pathways between components, within an ecosystem.

Structural Characteristics

The function and ecological character of a stream or riparian system are closely related to the system’s structural characteristics. The following list describes some of the structural characteristics that play an important role in defining ecological function.

1. Hydrology and Hydraulics, including quantity of discharge on annual, seasonal, and episodic basis; timing and duration of discharge; surface flow processes, including velocities, turbulence, and shear stress; ground water flow and exchange processes, bank/stream storage; retention times; particle size distribution and quantities of bed load and suspended sediment; and sediment flux.

2. Water Quality including measures of dissolved oxygen, dissolved salts, dissolved toxins and other contaminants, floating or suspended matter, pH, odor, opacity, temperature profiles, and other indicators.

3. Soil and Sediment Condition as revealed by soil chemistry; erodibility; permeability; organic content; soil stability; physical composition, including particle sizes and microfauna; and other factors.

4. Geological Condition as indicated by surface and subsurface rock and other strata, including aquifers.

5. Topography as indicated by surface contours; the relief (elevations and gradients) and configuration of site surface features; and project size and location in the watershed, including position relative to similar or interdependent ecosystems.

6. Morphology as indicated by the shape and form of the ecosystem, including subsurface features. For rivers and streams, this includes channel slope, planform, and geometry at various spatial and temporal scales.

7. Flora and fauna, including density, diversity, growth rates, longevity, species integrity (presence of full complement of indigenous species found on the site prior to disturbance), productivity, stability, reproductive vigor, size-and age-class distribution, impacts on endangered species, incidence of disease, genetic defects, genetic dilution, elevated body burdens of toxic substances, and evidence of biotic stress.

These structural characteristics define the *habitat* of the ecosystem. Habitats are the places where individuals, populations, or assemblages of fishes, wildlife, and other organisms can find the physical and chemical features needed for life. Habitat quality affects abundance and health of aquatic organisms as well as the species composition.

Instream Habitat

Instream habitat features include water quality, spawning sites, feeding areas, and migration routes. Much of the spatial and temporal variability of stream biota reflects variations in both abiotic and biotic factors, including water quality, temperature, streamflow and flow velocity, substrate, the availability of food and nutrients, and predator-prey relationships. These factors influence the growth, survival, and reproduction of aquatic organisms.

A number of measurement techniques and models are used to assess the physical character of instream habitats as they relate to aquatic organisms. These techniques utilize a variety of habitat features as indices of fishery health. Similar approaches are used to evaluate invertebrate habitat. The major stream habitat types that are colonized by epifaunal macroinvertibrates and generally support the highest quality diversity in stream ecosystems are described below.

Flow Condition

The spatial and temporal characteristics of streamflow, such as fast versus slow, deep versus shallow, turbulent versus smooth, and flooding versus low flows, are can affect both micro- and macro-distribution patterns of biota. Many organisms are sensitive to velocity because it represents an important mechanism for delivering food and nutrients yet also may limit the ability of organisms to remain with a stream segment. Some organisms also respond to temporal variations in flow, which can change the physical structure of the stream channel, as well as increase mortality, modify available resources, and disrupt interactions among.

Extreme low flows may limit young fish production because such flows often occur during periods of recruitment and growth. Extreme high flows can mobilize significant amounts of bed material and dislocate a large fraction of the invertebrate community in a stream reach. High flows are also cues for timing migration and spawning of some fishes. The velocity in streams determines the vegetation forms that can develop and sustain themselves.

Riffles and pools (and runs) are common features throughout most mountain and piedmont streams. Riffle/pool streams provide a great diversity of velocity conditions and, in turn, are most apt to support a diverse faunal community. In many high-gradient streams, riffles will be dominant. However, riffles are not a common feature of most coastal or other low-gradient streams.

Cover

Instream cover, usually in the form of boulders or large woody debris, can provide habitat for invertebrates, velocity refuges, hiding places from predators, and attachment sites for adhesive fish eggs. Because depth and velocity of flow are closely related to certain types of cover features, maximizing cover often increases diversity in depth and velocity. Instream cover is an important component of most lotic habitats and generally, more instream cover means better fish habitat.

Riparian vegetation is also an important cover feature because of its ability to attenuate light and temperature in streams. Direct sunlight can significantly warm streams, particularly during summer periods of low flow. A lack of cover also affects stream temperature during the winter. Sweeney (1993) found that while average daily temperatures were higher in a second-order meadow stream than in a comparable wooded reach from April through October, the reverse was true from November through March. Temperature differences of 2-6 °C can be biologically significant and may alter key life-history characteristics of aquatic species.

Substrate

Stream substrates are composed of various materials, including clay, sand, gravel, cobbles, boulders, organic matter, and woody debris. Substrates form solid structures that modify surface and interstitial flow patterns, influence the accumulation of organic materials, and provide for production, decomposition, and other processes.

Stream biota respond to the many abiotic and biotic variables influenced by substrate. As a general rule, substrate size decreases with increasing stream order, with substrate in the largest rivers usually consisting of sand, silt, and clays. Many fishes, including some culturally and economically important species, cannot reproduce successfully unless gravel or larger substrate is available. Thus, gravel and larger substrates are often very important habitat components.

Differences in species composition and abundance can be observed among macroinvertebrate assemblages found in snags, sand, bedrock, and cobble within a single stream reach. This preference for conditions associated with different substrates contributes to patterns observed at larger spatial scales where different macroinvertebrate assemblages are found in coastal, piedmont, and mountain streams. Sand and silt are generally the least favorable substrates for supporting aquatic organisms and support the fewest species and individuals. Flat or rubble substrates have the highest densities and the most organisms. In forested watersheds, and in streams with significant areas of trees in their riparian corridor, large woody debris (LWD) that falls into the stream can be the most important substrate.

Stream substrates constitute the interface between water and the hyporheic zone of the aquatic system. The hyphorheic zone is the area of free exchange between surface and ground water. On small streams, the hyphorheic zone is limited to small floodplains, meadows, and stream segments where coarse sediments are deposited over bedrock and are generally not continuous. On mid-order channels with more extensive floodplains, the spatial connectivity of the hyphorheic zone increases. The hyphorheic zone is usually largest on high-order streams, but tends to be discontinuous because of features such as oxbow lakes and cutoff channels, and because of complex interactions of local, intermediate, and regional ground water systems.

Primary Productivity and Organic Material

The role of primary productivity of streams can vary depending on geographic location, stream size, and season. Primary productivity is of less importance in shaded headwater streams than in larger streams where riparian vegetation no longer limits the entry of light to stream periphyton. The loading of nitrogen and phosphorus to a stream can increase the rate of algae and aquatic plant growth, a process known as eutrophication. Decomposition of this excess organic matter can deplete oxygen reserves and result in fish kills and other aesthetic problems. Stream eutrophication can result in excessive algal mats and oxygen depletion at times of decreased flows and higher temperatures. Furthermore, excessive plant growth can occur in streams at apparently low ambient concentrations of nitrogen and phosphorus because the stream currents promote efficient exchange of nutrients and metabolic wastes at the plant cell surface.

In many streams, shading or turbidity limit the light available for algal growth, and biota depend highly on allochthonous organic matter, such as leaves and twigs produced in the surrounding watershed. Once leaves or other allochthonous materials enter the stream, they undergo rapid changes. Soluble organic compounds, such as sugars, are removed via leaching. Bacteria and fungi subsequently colonize the leaf materials and metabolize them as a source of carbon. The presence of the microbial biomass increases the protein content of the leaves, which ultimately represents a high quality food resource for shredding invertebrates.

Leaf decomposition occurs by a sequential combination of microbial decomposition, invertebrate shredding, and physical fractionation. Leaves and organic matter itself are generally low in protein value. However, the colonization of organic matter by bacteria and fungi increases the net content of nitrogen and phosphorus due to the accumulation of proteins and lipids contained in microbial biomass. These compounds are a major nutritive source for aquatic invertebrates. The combination of microbial decomposition and invertebrate shredding/scraping reduces the average particle size of the organic matter, resulting in the loss of carbon both as respired $CO2$ and as smaller organic particles transported downstream. These finer particles, lost from one stream segment, become the energy inputs to the downstream portions of the stream. Decaying organic matter represents a major storage component for nutrients in streams, as well as a primary pathway of energy and nutrient transfer within the food web. Ultimately, the efficiency of retention and utilization is reflected at the top of the food web in the form of fish biomass.

Riparian and Floodplain Habitat

Aquatic river-edge ecotones provide outstanding ecological boundaries. The riverine littoral zone provides comparatively calm water and stable sediments, with habitat structure provided by rocks, snags, plants, and bank irregularities. The littoral boundary is a key part of the riparian corridor, being a zone of concentrated physical and biological diversity and a resource for both riverine and terrestrial communities.

The riverine littoral zone is characterized in most areas as the riverbank, from the edge of the water to the top of the bank. This zone is unique because it provides constant contact between the aquatic and terrestrial portions of the riparian corridor. The hydrologic and hydraulic character of the river directly affects it. High river stages inundate the entire littoral zone and provide access to the upper littoral zone resources by fish and other aquatic or amphibious species. Low river stages remove access to refuge, food, and spawning areas for aquatic and amphibian animals as the higher elevation areas become exposed.

Overhanging vegetation in this zone shades and cools the water and surroundings, helping to provide thermal refuges. Roots and debris are colonization sites and food sources for macroinvertebrates and provide refuge from predators and currents among the roots, rocks, and other structures. Vegetation in this zone stabilizes streambanks and improves water quality. Stable banks provide nesting sites for a variety of vertebrate species. Several elements of fish habitat, including temperature, cover, and food are influenced by the riparian zone.

Backwater areas are an important component of the riparian zone. Longevity, productivity, and habitat quality of backwaters are greatly affected by the amount of protection from main river channel flooding and sedimentation, number and type of connections to the river, flushing rate, and degree of water-level fluctuation. Direct openings to the river permit water exchange that can prevent stagnation and oxygen depletion, renew organic material and nutrients, and allow export of materials such as detritus, plankton, and aquatic invertebrates to the river. Fish are known to readily enter backwaters, especially for spawning, and the free movement of fish into and out of these areas in response to changing conditions is important for maintaining healthy populations. However, if there are numerous uncontrolled connections to the main channel, then high rates of water movement throughout the backwater will flush out nutrients and preclude development of slow-water habitat features.

Riparian vegetative communities are a valuable source of energy for the biological communities, provide physical habitat, and moderate solar energy fluxes to and from the surrounding aquatic and terrestrial ecosystems. The vegetative community grows in an annual cycle of active growth/production, senescence, and relative dormancy. The growth period is characterized by the photosynthetic process, through which inorganic carbon is converted to organic plant materials. A portion of this organic material is stored as above- and below-ground biomass, while the remainder is lost to the stream or to the soil in the form of leaves, twigs, and decaying roots. This organic fraction, rich in biological activity of microbial flora and microfauna, represents a major storage and cycling pool of available carbon, nitrogen, phosphorus, and other nutrients. Some of this material, particularly the LWD, provides important cover and substrate for aquatic organisms.

The characteristics of the vegetative communities directly influence the diversity and integrity of the faunal communities. Vegetative communities that cover a large area and that are diverse in their vertical and horizontal structural characteristics can support far more diverse faunal communities than relatively homogenous vegetative communities.

The quantity of terrestrial vegetation, as well as its species composition, can directly affect stream channel characteristics. Root systems in the stream bank can bind bank sediments and moderate erosion processes. Trees and smaller woody debris that fall into the stream can deflect flows and induce erosion at some points and deposition at others. Thus woody debris accumulation can influence pool distribution, organic matter and nutrient retention, and the formation of microhabitats that are important fish and invertebrate aquatic communities.

In most instances, the functions of vegetation that are most apparent are those that influence fish and wildlife. At the landscape level, the fragmentation of native cover types has been shown to significantly influence wildlife, often favoring opportunistic species over those requiring large blocks of contiguous habitat. In some systems, relatively small breaks in corridor continuity can have significant impacts on animal movement or on the suitability of stream conditions to support certain aquatic species. In others, establishing corridors that are structurally different from native systems or that are inappropriately configured can be equally disruptive. Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators, and, where corridors have been established across historic barriers to animal movement, they can disrupt the integrity of regional animal assemblages.

Functional Characteristics

In addition to viewing ecosystems in terms of their structure, or habitat provision, ecosystems can and should be viewed in terms of the important processes they support. Streams and riparian ecosystems perform three basic functions related to processes:

1. They maintain hydrologic processes and continuity
2. They adjust and regenerate through morphologic processes
3. They maintain chemical and biological processes

Within each of these general categories are subsets of processes. The most fundamental function of rivers is the transport of water and sediments, and most of the physical, biological, chemical and sociological functions are derived from these basic functions. The transport of water and sediment are, in turn, influenced by the interaction of geologic, climatic, hydrologic, geomorphic, pedogenic (soil), and biotic processes. So many of the functions performed by streams are interrelated.

Hydrologic Processes

Stream channels and their associated riparian zones serve four primary physical functions related to hydrology and hydraulics: 1) they maintain surface water storage processes, 2) they maintain subsurface water storage processes, 3) they maintain surface/subsurface water connections, continuity, and processes, and 4) they maintain energy processes.

Storage - The ability of stream channels and riparian zones to store water is critical in moderating extreme high and low flow periods. Through water storage, riparian zones provide soil moisture necessary for plant growth, biological linkages, and biogeochemical processes to occur. The riparian corridor provides areas for surface water storage within the floodplain and active channel during times of high flows. Microtopographic changes in the floodplain provide areas of inundation and saturation at critical frequencies and durations within the soil surface leading to a diversity of plants and animals within them. Established vegetation adds resistance to flow, which dissipates energy and increases detention times. This causes sediments, along with metals and nutrients they carry, to settle within the floodplain and replenish required nutrients. Long-term surface water storage facilitates similar processes and benefits, but to a greater extent. This is due to the increase in duration of time the water is held within an area, which facilitates increased nutrient inputs and water necessary to carry out more biotic and abiotic processes over time.

Water Connections - The connectivity of surface and subsurface water is important in maintaining the exchange of chemicals, nutrients and water between these two zones. This connectivity provides habitat for organisms dependent on flux of water level and exchange of nutrients. Alluvial riparian zones function as shallow aquifers that recharge at high flows and drain at low flows. This interaction between surface flows and groundwater storage results in moderated high flows and enhanced or prolonged base flows. The shallow aquifer condition also creates moist soil conditions favorable for riparian plant growth. During times of high stream flow, some water that flows in the channel infiltrates into the channel bed and banks in response to hydraulic gradients. This process is reversed at times of lower flows to supplement stream flows. This function facilitates nutrient exchange, and maintains habitat complexity at a variety of flow conditions. Most riparian wetlands are groundwater discharge wetlands in response to hydraulic gradients; however, some can serve as groundwater recharge areas part of the year in response to changes in hydraulic gradients. It can be difficult and expensive to make this distinction, but water within a wetland can be tested to determine its source because surface water and groundwater often have different chemical constituents.

Energy - The ability of a stream to convert energy between its potential and kinetic forms through changes in physical features, hydraulic characteristics, and sediment transport processes is important in creating complex habitats, generating heat for biochemical reactions, and oxygenating flows. Stream and riparian management activities often impact this energy gradient.

Morphologic Processes

Stream channels and their associated riparian zones serve four primary functions related to morphology: 1) they maintain sedimentation processes, 2) they maintain stream evolution and riparian succession processes, 3) they maintain substrates and structural processes, and 4) they maintain unique landscape positional characteristics and processes.

Sedimentation - Sedimentation embodies the erosion, transport, deposition, and consolidation of sediments and implies that the laws of continuity are upheld. The interaction of geologic, climatic, hydrologic, geomorphic, pedogenic (soil), and biotic processes influence this function. Hydrology, topography, vegetation, and their interaction influence the magnitude and direction of these functional relationships in riparian zones. A major role of the riparian zone is to dissipate stream energies associated with high flows. This, in turn, permits sediments to deposit and continue development of the alluvial valley floor and the stream channel. These processes maintain substrate sorting and armoring capabilities and are an important component of water quality maintenance.

Erosion is the removal of sediment from the bed and banks of the stream. It occurs when the amount of shear stress is at or exceeds that which is required to entrain sediments, (i.e. critical shear stress). Erosion is always occurring as a natural process in streams; however, rates of erosion can be altered by a variety of factors including land use practices and changes in riparian vegetation. Altered rates of erosion can cause adverse impacts to aquatic habitat and organisms. Within naturally meandering channels, helical circulation flow patterns erode particles from outside mender bends and deposit them on downstream point bars on the inside of meander bends. Once sediments are entrained they are transported varying distances. Deposition occurs when streams no longer have the energy to carry particles.

This erosion and deposition pattern results in streams moving laterally across floodplains (i.e. lateral stream migration). The process can result in the creation of beneficial aquatic habitat features such as cut banks under overhanging vegetation and root masses. At low rates of erosion, aquatic habitat features are lost and gained as part of the natural erosion process, and aquatic organisms can acclimate and adapt to this. Erosion can, however, adversely impact aquatic habitat features by removing bank vegetation through accelerated lateral stream migration. At accelerated rates of erosion, more habitat features may be lost than gained or degraded at such rates that aquatic organisms cannot acclimate or adapt. Similarly, entrainment of bed materials (vertical migration) can result in beneficial habitat features such as scour pools if the bed scour is confined to a localized areas. However, large-scale accelerated erosion of bed materials can result in adverse impacts to aquatic organisms by incising channels which eliminates both bed material and undercut banks.

Succession - The maturation process of natural plant communities is termed "succession" or community development. Plant communities develop from two starting conditions. The first type of development, often called primary succession, takes place on newly formed areas where no plant community as ever occurred before, such as on volcanic flows, that eventually support diverse, mature plant communities. In this situation, community development can be extremely slow. Soils must form. Colonization by microbes, plants, and animals is slow at first due to the extremely harsh and stressful conditions. Establishment of riparian plant communities on newly formed point bars can be considered to be primary succession.

Plant communities, however, more commonly develop following a disturbance that is severe enough that community development is set back to earlier developmental stages or the system must develop anew. This second type of development is called secondary succession. Soils capable of supporting plants are already formed. Site conditions are not as harsh and colonization is rapid; annual plant species are present in the first year. The types of plants and animals present will change over time. For example in classical old field succession, annual and grass species are often the first dominant plant species as a site develops. As colonizing plants become established, conditions for plant growth are improved and different species become dominant that are not tolerant of the harsher site conditions. Shrubs may dominate early and mid developmental stages. Trees begin to colonize a site during early succession, but do not dominate the site structurally until mid to late successional phases. Eventually, the rate of new species introductions decreases, the plants on site regenerate themselves, and the species composition stabilizes. At this point, the community is considered to be a in a "climax" or steady state. Many cases of riparian community succession can be considered secondary succession because site conditions retain some of the components of the degraded system after the disturbance.

Succession of riparian plant communities is integrally related with the associated stream dynamics. It is the sequence of floods and shifting sediments that create new surfaces and deliver seeds of colonizing species. Seeds of many riparian species such as maples and willow are carried by water and deposited on newly exposed areas. Animals deposit seeds from fruit they have eaten such as mulberry and elderberry (*Sambucus* spp). Colonizing plants may also result from clumps of plants that have broken off eroding areas and subsequently stranded on bars downstream.

There are relatively few plant species that are capable of becoming established on newly developed bars because the environmental conditions are often very harsh. With little organic matter or soil development, the exposed bars dry rapidly following falling river levels. Seeds and new seedlings are often desiccated and die before root systems are developed that can reach the groundwater. Annual floods inundate and destroy much of the existing vegetation. In addition, as the bars dry out, winds blow sands that may completely cover seedlings, uncover roots, or undermine plants and blow them away. The point bar colonizing species share several adaptations that ensure the establishment of floodplain forests despite the vagaries of the river.

These include an extended period of seed dispersal, large numbers of seeds, and plumes that carry the seed on the water and become entrapped in sands.

In spite of the harsh conditions, there is often a fairly dense cover of plants on newly deposited bars. Willow, cottonwood, and alders are the most common tree species that colonize newly developed bars in many kinds of streams. Grasses and herbs are often among the colonizing plants on depositional bars, but they tend to comprise a minor component of the total biomass that is dominated by woody species. Because they are not structurally resistant to the stress of flood flows, seedling herbs are often uprooted and washed away if flooded too soon after germination. Herbaceous species tend to become established, therefore, on higher or protected portions of depositional bars or following the establishment of shrubs. Alternatively, if depositional bars are adjacent to established herbaceous communities, existing plants may be able to spread vegetatively onto the new bars and rapidly establish robust vegetation. There are many desirable species capable of vegetative spread. However, common reed and cattails are examples of nuisance species with horizontal underground stems that readily spread vegetatively. These are very aggressive species that can become nuisances along many waterways due to their dense growth and minimal wildlife habitat value.

Once established, the vegetation on depositional bars provides resistance to flood waters, slowing the velocity and increasing further deposition. Elevation of the bar surface increases as sediments accumulate around stems. All plants contribute to the resistance but woody perennials are most important. Deposition amounts eventually decrease as the bar becomes inundated less frequently. Decreased periods of inundation and reduced current velocities over the bar result in improved conditions for establishment of additional species. Further increases in elevation with sedimentation and organic matter accumulation allow continued decreases in period and frequency of inundation and additional species to survive. Surviving willow trees in interior portions of the diverse bottomland hardwood forests of the Southeast are evidence of historic river movements.

The degree to which a plant community will develop and change over time since establishment on a river bar depends on the area and behavior of the river. The lack of succession from colonizing species in the arid Southwest forms one end of a continuum. Floods that destroy riparian forests recur on roughly 100-year cycles in the Southwest; this may be adequate to retard succession. While floods may destroy some newly colonized areas, many are eventually abandoned by the river as it changes course. Although floods still occur in the abandoned areas, succession can proceed under less stressful conditions. Just as stable river channels have areas of erosion and deposition, stable riparian plant communities have areas of regeneration and loss. Ideally, as point bars are creating areas for colonization, eroding banks are removing equal areas of mature communities in a dynamic equilibrium.

Substrate and Structural Processes –. Stream channels and riparian zones provide substrates and structural architecture that provide diverse habitats for various biologic communities. Generally, the more complex the structure of riparian zones and stream systems is, the more diverse and healthy the biotic communities associated with these areas are. Complex habitats also naturally attenuate the effects of episodic natural disturbance processes and small-scale anthropogenic disturbances. Physical stream features such as bedform (i.e. riffles, pools and runs) provide habitat for aquatic organisms. Benthic macroinvertebrates, fish, and periphyton use these diverse habitats to varying degrees. Stream cross-sectional area constrictions and expansions change over the longitudinal distance of streams. This is caused by bedforms, and provides downstream and upstream hydraulic controls which form backwater pools or shallow, swift flows through riffles. Changes in bed elevations and slope also provide changes in bedforms, which increases habitat diversity. Local geology influences bedform development by providing natural grade control riffles at erosion resistant rock constrictions along the streams longitudinal profile. Similarly, soft geologic materials are eroded away easily, leading to the formation of deep scour pools. Channel point bars and island bars form as a result of erosion, deposition and transport processes. Bedform diversity, provides a diversity of habitat features and can potentially lead to a well-balanced aquatic community.

The composition of bed material comprises microhabitat features such as species between and beneath surface gravel or cobbles for benthic macroinvertebrates and small fish. A variety of benthic macroinvertebrates use this macrohabitat in different ways during different life stages. They may attach to substrate, burrow beneath it, feed from it etc. Small fish may hide among clustered gravel and cobbles, and mature fish use these substrate features as spawning habitat. In fine grained dominant streams where particles are more likely to be entrained and transported with greater frequency and duration, invertebrate entrainment and mortality may increase as a result of limited available near-surface refugia. Dramatic changes in the distribution and abundance of benthic macroinvertebrates results from a variety of flow events causing various degrees of bed mobility. Rapid recovery has been documented and attributed to drift from areas of mild disturbance. Gravel, cobble substrate microhabitat may also serve as refuge within areas of greater disturbance. The interstitial spaces and hydrodynamics of this microhabitat has a strong influence on the invertebrate community (Allan, 1995).

Unique Landscape Positional Characteristics and Processes – Stream systems and riparian zones occupy unique landscape positions which are critical to the survival of many plant and animal species. The longitudinal connectivity provided by these systems allows for biotic and abiotic energy pathways that link ecological processes and communities. They can also serve as important barriers, and buffers to plant and animal migration. Finally, these ecologically diverse areas often provide critical source and sink areas for maintaining population equilibrium of some plant and animal species, especially during large-scale disturbances that affect large portions of habitat.

Chemical and Biological Processes

Riparian vegetation plays a vital role in the water quality functions of riverine systems. Due to their landscape position, riparian areas intercept overland and ground water flows from adjacent uplands as well as overbank flow from rivers. They are buffers where materials and energy from a broad areas and diffuse sources converge. Floodplains control large exchanges of sediments, organic matter, and nutrients among these ecosystems.

The quality of water flowing through riparian areas is changed by the contact with soils and vegetation. There is a flux of material that often results in improved water quality, but the pathways along which materials move in riparian ecosystems are complex and highly interrelated and thus difficult to quantify.

Water quality functions performed in riparian ecosystems are dominated by particulate removal because the hydrology is dominated by surface flow and erosion is a natural source of particulates. Riparian corridors differ in their particle retention effectiveness, depending largely on roughness and the capability to trap materials. Plant stems, woody debris, root mounds from fallen trees, and leaf litter are the primary features the contribute to ground surface roughness in riparian areas. Vegetative cover in riparian areas reduces sediment inputs into streams by reducing potential soil erosion. As organic and mineral sediments are trapped, a great deal of dissolved materials in surface water can also be removed from the water column by adsorption to the particles. In addition to trapping sediments, plants also reduce concentrations of dissolved materials in surface and subsurface water by taking up nutrients and incorporating them into plant matter.

Dissolved materials such as nutrients and metals are removed from surface and subsurface water by several mechanisms. The most effective removal mechanism, particularly for phosphorus, is adsorption to mineral and organic particulates. The particles fall out of suspension and become buried, removing the materials from further cycling. Some nutrients such as nitrogen are lost to the atmosphere as gases released from anaerobic microbial processes in wetlands. Plants contribute to these mechanisms and also take up nutrients that become incorporated into leaves, stems, and roots.

Stream and stream corridors provide habitat for supporting the development and interaction of a variety of aquatic and terrestrial species. The dynamic interaction of these species supported by stream and stream habitats form populations of individual species into communities of diverse organisms. Stream and stream corridors provide nesting, resting and rearing habitat, supporting reproduction in aquatic and terrestrial organisms. Stream and stream corridors provide migration and overwintering corridors for aquatic and terrestrial species.

A diverse biologic community requires a balance of primary producers (autotrophs) and consumers/decomposers (heterotrophs). Predator, prey interrelationships and interactions are a key component of trophic complexity.

Stream corridors provide habitat which includes providing the necessary staples for life. Organisms grow over their life spans by conducting such processes as respiration and photosynthesis as a result of these staples being provided by streams. This function is a measure of a stream's ability to promote growth. These processes facilitate biomass production (organism growth). These processes occur in all organisms including vegetation, algae, bacteria, fungi, protists, invertebrates and vertebrates.

Impacts from Stabilization Measures

The practice of stabilizing streambanks affects many of the structural characteristics and functions of a stream. In point of fact, the basic purpose of any stabilization project is to interrupt erosion processes where they are deemed to conflict with social needs. In so doing, they interrupt or affect other processes and alter the physical environment. Because of the strong interrelation among the structural components and functions of a stream/riparian system, a number of secondary and tertiary impacts are associated with bank stabilization measures.

This is not to say that bank stabilization is "bad". Knowledge of the direct and ancillary impacts of stabilization can be used, for example, to select a measure and develop a design that restores or enhances the structure or function of a degraded ecosystem. Furthermore, few alterations to the structure or function of the environment are universally adverse or universally beneficial. Most benefit some components of the ecosystem at the expense of others.

For the purpose of this paper, the term "impact" is used to denote a measurable change, without regard for the significance or value of the change. These changes or impacts are, by nature, very site-dependent, so the generalizations provided herein will inevitably run contrary to observations in some cases. Factors that influence the nature of impacts are too numerous to mention, but in addition to those associated with the stabilization measures themselves, the nature and extent (spatial and temporal) of impacts will be influenced by:

- Local geology
- Climate
- Physical characteristics of the stream
- Physical characteristics of the riparian zone
- System stability
- Watershed and adjacent land use
- Proximity to control features (bridges, bedrock, etc.,)
- Construction practice
- Timing

With the above cautions in mind, the following sections present an overview of likely impacts from common bank stabilization practices. These are based on the review of the materials summarized in the attached bibliography, along with hundreds of other written works reviewed by the author over the years, and the experiences of the author in research, design, construction, and monitoring literally thousands of bank stabilization structures.

The scope of this effort limits the focus to a few specific structural characteristics and processes. The requested impact assessment includes a review of:

- Impacts on water surface elevations.
- Impacts on velocities, including secondary velocities.
- Impacts on erosion/scour and deposition.
- Impacts on sediment transport through the design reach.
- Length of the river that is impacted by the specific structure type.

Impacts on water surface elevations

Stabilization practices can alter water surface elevations in one of two ways: 1) by changing the resistance characteristics (either form or friction) of the reach, or 2) by altering the channel geometry (slope or cross section). These changes can be direct (such as the addition of a weir that changes the channel slope), or indirect (structures may cause a sorting of bed materials, resulting in a coarser surface fraction with higher resistance). In addition to the type of stabilization measure, the materials used and the geometry and location of the measures are the primary determinants of the extent of impacts. The impact, or change, must be related to some baseline condition. In this case, it is assumed to be the immediate pre-project condition, not some former "stable" condition. Impacts to water surface elevations are seldom static. Channels tend to adjust their bed elevations to compensate for changes in water surface, and the resistance characteristics of most stabilization measures change as they mature (vegetation growth is the primary factor).

Table 4. Impacts on Water Surface Elevations

Category	*Impacts*
General	No generalization can be made regarding the impacts of bank stabilization on water surface elevations.
Armor Techniques	Armoring techniques in general have no local or cumulative effect upon water surface elevations beyond the influence of the change in resistance. Exceptions occur when the measure requires an alteration to the channel cross section that results in an expansion or contraction of the cross section area. Impacts from resistance or cross section changes can be readily quantified through the application of the de Saint Venant Equations and resistance compositing techniques. Expansions and contractions of less than 10 percent generally result in negligible impacts. Impacts from changes to resistance are greatest for streams with a low width/depth ratio and depend upon the magnitude and length of the change. Measures with potential to increase water surface elevation: - Any bioengineering technique or other method that employs dense woody vegetation Measures with potential to decrease water surface elevation: - Bulkheads, gabions, and other vertical architecture structures - Any structure that uses concrete or other smooth finishes
Deflection Techniques	Deflectors create form roughness and reduce the cross sectional area of the channel, so they have the potential to increase water surface elevations and frequently do so. They also commonly generate scour and deepen the unprotected portion of the channel, which has the effect of offsetting the cross sectional reductions. Unfortunately, techniques to quantify these impacts are generally lacking. Furthermore, the impacts are highly dependent upon the flow condition, character of the channel, and geometry of the deflector, so empiricism is of limited use in evaluating impacts. Impacts depend also on flow magnitude, and diminish with increasing depth of flow over the top of the structure. Measures with potential to increase water surface elevation: - Any deflector that extends more that 15 percent across the channel or occupies more than 10 percent of the cross section area. Measures with potential to decrease water surface elevation: - Closely-spaced, low-profile structures that induce scour
Slope Stabilization Techniques	Slope stabilization techniques in general have no local or cumulative effect upon water surface elevations beyond the influence of the change in resistance. Exceptions occur when the measure requires an alteration to the channel cross section that results in an expansion or contraction of the cross section area. Impacts from resistance or cross section changes can be readily quantified through the application of the de Saint Venant Equations and resistance compositing techniques. Expansions and contractions of less than 10 percent generally result in negligible impacts. Impacts from

	changes to resistance are greatest for streams with a low width/depth ratio and depend upon the magnitude and length of the change. Measures with potential to increase water surface elevation: - Any bioengineering technique or other method that employs dense woody vegetation Measures with potential to decrease water surface elevation: - Bins, crib walls, and other vertical architecture structures
Energy Reduction Techniques	Energy reduction techniques are measures that reduce kinetic energy. In general, this kinetic energy is converted to potential energy in the form of increased water surface elevation. Channel blocks and grade control structures also modify the slope of the channel, further raising water levels. Methods to quantify impacts to water surface elevations are straight-forward, and generally consist of backwater analyses. An exception is the impact of vanes, which have not been adequately studied for this impact. Clearing and snagging reduces local turbulent energy and removes form roughnes from the channel, so it is a different form of energy reduction and can lower water surface elevations. Measures with potential to increase water surface elevation: - Grade control, channel blocks and (to a lesser extent) vanes Measures with potential to decrease water surface elevation: - Clearing and snagging of large woody debris

Impacts on velocities, including secondary velocities

Bank stabilization measures can have a number of impacts upon velocities, and the impacts from a single structure can vary spatially. For example, a structure that causes a constriction in the channel cross section will generally increase local velocities, but the backwater effects will cause upstream velocities to decrease. Within a given cross section, a structure can have no effect on the average cross-sectional velocity, but will cause a redistribution of the velocities (higher in the zone adjacent the structure and lower elsewhere in the section, for example). In addition to the stream-wise velocity, stabilization measures can increase or decrease turbulent velocities and secondary current velocities. Variables that influence the impact of stabilization measures on velocity include 1) the materials (which affect resistance and turbulence), 2) structure geometry and location (which affect the slope, degree of expansion or contraction, flow convergence or separation, and influence upon secondary currents), and 3) structure type. Impacts to velocity tend to be localized, and only extend far beyond the project reach when the stabilization measure induces backwater conditions.

Table 5. Impacts on Velocities

Category	*Impacts*
General	No generalization can be made regarding the impacts of bank stabilization on velocities.
Armor Techniques	Armoring techniques in general have no local or cumulative effect upon velocities beyond the influence of the change in resistance. Exceptions

occur when the measure requires an alteration to the channel cross section that results in an expansion or contraction of the cross section area (contractions cause an increase in velocity, expansions a decrease). Impacts from resistance or cross section changes can be quantified with one-dimensional backwater models (for average velocity), or two-dimensional hydraulic models (for velocity variation across a section). Impacts to the vertical velocity profile can also be quantified by assuming a logarithmic velocity profile, a resistance coefficient, and using a known water surface elevation and mean velocity. Average channel velocities tend to be insensitive to armoring of the banks. Local velocity (within a few feet) tends to increase for smooth surfaces and decrease for rough surfaces (such as vegetation). Armor materials frequently increase local turbulence, but have little impact upon secondary currents.

Measures with potential to increase velocity:
- Any structure that uses "smooth" materials or constricts the channel

Measures with potential to decrease velocity:
- Any bioengineering technique or other method that employs dense woody vegetation

Deflection Techniques

Deflectors reduce the cross sectional area of the channel, causing a constriction, so they tend to both mean cross-section and local velocities. They also commonly disrupt secondary currents, generate eddies, and increase turbulence. Unfortunately, techniques to quantify these impacts are generally lacking. Furthermore, the impacts are highly dependent upon the flow condition, character of the channel, and geometry of the deflector, so empiricism is of limited use in evaluating impacts. Impacts depend also on flow magnitude, and vary with varying depth of flow over the top of the structure. Impacts to velocity from deflectors tend to be localized, but these structures create the most dynamic and diverse velocity fields of any stabilization technique.

Slope Stabilization Techniques

Slope stabilization techniques effect velocities only slightly, due to changes in resistance or alteration to the channel cross section area (contractions cause an increase in velocity, expansions a decrease). Impacts can be quantified with the same means characterized for armor techniques. Average channel velocities tend to be insensitive to slope stabilization, but local velocity (within a few feet) tends to increase for smooth surfaces and decrease for rough surfaces (such as vegetation). Slope stabilization can increase local turbulence, but has little impact upon secondary currents.

Measures with potential to increase velocity:
- Any structure that uses "smooth" materials or constricts the channel

Measures with potential to decrease velocity:
- Any bioengineering technique or other method that employs dense woody vegetation

Energy Reduction Techniques

Energy reduction techniques are measures that reduce kinetic energy (which is proportional to the velocity squared), so reductions in velocity are the

	intent of these measures. Channel blocks and grade control structures reduce velocity for as far upstream as the backwater conditions persist, and completely disrupt secondary currents except when overtopped by more that three - five times the height of the structure. Clearing and snagging reduces turbulent velocity only, and mean channel velocity generally increases slightly. Removal of debris obstructions can also restore secondary currents. Vanes are intended to reduce secondary velocities, which has the effect of increasing the local cross-section average velocity. Methods to quantify impacts to velocity from channel blocks and grade control measures are straight-forward, and generally consist of backwater analyses. Quantification of the impacts to velocity from vanes and clearing and snagging have not been adequately studied for this impact. Measures with potential to increase velocity: - Clearing and snagging (though they reduce turbulence) and vanes (though these reduce secondary velocities) Measures with potential to decrease velocity: - Grade control and channel block structures

Impacts on erosion, scour, and deposition

All stabilization structures and measures impact sedimentation processes. At a minimum, they reduce or eliminate sediment yield to a system from the bank they are intended to stabilize. They also tend to generate local scour, usually at the toe of the stabilized bank or immediately downstream of the stabilization measure. Measures that reduce local transport capacity tend to induce sediment deposition in those areas. Rates of sediment sorting, both from the streambed and from the water column tend to increase in stabilized areas. The primary variables that influence sedimentation processes are sediment yield, sediment characteristics, and the impacts of the stabilization measure upon flow parameters, particularly velocity, stream power, and shear stress. Algorithms exist for the computation of erosion, deposition, and scour, but these are often inaccurate and of limited value in assessing the true impacts and localized nature of these processes associated with bank stabilization.

Table 6. Impacts on Erosion and Deposition

Category	***Impacts***
General	All bank stabilization measures at least temporarily change sediment yield characteristics of a channel. Most cause local scour and many induce sediment deposition. These impacts tend to be temporary, though their results may persist for long periods of time, particularly in streams with armored beds and few tributaries.
Armor Techniques	Armoring techniques generally reduce local bank erosion, but induce local scour. Scour generally occurs at the toe of the armor structure, and extends riverward about two – three times the scour depth. Algorithms to compute scour depths are notoriously poor, but provide some means of estimating the magnitude of the scour depth. Armor techniques that utilize materials with high resistance values can also induce local sediment deposition – usually on and within the armor material.

Deflection Techniques

Flow deflection structures alter the channel geometry, create flow blockages, and generate form roughness. Consequently, they tend to significantly alter the flow field. This, in turn, generates zones where both scour and deposition occur within relatively small areas and in close proximity to each other. Scour holes nearly always form off the ends of the structures, but may also occur on the face of the structure if it is oriented perpendicular to the flow or angled downstream. Deflection structures usually establish an eddy on their downstream side and, if strong enough, may create some scour in concentrated areas. More often, however, the zone immediately downstream of a deflection structure is subject to sediment deposition as the flow velocity and shear stress decrease in these zones. The overall impact on scour, deposition, and sediment movement varies greatly with the channel type, planform, bed material characteristics, nature of transported sediments and the location, geometry, and orientation of the deflectors. Scour and deposition increase with structure length, height, and angle from the upstream bank and with increasing values of the ratio of the stream width to the radius of curvature of the bend, though there are limits to each of these values beyond which impacts tend to diminish.

Slope Stabilization Techniques

Slope stabilization techniques generally reduce local bank erosion, but may also increase local scour. Scour generally occurs at the toe of the structure, and extends riverward about two – three times the scour depth. Algorithms to compute scour depths are notoriously poor, but provide some means of estimating the magnitude of the scour depth. Techniques that utilize materials with high resistance values can also induce local sediment deposition – usually on the slope itself. Regrading an eroding bank can modify the strength of secondary currents in a bendway – affecting the growth and development of point bars, modifying thalweg depths, and altering secondary transport of sediments.

Energy Reduction Techniques

The techniques used to reduce energy within a stream have a significant impact on sediment transport, scour and deposition. Grade control measures create backwater in upstream reaches – increasing depth and reducing velocity. These upstream impacts reduce sediment transport capacity and stream reaches immediately upstream of these structures often have deposited sediments on the bed that are finer than those found in adjacent reaches. The extent of the upstream impacts depend upon the height of the structure and the streambed slope. Downstream of the structure, a scour pool is generally formed with a bed material composition more coarse than adjacent reaches. The size of the pool is dependant on the relative height of the structure and its geometric configuration. Secondary channels blocked with chute closures may become backwater zones or wetlands – trapping fine sediments during flood events. Flows in the main channel may deepen, with a corresponding coarsening of the bed material and corresponding increase in sediment transport. Vanes have similar effects to those described above for deflection structures, but the magnitude of scour and deposition is diminished compared to conventional deflection structures. Snagging and clearing reduce local turbulence, decrease local scour and deposition, but increase overall sediment transport capacity for a stream reach.

Impacts on sediment transport through the design reach

Many stabilization measures temporarily affect sediment transport through a design reach. Some are intended to promote deposition or scour, and all are intended to reduce sediment yield from an eroding bank. So virtually all stabilization measures affect sediment transport capacity, but they may or may not affect actual transport, which is determined also by upstream sediment yield in areas beyond the influence of the stabilization measures. Streams generally adjust to the changes imparted by stabilization and reestablish sediment continuity through a design reach in time. A number of analytical tools exist with which estimates of sediment transport capacity can be made. Determination of actual transport requires either direct measurement, or capacity analyses coupled with knowledge of sediment yield characteristics.

Table 7. Impacts on Sediment Transport

Category	*Impacts*
General	No generalization can be made regarding the impacts of bank stabilization on sediment transport through a project reach except to note that, given sufficient time, streams generally reestablish sediment continuity through a reach modified by stabilization measures.
Armor Techniques	Armoring techniques in general have only limited effects upon sediment transport beyond the influence of the change in resistance and the reduction of sediment yield from the eroding bank. Any impacts tend to be short-term, and the channel will reestablish continuity through the reach through slope adjustments and sorting processes.
Deflection Techniques	Deflection techniques in general have only limited effects upon sediment transport beyond the influence of the change in resistance, alterations to secondary currents and turbulence, and the reduction of sediment yield from the eroding bank. Like armoring techniques, impacts tend to be short-term (especially in braided systems), and the channel will reestablish continuity through the reach through slope adjustments and sorting processes.
Slope Stabilization Techniques	Slope stabilization techniques in general have only limited effects upon sediment transport beyond the influence of the change in resistance and the reduction of sediment yield from the eroding bank. Any impacts tend to be short-term, and the channel will reestablish continuity through the reach through slope adjustments and sorting processes.
Energy Reduction Techniques	Energy reduction techniques generally reduce velocity, shear stress and stream power - three surrogate measures for sediment transport. Channel blocks and grade control structures reduce sediment transport through a reach and induce local sediment deposition. In time, continuity may be reestablished, but this depends upon the sediment yield and the characteristics of the stream and structure. Clearing and snagging reduces turbulent velocity only, and mean channel velocity, power, and shear stress generally increases slightly. Removal of debris obstructions can thus increase sediment transport capacity through a reach. Vanes are intended to reduce secondary velocities, which has the effect of reducing secondary

	sediment transport, but this is generally a minor transport component and is usually offset by an increase in longitudinal transport. Measures that don't affect or increase sediment transport: - Clearing and snagging and vanes Measures with potential to decrease sediment transport capacity: - Grade control and channel block structures

Length of the river that is impacted by the specific structure type

Slope of the channel is the primary determinant in defining the length of river that is impacted by stabilization measures. Techniques that realign the channel or adjust the planform tend also to have impacts that extend further up- or downstream than techniques that are employed within the existing channel geometry. Streams with highly erodible beds and banks are most sensitive to change, and impacts on these systems are more widely distributed than for relatively erosion-resistant streams. The extent of impacts can be limited by geologic or anthropogenic controls. In general, however, impacts from stabilization measures tend to be localized unless they modify the energy gradient or significantly alter the cross section.

Table 8. Length of River Impacted

Category	*Impacts*
General	No generalization can be made regarding the lengths of river that bank stabilization impacts except to note that the length is very closely related to the channel slope and bed material composition. Impact lengths are greatest over low-gradient streams and streams with sand beds. Impact lengths are least on steep gradient streams, streams with erosion-resistant bed materials, and streams with controls.
Armor Techniques	Armoring techniques seldom affect the channel more than a few feet up- or downstream of the project extents. Erosion may persist downstream of an improperly terminated armor structure, and the local scour and increased local velocities can accelerate and exacerbate this erosion. But it would be very uncommon to identify an armor structure that impacts areas of the channel further than ½ a meander wavelength up- or downstream (for a meandering stream) or more than two channel widths up- or downstream (for a braided stream). Sediment transport models could be applied to evaluate up- and downstream extents of impacts as they relate to hydraulic or sediment transport variables. No models exist for the prediction or quantification of impacts to up- or downstream bank erosion. Measures with potential to affect areas outside the zones defined above: - Armor devices that constrict the channel to the extent that contraction scour occurs completely across the section. This could induce a nick point that travels further upstream. - Any armor that protects a bank that was a significant sediment source for the channel could result in increased or accelerated bed or bank erosion downstream.

Deflection Techniques	Deflectors create a greater number of and more substantial local impacts than do armoring techniques. And the potential for cumulative impacts and impacts of greater spatial extent is higher from some of these measures than for armoring techniques. Impacts from deflectors that significantly alter flow fields generally persist for one bendway (½ a meander wavelength) up- or downstream for a meandering stream) or about four channel widths downstream and one or two widths upstream for a braided stream. Though hydraulic and sediment transport modeling could be applied to assess the sensitivity of a system to up- and downstream perturbations from deflectors, actual quantification of the impacts would be highly suspect in terms of accuracy. In general, the greater the impact to the flow field, the further up- and downstream impacts can be expected.
Slope Stabilization Techniques	Slope stabilization techniques seldom affect the channel more than a few feet up- or downstream of the project extents. Erosion may persist downstream of an improperly terminated structure, and the local scour and increased local velocities can accelerate and exacerbate this erosion. But it would be very uncommon to identify a structure that impacts areas of the channel further than ½ a meander wavelength up- or downstream (for a meandering stream) or more than two channel widths up- or downstream (for a braided stream). Measures with potential to affect areas outside the zones defined above: - Measures that constrict the channel to the extent that contraction scour occurs completely across the section. This could induce a nick point that travels further upstream. - Any stabilization of a bank that was a significant sediment source for the channel could result in increased or accelerated bed or bank erosion downstream.
Energy Reduction Techniques	Energy reduction techniques tend to have the greatest spatial extent of all stabilization measures. Channel blocks can raise upstream water surface elevations and can dewater the entire downstream reach. Grade control structures also modify the slope of the channel, raising water levels and decreasing velocity and sediment transport upstream. They can also trap sediments and induce downstream degradation. Impacts from clearing and snagging operations tend to be limited to the local area and a distance upstream to where the backwater reductions no longer persist. They seldom affect downstream reaches beyond ½ a meander wavelength up- or downstream (for a meandering stream) or more than two channel widths up- or downstream (for a braided stream). Impacts from vanes are comparable to those described above for deflector structures. Methods to quantify impacts to water surface elevations, velocities and sediment transport in up- and downstream reaches are straight forward for energy reduction measures, and generally consist of backwater and sediment transport analyses. An exception is the impact of vanes, which have not been adequately studied for this impact.

Summary

The practice of stabilizing streambanks affects many of the structural characteristics and functions of a stream. In point of fact, the basic purpose of any stabilization project is to interrupt erosion processes where they are deemed to conflict with social needs. In so doing, they interrupt or affect other processes and alter the physical environment. Because of the strong interrelation among the structural components and functions of a stream/riparian system, a number of secondary and tertiary impacts are associated with bank stabilization measures. These impacts can often be viewed as either adverse of beneficial, depending upon the perspective of the individual assigning values to the system.

This report focuses on the affects of stabilization measures upon measurable aspects of a stream's structure and function. The extent to which these impacts are viewed as adverse or beneficial are left to the reader. The prevailing philosophy in ecosystem management is that physical alterations of the structure and character of an ecosystem are most significant if they also impact process-based functions. For this reason, each of the stabilization measures described in this report is described in terms of its influence upon processes.

Distinctions among various bank stabilization measures can be made on the basis of 1) how they work, 2) the materials used, 3) their geometry and position in the landscape, and (in some cases) 4) the character of stream system to which they are applied. Stabilization measures can be generally grouped into four broad categories based upon how they work or function:

- Structures whose primary function is to prevent erosion by armoring the eroding bank
- Structures that prevent erosion by deflecting the current away from the bank
- Methods that reduce the erosive capability within the channel
- Geotechnical methods of slope stabilization

The geometry and position of a structure can influence its function and impact. The nature and extent of impact depends also upon the character of the stream and riparian system. The various materials, design, and construction methods used for a particular stabilization measure can result in a wide range of positive and adverse environmental impacts. Through proper planning and design, negative impacts can be minimized and positive impacts maximized. Factors that influence the nature of impacts are too numerous to mention, but in addition to those associated with the stabilization measures themselves, the nature and extent (spatial and temporal) of impacts will be influenced by:

- Local geology
- Climate
- Physical characteristics of the stream
- Physical characteristics of the riparian zone
- System stability
- Watershed and adjacent land use
- Proximity to control features (bridges, bedrock, etc.,)
- Construction practice
- Timing

Tables 4 through 8 in the report outline the anticipated impacts from bank stabilization activities in the four categories outlined above.

Annotated Bibliography

Abam, T. K. S. (1995) "Factors affecting performance of permeable groins in channel bank erosion control," Environmental Geology, 26, 53-56.

(The factors affecting the performance of permeable groins are investigated by an analytical approach supplemented with field observation. The results obtained show that depth of the groin is the most critical factor that determines groin stability. The depth is followed by flow velocity and discharge, unit weight of water, unit weight of soil, and cohesion.)

Abbe, T. B., and Montgomery D. R. (1996) "Large woody debris jams, channel hydraulics and habitat formation in larger rivers," Regulated Rivers: Research & Management 12, 201-221.

(Calculations, field observations and historical evidence show that accumulation of large woody debris (LWD) can form stable structures controlling local channel hydraulics and providing refugia for riparian forest development over decades and possibly centuries. Individual jams can be remarkably stable, providing long-term bank protection that creates local refugia for mature forest patches within a valley floor environment characterized by rapid channel migration and frequent disturbance. Processes controlling the formation, structure and stability of naturally occurring LWD jams are fundamental to the dynamics of forested river ecosystems and provide insights into the design of both habitat restoration structures and ecosystem-based watershed management.)

Abbe, T. B., Montgomery, D. R., and Petroff, C. (1997) "Design of stable in-channel wood debris structures for bank protection and habitat restoration: an example from the Cowlitz River, WA," Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 809-815.

(After appropriate analysis to determine the appropriate size, position, frequency, and type of wood debris (WD), engineered log jams (ELJs) can restore riverine habitat and in some situations provide effective bank protection. Research has documented that stable WD jams can occur throughout a drainage basin. Even in large alluvial channels that migrate at rates of 10 m/yr, jams can persist for centuries. This experimental project demonstrates that ELJs can meet erosion control objectives while restoring riverine habitat in large alluvial rivers.)

Abt, S. R., Johnson, T. L., Thornton, C. I., and Trabant, S. C. (1998) "Riprap sizing at toe of embankment slopes," Journal of Hydraulic Engineering, 124-7, 672-677.

(A pilot study was conducted to evaluate existing rock-sizing techniques for stabilizing transition toes of embankments. The results indicate that an embankment toe can be stabilized with a smaller median stone size than previously anticipated.)

Abt, S.R., Watson, C.C., Fischenich, J.C., and Peters, M.R. 1995. "Bank Stabilization and

Habitat Aspects of Low-Flow Channels," Land & Water, The Journal of the International Erosion Control Association, January/February 1995, pp 10-13.

(Presents a bivariate habitat assessment technique and its application to three stream systems.)

Fischenich, J.C., and Allen, H.H., 1999. Coir Geotechnical Roll and Wetland Plants for Streambank Erosion Control, TN SR-99-4, USACE WES, Vicksburg, MS. April, 1999.

(The coir geotextile roll (CGR) is a sausage-like roll of nonwoven fibers made from coconut husks bound within a polyethylene or coir woven mesh rope. The CGR incorporates wetland plants (usually as rooted sprigs or cuttings) whose roots become interlocked with the CGR fibers. The CGR with its plants is used along the face of an eroded streambank and acts principally to armor the bank, though it can also be configured to act as a current deflector. The CGR has the potential to accumulate sediment and, together with the plants, develop a strong network of interlocking roots and plant stems. The CGR concomitantly benefits fisheries habitat by providing both food and cover due to its proximity to the edge of the stream. When rocks are used at the base of the CGR, the rocks and CGR act together to produce substrates suited for an array of aquatic organisms. Some of these organisms adapt to living on and within the rocks, and some attach themselves to the plants, which they may also use for food. The CGR can improve water quality and aesthetics. Plants within the CGR, especially emergent aquatic plants, such as bulrush (*Scirpus spp*.) and sedges (*Carex spp.*), will assimilate contaminants within the water column, though the total mass uptake may be small. The CGR can also improve non-point pollution control by intercepting sediment and associated pollutants coming into the stream from overbank areas. Plants within the CGR can be somewhat tailored to provide color, texture, and other attributes that add a pleasant, landscaped appearance. Such plants include blueflag (*Iris versicolor,* a wetland wild iris with a blue flower), pickerelweed (*Pontedaria cordata),* monkey flower (*Mimulus ringens),* and cardinal flower (*Lobelia cardinalis)*.)

Allen, H. H., and Leech, J. R. (1997) "Bioengineering approaches to streambank stabilization - Do they work?"

(Some of the bioengineering techniques installed include root wads, vegetative geogrids, dormant willow posts, log revetment and coir fascine combinations, and emergent aquatic and woody vegetation in conjunction with coir fascines and mats. All streams were subjected to flooding conditions. Results indicate that certain bioengineering treatment can succeed in velocities up to 10 feet per second if they are properly designed and installed with scour and flanking protection at the toe and the upper and lower ends.)

Benke, A. C., Henry, R. L., III, Gilespie, D. M., and Hunter, R. J. (1985) "Importance of snag habitat for animal production in southeastern streams," Fisheries, 10-5, 8-13.

(The major objective of this study was to assess the relative importance of the snag habitat as a site of invertebrate production in comparison to benthic habitats. Management practices involving wood removal from rivers could be devastating to the invertebrate community and consequently to the several fish species that depend upon them. The return of woody material to previously snagged streams may help restore their natural levels of animal productivity.)

Bingham, C. R. (1982) "Benthic macroinvertebrate study of a stone dike," Environmental & Water Quality Operational Studies Information Exchange Bulletin, E-82-4, Environmental Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

(The stone dikes of the lower Mississippi River have been shown to be high-quality environment for macroinvertebrates requiring a hard substrate. Average macroinvertebrate density of the stone dike substrate was 102,485 organisms/m^2 as opposed to an average of 865 organisms/m^2 from natural substrates.)

Binns, N. A. (1986) Stabilizing Eroding Stream Banks in Wyoming, Wyoming Game and Fish Department, Cheyenne, Wyoming.

(This guidebook summarizes some key principles of river mechanics and details bank stabilization methods used on Wyoming streams. The structures and techniques have been successfully used to stabilize eroding banks on a wide variety of Wyoming streams.)

Bodie, R. (1998) "Waverly Park Drainage Channel Improvements," Land and Water, 42-6, 25.

(The Waverly Park channel, a typical vegetated drainage channel, had exceeded its flow capacity. The problem was solved with an erosion control system of modular concrete walls and articulating concrete blocks with a cost savings of 10 to 20 percent less than the cost of conventional alternatives.)

Boelman, S. F., Stein, O. R., and Seal, R. (1997) "Hydraulic and geomorphic assessment of in-stream boulder clusters," Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 684-688.

(Much of the St. Regis River in western Montana has been relocated and/or channelized. Fishery improvement structures were installed in several miles of river reach between 1972 and 1982. Biological assessment in 1976 and 1982 concluded that random boulder clusters and associated scour pools were effective mitigation for loss of trout habitat.)

Boeters, R. E. A. M., Verheij, H. J., and van der Wal, M. (1991) "Environmental-friendly bank protections," Environmental Hydraulics, Lee & Cheung (eds), Balkema, Rottendam, pp. 1437-1442.

(With increased public awareness, more environmental-friendly solutions have been leading to greater attention for design criteria for protective structures allowing the presence of vegetation. This paper looks at other studies dealing with the current environmental bank protection research in the Netherlands.)

Burke, T. D., and Robinson, J. W. (1979) River structure modifications to provide habitat diversity," A National Workshop on Mitigating Losses of Fish and Wildlife Habitats, General Technical Report RM-65, Colorado State University, pp. 556-561.

(Discussion of beneficial and detrimental effects of Missouri River Bank Stabilization and Navigation Project and description of structure modifications used to improve fish and wildlife habitats, flood carrying capacity, and for controlling accretions. Methods include notched, rootless, and low elevation structures.)

Burroughs, M. A. (1979) "Gabions: economical, environmentally compatible bank control," Civil Engineering, January, 58-61.

(Gabions are wire baskets, filled with rock and wired together to form a wall or lining. As an erosion control or channel-lining system, gabions are economical, permeable and flexible. In this article, an overview of an erosion control project is briefly discussed.)

Cabalka, D., and Trotti, J. (1996) "The Grass-Lined Channel," Erosion Control, 3-6, 42-50.

(Grass-lined channels (GLC's) provide a welcome alternative to conventional riprap and cast-in-place concrete linings. GLC's employ vegetation alone or in concert with other materials to cover the subgrade defining the shape of the channel.)

Colorado Erosion Control Manual (1992) U. S. Army Corps of Engineer District, Omaha and the State of Colorado (Colorado Water Conservation Board).

This manual provides the necessary information for a local or regional planner or engineer to effectively address streambank erosion, either through design of remedial measures or by providing insight into the selection and oversight of a company consultant. In addition, the processes of evaluating an erosion problem, selecting appropriate solutions, designing structures and performing monitoring and maintenance are described in this manual.)

Connelly, R. R. II, and Lin S. S. (1996) "Dam alteration issues and concepts regarding sediment control," Erosion Control, 3-5, 40-47.

(Virginia's erosion and sediment control regulations established in 1973 are intended to prevent the unreasonable degradation of downstream properties, stream channels, and other natural resources of the state as a result of land-disturbing activities and to minimize sediment impacts on the environment.)

Dardeau, E.A., and Fischenich, J.C. 1995. "Environmental Mitigation and the Upper Yazoo Projects", Environmental Geology, Vol. 25, No. 1, pp 55-64.

(Presents a new algorithm to optimize designs for flood protection works so as to minimize and mitigate environmental impacts for aquatic, terrestrial, wetland, and waterfowl habitats. Includes modifications to levee and borrow pit designs, instream and streambank habitat features, and land management practices for riparian and wetland systems. Focuses on the application of the methodology to the Upper Yazoo Projects, wherein mitigation costs were reduced from $31M to $16M by modifying the project design.)

Derrick, D. L. (1997) "Harland Creek bank stabilization demonstration project," Land and Water, 41-5, 22-25.

(Bendway weir, willow post, and longitudinal peaked stone toe protection bank protection methodologies were successfully applied to 14 eroding bends of a stream. Results show satisfactory project performance, with most reaches appearing stable and maturing quickly.)

Field, J. J. (1997) "Channel modifications along an artificially constructed channel designed to provide salmon habitat," Proceedings of the Conference on

Management of Landscapes Disturbed by Channel Incision, 822-827.

(Channel modifications along an artificially relocated reach of Schell Creek near Ferndale, WA damaged 68 percent of the 59 habitat improvement structures placed in the channel. Damage resulted from channel aggradation, bed erosion, and bank scour. All of the damage occurred in the first year during three bankfull or near bankfull flows. Future attempts at stream location should allot time for the channel to reach a quasi-equilibrium condition before placing habitat structures in the channel. Evaluation of stream enhancement projects is critical if past mistakes are to be avoided in future projects.)

Fischenich, J.C., 1990. "Cumulative Impacts Analysis of a Midwest Fluvial System," Proceedings of the 1990 ASCE Hydraulic Engineering Conference, San Diego, CA.

(Summarizes an analysis of the cumulative impacts of bank stabilization activities along 314 miles of the Platte River in Nebraska. The study defines limits of bank stabilization actions before causing impacts to sediment transport, bed level, and water surface elevation.)

Fischenich, J. C. 1991. "In-Stream Fish Habitat Improvement Using Structural Measures: A Case Study on the South Platte River in Colorado". Proceedings of the ASCE 24th Annual Water Resources Conference, St. Paul, MN.

(Presents designs and analyses for eight streambank and instream erosion control measures and their impacts upon aquatic biota.)

Fischenich, J.C. 1994. "Design Criteria for In-Stream and Streambank Environmental Features.@ Proceedings of the 1994 ASCE National Conference on Hydraulic Engineering, Buffalo, NY

(Provides guidelines for the design of erosion control features so that environmental benefits and stability are optimized).

Fischenich, J.C., and Theriot, R., 1998. “Integrating New Technologies Into Stream Restoration,” Proceedings, Special Meeting of the Society of Ecological Engineering, Paris, France, August, 1998.

(Characterizes the state of knowledge in stream restoration, lists ongoing research efforts in the US, and identifies future research needs).

Fischenich, Craig J. and Allen, Hollis H., “Protocol for Design of Stream and Floodplain Restoration Projects,” Association of State Wetland Managers Wetlands ‘99” Conference, Annapolis, MD, October 25-27, 1999

(Proposes a means for evaluating an impacted stream system to ascertain the cause, and a sequence of efforts to establish the appropriate restoration strategy. Focuses on stream instabilities.)

Fischenich, J.C., and Morrow, J.V., Jr., 1999. Restoration Strategies to Reconnect Floodplains With Incised Channels. TN SR-99-9, USACE WES, Vicksburg, MS. April, 1999.

(This technical note describes two alternatives for the reestablishment of floodplain functions on incised streams. The first is to reestablish the hydrologic connection with the historic floodplain by raising the water or bed level on the incised stream. The second alternative is the construction of psuedo-floodplains within the incised channel margin.)

Fischenich, J.C., and Morrow, J.V., Jr., 1999. Streambank Habitat Enhancement With Large Woody Debris. TN SR-99-13, USACE WES, Vicksburg, MS. April, 1999.

(Naturally occurring large woody debris (LWD) (i.e., > 10 cm diameter and 2 m in length) is an important component of many lotic systems. It provides velocity refuge and overhead cover for fishes, substrate for aquatic invertebrates, and can be an important source of particulate organic matter adding to primary productivity of a stream. Large woody debris also plays a major role in stream channel morphology, contributing to formation of pool habitat, increasing meandering, and increasing sediment capacity. Large woody debris dissipates flow energy, resulting in improved fish migration and channel stability. It also provide basking and perching sites for reptiles and birds. Positive effects of LWD are well- documented in high-gradient streams, and recent studies show that LWD is an important habitat component of low- gradient streams with fine substrates. This paper discusses problems and techniques associated with placing LWD in stream habitats.)

Fischenich, J. C., and Seal, R., 1998. Design and Layout of Boulders for Instream Habitat, TN SR-98-11, USACE WES, Vicksburg, MS. April, 1998.

(Boulder clusters are groups of large rocks (>10 in. diameter) placed in a stream to improve habitat. Flow separation around the boulders leads to the formation of eddies or vortices in their wake. These vortices diffuse sunlight and create overhead cover for fish. They also generate scour that develops pockets of deeper water and associated coarse substrate that add to the physical diversity of a stream reach. Boulders and the turbulence and scour they create are among the types of habitat used by both juvenile and adult fish, particularly salmonids. Preferred summer microhabitat for juvenile salmonids consists of deep water in conjunction with submerged cover. This cover is used to elude predators. Adult fish also rest and hide in the scour pools. Spawning adults appear to select spawning sites based on the closeness of cover. Evaluations of fish habitat improvement projects have shown a high variability in the benefits of instream boulders. This variability is due to differences in fish seeding levels, species and ages of fish, season of year, the design of the project, time since implementation, and sampling method.)

Fischer, R.A., Martin, C.O., and Fischenich, J.C., "Improving Riparian Buffer Strips and Corridors for Water Quality and Wildlife," American Water Resources Association International Summer Specialty Conference, Portland, OR, August 27-30, 2000

(Provides a summary of the literature on the environmental benefits of riparian corridors and buffers. Proposes a set of riparian functions, then presents design guidelines relating buffer characteristics to desired functions.)

Freeman, G. E., and Fischenich, J.C. (2000). "Gabions for streambank erosion control," EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-22), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

(Gabions come in three basic forms, the gabion basket, gabion mattress, and sack gabion. All three types consist of wire mesh baskets filled with cobble or small boulder material. The fill normally consists of rock material but other materials such as bricks have been used to fill the baskets. The baskets are used to maintain stability and to protect streambanks and beds. The rocks contained within the gabions provide substrates for a wide variety of aquatic organisms. Organisms that have adapted to living on and within the rocks have an excellent home, but vegetation may be difficult to establish unless the voids in the rocks contained within the baskets are filled with soil. If large woody vegetation is allowed to grow in the gabions, there is a risk that the baskets will break when the large woody vegetation is uprooted or as the root and trunk systems grow. Thus, it is normally not acceptable to allow large woody vegetation to grow in the baskets. The possibility of damage must be weighed against the desirability of vegetation on the area protected by gabions and the stability of the large woody vegetation. If large woody vegetation is kept out of the baskets, grasses and other desirable vegetation types may be established and provide a more aesthetic and ecologically desirable project than gabions alone.)

Fripp, J., Fischenich, J.C., Martyn, M., 1999. "The Design and Function of Stone Weirs in Stream Restoration", <u>ASCE Int. Water Resources Engineering Conference</u>, Seattle, WA, August 8-11, 1999

(Provides design guidelines for low-head stone weir structures for use in concurrently stabilizing streams and generating aquatic habitat.)

Georgia Soil & Water conservation Commission (1994) <u>Guidelines for Streambank Restoration</u>

(This manual was published to help owners of streamside property understand how to prevent and correct simple streambank erosion problems utilizing live plant material, structural measures, or a combination of both. The techniques described in this manual are intended for small streams systems with uncomplicated erosion problems.)

Gippel, C. J., O'Neill, I. C., Finlayson, B. L., and Schnatz I. (1996) "Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers," <u>Regulated Rivers: Research & Management</u> 12, 223-236.

(The volume of large woody debris (LWD) in most of the world's lowland rivers has been depleted. However, the now recognized important environmental role of LWD in rivers and the movement towards rehabilitation of degraded riverine habitats demand more objective procedures for management of LWD in streams. This paper presents the results of laboratory and field hydraulic investigations relevant to the problem of managing debris in lowland rivers. The models of debris hydraulics presented, can be used to predict the effect of removing, lopping, rotating or re-introducing debris to rivers.)

Goff, K. (1999) "Designer Linings," <u>Erosion Control</u>, 6-5, 58-65.

(The indiscriminate use of riprap to prevent scour and erosion, the lining of once-vegetated riverbanks with concrete, and too many locks, levees, and dams are perceived by most to be

undesirable vestiges of past environmental folly. Therefore, it is time to reassess our traditional approaches to waterway stabilization and develop a systematic approach to the problem of streambank erosion. Combining armor-type protection with softer, bioengineered techniques is proving to be a viable approach to many embankment stabilization problems. In fact, the effectiveness of armoring techniques is improved when vegetation is included in stabilization projects.)

Goldsmith, W. (1999) "Practical bioengineering applications in watershed management," Watershed Management, July/August, 11-15.

(Successful restoration of a river environment depends on a broad understanding of conditions on site and throughout the watershed. Analysis of existing conditions should include the potential impacts of disturbance and stream modification, and an appreciation of historical changes in the land.)

Gore, J. A., and Shields, F. D., Jr. (1995) "Can large rivers be restored," BioScience, 45-3, 142-152.

(Although restoration of large rivers to a pristine condition is probably not practical, there is considerable potential for rehabilitation, that is, the partial restoration of riverine habitats and ecosystems. Renewal of physical and biological interactions between the main channel, backwaters, and floodplains is central to the rehabilitation of large rivers.)

Gore, J. A., and Hamilton, S. W. (1996) "Comparison of flow-related habitat evaluations downstream of low-head weirs on small and large fluvial ecosystems," Regulated Rivers: Research & Management, 12, 459-469.

(The focus of within-channel restoration is the placement and construction of instream habitat structures to enhance the capture of organic detritus and aufwuchs, as well as, colonization by macroinvertebrate and fish species. These instream structures also modify local hydraulic conditions to present preferred habitat to benthic invertebrates.)

Gorman, O. T., and Karr, J. R. (1978) "Habitat structure and stream fish communities," Ecology, 59-3, 507-515.

(Increasing community and habitat diversity followed stream-order gradients. Natural streams supported fish communities of high species diversity which were seasonally more stable than the lower-diversity communities of modified streams. After disturbances such as channelization, seasonal peaks in species diversity attain levels typical of undisturbed streams."

Grubbs, J., Sampson, B., Carroll, E., and Dovak, J. (1997) "Guidelines for stream and wetland protection in Kentucky," Kentucky Division of Water, Water Quality Certification Section.

(This manual introduces the reader to concepts of stream and wetland restoration by attempting to identify some approaches for restoring streams and mitigating wetlands so that water quality and aquatic life are not severely impacted. Principles of how streams behave, stream restoration, bank erosion, and how to prevent streambank erosion is covered.)

Haltiner, J. (1995) "Environmentally sensitive approaches to river channel management," River, Coastal and Shoreline Protection: Erosion Control Using

Riprap and Armourstone, John Wiley & Sons Ltd., 545-556.

(Traditional engineering approaches to river channel erosion and flood hazards have focused on single-purpose, structurally intensive solutions such monolithic riprap or concrete-lined channels, and drop structures. While often successful in reducing erosion, they provide little or no environmental, aesthetic or recreational value. However, biotechnical approaches integrating riprap or other structural measures with vegetation provide a range of bank and channel stabilization methods consistent with a multi-objective approach.)

Hemphill, C., Fischenich, J.C., Redigan, J., 1999. “Bioengineered Streambank Stabilization Methods to Reduce Costs and Improve Habitat”, ASCE Int. Water Resources Engineering Conference, Seattle, WA, August 8-11, 1999

(Describes the use of bioengineering techniques on the Sauquoit River in New York. Emphasizes the benefits of selected techniques verses conventional flood channel design and stabilization).

Henderson, J. E., and Shields, F. D., Jr. (1984) "Environmental features for streambank protection projects," Technical Report E-84-11, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

(This report provides guidance for incorporating environmental considerations into streambank protection projects. Each feature is discussed in terms of concept, the purpose or appropriate use of the feature, environmental considerations, limitations to use of the feature, performance history, and cost.)

Henderson, J. E. (1986) "Environmental designs for streambank protection projects," Water Resources Bulletin, 22-4, 549-558.

(Adverse environmental impacts have been minimized and enhancement of existing habitat and aesthetics have been achieved through the development of new, innovative designs or modifications to existing designs and through use of construction and maintenance practices that promote habitat and aesthetics. Use of vegetation for bank protection is most effective when used in combination with structural components.)

Henszey, R. J., Wesche, T. A., and Skinner, Q. D. (1989) "Evaluation of the state-of-the-art streambank stabilization," Wyoming Department of Environmental Quality, Cheyenne, WY.

(The purpose of this report was to assemble and review the current literature on streambank stabilization techniques, and to compile a state-of-the-art streambank stabilization bibliography. Classical treatments such as riprap, gabions, and tree revetments were included, but primary emphasis was on the characteristics and requirement of plant species suitable for bank revegetation in the semiarid western U. S.)

Hilderbrand, R. H., Lemly, A. D., Dolloff, C. A., and Harpster, K. L. (1996) "Effects of large woody debris placement on stream channels and benthic macroinvertebrates," Canadian Journal of Fisheries and Aquatic Science, 54, 931-939.

(Large woody debris (LWD) was added as an experimental stream restoration technique in two streams in southwest Virginia. Additions were designed to compare human judgement in log placements against a randomized design and an unmanipulated reach, and also to compare effectiveness in a low- and a high-gradient stream.)

Hoitsma, T. (1999) "Banking on bioengineering," Civil Engineering, 69-1, 60-62.

(Bioengineered fabric solutions to riverbank stabilization can preserve an area's natural habitat, improve aesthetics and eliminate expensive off-site mitigation. As an emerging field without performance standards or even agreed-upon design guidelines, the methods are proving themselves by withstanding high flood events on large rivers in difficult urban rural locations.)

House, R. A., and Boehne, P. L. (1986) "Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon," North American Journal of Fisheries Management, 6, 38-46.

(Differences between a young-alder stream section logged and cleared of large debris 20 years ago and a mature mixed-conifer section unlogged and containing large amounts of large woody debris was studied. Stream enhancement techniques were used to simulate large woody debris in the logged alder section to try to increase salmonid use. Large woody debris in the channel caused the development of secondary channels, meanders, pools, and undercut banks in the unlogged, mature-conifers, stream section. Salmonid biomass was significantly greater in the mature-conifer than the young-alder section prior to stream enhancement. After enhancement, no significant difference was found. The study revealed that structure is most likely a more important factor than shade in governing a stream's capacity for producing salmonids.)

Jackson, W. L., and Van Haveren, B. P. (1984) "Design for a stable channel in coarse alluvium for riparian zone restoration," Water Resources Bulletin, 20-5, 695-703.

(Geomorphic, hydraulic and hydrologic principles are applied in the design of a stable stream channel for a badly disturbed portion of Badger Creek, Colorado, and its associated riparian and meadow complexes. Gabion controls are recommended to help reduce the chance of lateral migration of the newly constructed channel. Controls are designed to allow for some vertical adjustment of the channel bed following increased bank stability due to revegetation.)

Jungwirth, M., Moog, O., and Muhar, S. (1993) "Effects of river bed restructuring on fish and benthos of a fifth order stream, Melk, Austria," Regulated Rivers, Research and Management, xx, 195-204.

(Studies conducted on 15 sections of seven different epipotamal streams established the impact of river bed structures on fish communities. Reduced spatial heterogeneity due to river straightening resulted in decreasing numbers of fish species, stock density and biomass. The variance of maximum depths used as a measure of habitat structure showed a highly significant correlation with the number and diversity of fish species.)

Karouna, N. (1991) "Stream restoration and bio-engineering techniques," Conference Paper presented: Restoring Our Home River: Water Quality and Habitat in the Anacostia, College Park, MD.

(This paper presents a comprehensive summary of structural methods that can be used to stabilize eroding streambanks and improve aquatic habitat within degraded urban stream systems. Many of the basic techniques were derived from work traditionally associated with the restoration of un-developed watersheds.)

Keown, M. P. (1983) "Streambank protection guidelines," U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

(Streambank protection is a complex subject. There are no engineering manuals available with construction plans for bank protection projects that are guaranteed to work. However, this pamplet does provide general information needed to develop a systematic plan of action for solving a streambank protection problem.)

Klingeman, P. C. (1984) "Evaluating hydrologic needs for design of stream habitat modification structures," Proceedings of the Pacific Northwest Stream Habitat Workshop, Arcata, CA.

(This paper describes the needs and uses of basic hydrologic, hydraulic, and geomorphic information for designing a stream habitat modification structure at a site. Also, common types of stream habitat modification structures are described.)

Lister, D. B., Beniston, R. J., Kellerhals, R., and Miles, M. (1995) "Rock size affects juvenile salmonid use of streambank riprap," River, Coastal and Shoreline Protection, pp. 621-632.

(Assessment of habitat alteration included comparisons of juvenile salmonid densities along banks of large and small riprap, and natural cobble-boulder material. Densities were found to be greater along large riprap than small riprap banks. By placing large boulders along the toe of the bank, appeared to increase rearing densities.)

Long, K.S., Nestler, J.M., Fischenich, J.C. 1997. Survey of Habitat-Related Channel Features and Structures in Tailwaters, EIRP TR EL-97-6, USACE WES, Vicksburg, MS.

(Summarizes a survey of instream and streambank features placed in tailwater reaches below reservoirs. Focuses on the impacts of the features to velocity and depth).

Marelius, F., and Sinha, S. K. (1998) "Expermental investigation of flow past submerged vanes," Journal of Hydraulic Engineering, 124-5, 542-545.

(The physics of the flow past a submerged vane at high angles of attack is studied. Data was collected during an experimental study of flow past vanes at various angles of attacks in a deformable-bed straight rectangular channel. Also established was the optimal angle of attack required to generate the strongest secondary circulation in the flow.)

Marzolf, G. R. (1978) "The potential effects of clearing and snagging on stream ecosystems," U. S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-78/14.

(This review examines the widely held contention that clearing and snagging reduces fish populations and is otherwise detrimental to the use of stream ecosystems. Because of the lack of direct quantitative evidence about clearing and snagging effects, the mechanisms involved in producing the effects are discussed indirectly as potential effects."

Masterman, R., and Thorne, C. R. (1992) "Predicting influence of bank vegetation on channel capacity," Journal of Hydraulic Engineering, 118-7, 1052-1058.

(Bank vegetation is often perceived to be a significant factor in reducing the discharge capacity of natural river and flood-control channels. This paper develops a theoretically based method that can be used to predict the effect bank vegetation has on channel capacity in natural rivers; thus, preventing unnecessary and unfriendly maintenance work that is carried out to remove bank vegetation, despite the acknowledged beneficial effects vegetation cover can have in increasing the stability of a bank and reducing erosion.)

Morrow, J.V., Jr., and Fischenich, J.C., 1999. Habitat Requirements for Freshwater Fish. TN SR-99-6, USACE WES, Vicksburg, MS. April, 1999.

(With very few exceptions, stream restoration projects will have consequences for fish communities and the user groups associated with those communities. An organism's habitat must contain all the physical, chemical, and biological features needed for that organism to complete its life cycle. For fishes this may include a variety of parameters such as water temperature regimes, pH, amount and type of cover, substrate type, turbidity, depth, water velocity, inorganic nutrient levels, and accessibility to migration routes. Habitat quality affects health of individual fishes, fish populations, and communities, and changes in habitat will usually result in changes to the species composition of a fish community. This technical note characterizes fish habitat and habitat requirements and preferences. It is designed to help water resource managers who may have little or no training in fishery science to better understand problems associated with freshwater fish habitat.)

Munsey, J.J., and Fischenich, J.C., 1996. National Review of Corps Environmental Projects, IWR Report 96-R-27, Institute for Water Resources, Alexandria, VA.

(Provides details of the nature and performance of 32 Corps of Engineers environmental restoration projects.)

Northcutt, G. (1998) "Hybrid structures turn hard armor green," Erosion Control, 5-7, 46-55.

(A new breed of structures blurs the distinction between hard armor and soft vegetative solutions. These hybrid solutions result in landscape features with natural-looking appearances that camouflage the structural integrity engineered into them.)

Nunnally, N. R., and Sotir, R. B. (1994) "Soil bioengineering for streambank protection," Erosion, 1-5, 38-44.

(Streambank protection and stabilization measures work either by reducing the force of flowing water, by increasing the resistance of the bank to erosion, or by some combination of the two. Soil bioengineering systems are natural in appearance; they provide shade, overhanging cover, and organic debris for aquatic ecosystems; and they provide good riparian habitat.)

Nunnally, N. R., and Sotir, R. B. (1997) "Criteria for selection and placement of woody vegetation in streambank protection," Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 816-821.

(Numerous soil bioengineering streambank protection systems employing woody vegetation have been constructed all over North America during the last ten to fifteen years. Some preliminary guidelines are presented for setting minimum stream stages above which woody vegetation can be expected to survive and for identifying what woody species to use.)

Office, Chief of Engineers, U. S. Army (1989) "Environmental Engineering for Local Flood Control Channels," Engineer Manual 1110-2-1205, Washington, DC.

(This manual provides guidance for incorporating environmental considerations in the planning, engineering, design, and construction of flood control channels, levees, and associated structures. Channel modifications for flood and erosion control include clearing and snagging; channel straightening; channel enlargement; streambank protection; channel lining; and construction of grade control structures, culverts, levees, and floodwalls.)

Pastorok, R. A., MacDonald, A., Sampson, J. R., Wilber, P., Yozzo, D. J., and Titre, J. P. (1997) "An ecological decision framework for environmental restoration projects," Ecological Engineering, 9, 89-107.

(Ecosystem restoration projects require planning and monitoring, yet projects completed thus far have been planned on an ad hoc, concensus basis and are virtually ignored after revegetation at the site is complete. A process was developed to integrate a fundamental understanding of ecological principles into the existing project planning framework used by the U. S. Army Corps of Engineers in their growing role in restoration of aquatic habitats, but it should be applied to terrestrial habitats as well.)

Pollowy, T. R. (1998) "The restoration and management of rivers and streams," Land and Water, 42-6, 14-16.

(The successful design and implementation of a riparian restoration project is not as simple as knowing what plant species to select. Without an understanding of influencing factors, both individually and collectively, we are treating symptoms while the degradation of these valuable natural resources continues and accelerates.)

Robinson, K. M., Rice, C. E., and Kadavy, K. C. (1998) "Design of rock chutes," American Society of Agricultural Engineers, 41-3, 621-626.

(Rock chute design information is consolidated from several sources to provide a comprehensive design tool. The rock slope stability, boundary roughness, and outlet stability of rock chutes are each discussed. This article contains information needed to perform a rock chute design.)

Roper, B. B., Konnoff, D., Heller, D., and Wieman, K. (1998) "Durability of Pacific Northwest instream structures following floods," North American Journal of Fisheries Management 18, 686-693.

(The durability of 3,946 instream structures in 94 streams that had floods with return intervals exceeding 5 years were assessed. Overall structure durability was high. The higher magnitude of flood events resulted in reduced durability. Stream order also affected structure durability.)

Rosgen, D. L. (1997) "A geomorphological approach to restoration of incised rivers," Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 12-29.

(Geomorphological concepts are described as integrated into incised river restoration projects. A range of restoration design concepts are presented including; returning the stream to its original elevation and re-connecting floodplains, widening the belt width to construct a new channel at the existing elevation, changing stream types, and stabilizing the existing incised channel in place.)

Rice, C. E., and Kadavy, K. C. (1998) "Low-drop grade-control structure," American Society of Agricultural Engineers, 41-5, 1337-1343.

(Design criteria is developed for a structural low-drop grade-control structure that will have good performance characteristics and have general acceptance by the engineering community involved with stabilization of degrading channels. Criteria are presented to design the structure given the channel width, critical depth, drop height, and tailwater elevation and to determine the size and placement of riprap downstream of the structure to ensure the integrity of the structure.)

Schmetterling, D. A., and Pierce, R. W. (1999) "Success of instream habitat structures after a 50-year flood in Gold Creek, Montana," Restoration Ecology 7-4, 369-375.

(Sixty-six structures made of natural materials (rock and wood) were constructed that resulted in 61 new pools in an attempt to restore salmonid habitat. Following an estimated 50-yr recurrence interval flood, 55 (85 percent) of the structures remained intact and stable.)

Shields, F. D., Jr. (1982) "Environmental features for flood control channels," Water Resources Bulletin, 18-5, 779-784.

(Environmental features for channel projects include selective clearing and snagging techniques, channel designs with nonuniform geometry such as single bank modification and floodways, restoration and enhancement of aquatic habitat, improved techniques for placement of excavated material, and revegetation.)

Shields, F. D., Jr. (1983) "Design of habitat structures for open channels," Journal of Water Resources Planning and Management, 109-4, 331-344.

(Rudimentary design guidelines are presented for simple structures used to accelerate biological recovery of modified stream channels. Data from nine case studies are presented, including stream channel characteristics, structure dimensions, and an analysis of biological effectiveness and structural durability.)

Shields, F. D., Jr., and Nunnally, N. R. (1983) "Environmental aspects of clearing and snagging," Journal of Environmental Engineering, 110-1, 152-165.

(Clearing and snagging is used as an economical technique for reducing the frequency and duration of high frequency flooding in environmentally sensitive locations. Complete clearing and snagging has detrimental effects on stream morphology, water quality, and aquatic and terrestrial ecosystems while modified clearing and snagging is less damaging. Guidelines for modified clearing and snagging are discussed.)

Shields, F. D., Jr. (1991) "Woody vegetation and riprap stability along the Sacramento

River mile 84.5-119," Water Resources Bulletin, 27-3, 527-536.

(Stability of vegetated and bare riprap revetments along a Sacramento River reach during the folld of record was assessed. Damage rates for revetments supporting woody vegetation tended to be lower than for unvegetated revetments of the same age located on banks of similar curvature.)

Shields, F. D., Jr., and Hoover, J. J. (1991) "Effects of channel restabilization on habitat diversity, Twentymile Creek, Mississippi," Regulated Rivers: Research & Management, 6, 163-181.

(Twentymile Creek was channelized prior to 1910, in 1938, and in 1966. Straighting and enlargement in 1966 resulted in channel instability, rapid bed degradation and cross-section enlargement. Grade control structures and various types of streambank protection were constructed along the channel in the early 80's to restore stability. This paper studies the effects of restabilization of Twentymile Creek on aquatic habitats.)

Shields, F. D., Jr., and Smith, R. H. (1992) "Effects of large woody debris removal on physical characteristics of a sand-bed river," Aquatic Conservation: Marine and Freshwater Ecosystems 2, 145-163.

(Removal of large woody debris (LWD) is one of the most widely practiced stream alterations, particularly in sand-bed rivers. Conservation of stream habitats requires quantification of LWD removal impacts on physical habitat. This paper attempts to quantify these impacts.)

Shields, F. D., Jr., Cooper, C. M., and Knight, S. S. (1993) "Initial habitat response to incised channel rehabilitation," Aquatic Conservation: Marine and Freshwater Ecosystems 3, 93-103.

(Incised stream channel aquatic habitats typically are severely degraded. However, habitat recovery might be accelerated in channels that have incised and are regaining equilibrium through deposition of sandy berms by placing rock spurs in the channel and by planting woody vegetation on the berms.)

Shields, F. D., Jr. (1995) "Fate of Lower Mississippi River habitats associated with river training dikes," Aquatic Conservation: Marine and Freshwater Ecosystems 5, 97-108.

(Regions of reduced velocity adjacent to spur dikes along the Lower Mississippi River are valuable habitats. However, since the dikes were constructed, the aquatic volume and area of associated low-velocity habitats have been reduced by 38 and 17 percent, respectively.)

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1995) "Rehabilitation of watersheds with incising channels," Water Resources Bulletin, 31-6, 971-982.

(Rehabilitation measures, which are selected and laid out using a subjective integration of hydraulic and geotechnical stability analyses, include grade controls, bank protection, and small reservoirs. Aquatic habitat studies indicate that stone-protected stilling basins below grade-control weirs and habitats associated with drop popes and stone spur dikes are assets to erosion-damaged streams.)

Shields, F. D., Jr., Bowie, A. J., and Cooper, C. M. (1995) "Control of streambank erosion due to bed degradation with vegetation and structure," Water Resources Bulletin, 31-3, 475-489.

(Combinations of vegetation and structure were applied to control streambank erosion along incised stream channels in northwest Mississippi. Tested configurations included eroding banks protected by vegetation alone, vegetation with structural toe protection, vegetation planted on re-graded banks, and vegetation planted on regraded banks with toe protection. Designs involving riprap toe protection in the form of a longitudinal dike and woody vegetation appeared to be most cost-effective.)

Shields, F. D., Jr., Cooper, C. M., and Knight, S. S. (1995) "Experiment in stream restoration," Journal of Hydraulic Engineering 121-6, 494-502.

(Aquatic habitats in a deeply incised sand-bed channel were modified by adding stone and planting dormant willow posts. Restoration structures were designed as complements to existing channel stabilization works. Fish numbers tripled, median fish size increased by 50 percent, and the number of species increased from 14 to 19.)

Shields, F. D., Jr., and Gippel, C. J. (1995) "Prediction of effects of woody debris removal on flow resistance," Journal of Hydraulic Engineering 121-4, 341-354

(A simple technique for predicting the Darcy-Weisbach friction factor for river channels with varying amounts of large woody debris was developed. The computational procedure explained 84 percent of the variance in observed values.)
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Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1994) "Effects of channel incision on base flow stream habitats and fishes," Environmental Management 18-1, 43-57.

(Fishes and physical habitat variables were sampled at base flow from three incised stream channels and one reference stream. Incised channel habitat quality was inferior to the reference channel despite the presence of structures designed to restore channel stability.)

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1995) "Incised stream physical habitat restoration with stone weirs," Regulated Rivers: Research and Management, 10, 181-198.

(Although a series of grade control weirs and bank protection works had been constructed before restoration, sediment production from channel erosion remained high and aquatic habitats were of poor value. Restoration works were designed to be compatible with existing channel stabilization works and economic criteria. Stone was added to extend the existing groynes across the base flow channel to create 18 small weirs, thus, causing the water to pool and increasing pool habitat availability, overall physical heterogeneity, riparian vegetation, shade and woody debris density.)

Shields, F. D., Jr., and Cooper, C. M. (1997) "Stream habitat restoration using spurs added to stone toe protection," Proceedings of the Conference on Management of

Landscapes Disturbed by Channel Incision, 667-672.

(Longitudianl stone toe is one of the most reliable and economically attractive approaches for stabilizing eroding banks in incised channels. However, aquatic habitat provided by stone toe is inferior to that provided by spur dikes. Results indicated that spur addition resulted in modest increases in baseflow stony bankline, water width and pool habitat availability, but had only local effects on depth.)

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1997) "Rehabilitation of warmwater stream ecosystems following channel incision," Ecological Engineering 8, 93-116.

Presented is a case study of two streams damaged by channel straightening and incision. One stream was stabilized by using a metal sheet piling weir and dormant willow post planting, while the other was treated with a stone weir, stone toe bank protection and willow strout planting.)

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1998) "Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi," Hydrobiologia 382, 63-86.

(A study of incised warmwater stream rehabilitation was conducted to develop and demonstrate techniques that would be economically feasible for integration with more orthodox, extensively employed watershed stabilization techniques. During the study two reaches were modified by adding woody vegetation and stone structure to rehabilitate habitats degraded by erosion and channelization. These experiments suggest that major gains in stream ecosystem rehabilitation can be made through relatively modest but well-designed efforts to modify degraded physical habitats.)

Shields, F. D., Jr., Knight, S. S., and Cooper, C. M. (1998) "Addition of spurs to stone toe protection for warmwater fish habitat rehabilitation," Journal of the American Water Resources Association 34-6, 1427-1436.

(Longitudinal stone toe is one of the most reliable and economically attractive approaches for stabilizing eroding banks in incised channels. However, aquatic habitat provided by stone toe is inferior to that provided by spur dikes. Tests designs were performed that combined features of stone toe and spurs. Overall results indicated that spur addition resulted in modest increases in baseflow stony bankline, water width and pool habitat availability, but had only local effects on depth.)

Shuler, S. W., Nehring, R. B., and Fausch, K. D. (1994) "Diel habitat selection by brown trout in the Rio Grande River, Colorado, after placement of boulder structures," North American Journal of Fisheries Management 14-1, 99-111.

(Brown trout distribution and microhabitat use were measured in 10 study sections on the Rio Grande River, Colorado, where three types of structures make from large boulders had previously been placed. On average, 65 percent of the adult brown trout and 69 percent of the juvenile brown trout observed were holding positions near structures.)

Smith, R. D., Sidle, R. C., Porter, P. E., and Noel, J. R. (1993) "Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream," Journal of Hydrology, 152, 153-178.

Expermental removal of woody debris from a small, gravel-bed stream in a forested basin resulted in dramatic redistributions of bed sediment and changes in bed topography. Removal of debris changed the primary flow path, thereby altering the size and location of bars and pools and causing local bank erosion and channel widening.)

Smith, R. H., Shields, F. D., Jr., Dardeau, E. A., Jr., Schaefer, T. E., Jr., and Gibson, A. C. (1992) "Incremental effects of large woody debris removal on physical aquatic habitat," Technical Report EL-92-35, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

(The objective of this study was to investigate incremental effects of selective clearing and snagging on physical conditions and aquatic habitat in a sand bed river. The study was part of a larger program to develop techniques to quantify and predict incremental physical and biological effects of large woody debris (LWD) removal. Long-term research objectives are to relate the densities and types of LWD formations in streams to specific biotic parameters, near-bank-full friction factor, and longitudinal dispersion as an indicator of the tendency of a channel reach to trap and hold fine particulate matter.)

Sotir, R. B., and Nunnally, N. R. (1995) "Soil bioengineering for stream restoration," Water Resources Engineering, Proceedings of the First International Conference Water Resources Engineering Div./ASCE et al. San Antonio, TX, pp. 795-799.

(Soil bioengineering is an effective technology for reducing streambank erosion and restoring degraded aquatic and riparian ecosystems. Soil bioengineering systems that are most effective for these purposes employ native, woody pioneer species that provide immediate bank protection and cover. These pioneer systems evolve through natural invasion and plant succession into diverse ecosystems capable of supporting a rich abundance of riparian and aquatic species.)

Sotir, R. B., and Nunnally, N. R. (1995) "Use of riprap in soil bioengineering streambank protection," River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone, John Wiley & Sons Ltd., 577-589.

(Streambank protection systems that incorporate woody vegetation provide additional benefits over those that do not. Soil bioengineering, employs woody vegetation as the major structural component in streambank protection designs. Although, in some applications, adequate protection against erosion can be provided by vegetation systems alone, most applications require the use of some rock in conjunction with vegetation to prevent damage to the system that would impair its effectiveness or reduce its environmental benefit.)

Sotir, R. B. (1998) "Soil bioengineering takes root," Civil Engineering, July, 50-53.

(Soil bioengineering is a natural way to restore, rehabilitate and reclaim watersheds that suffer from erosion. But it should be used in conjunction with other methods such as riprap, articulated block systems, geogrids, geotextiles, gabions and cellular confinement systems.)

"Stability of Flood Control Channels" (1990) U. S. Army Engineer Waterways Experiment Station and the Committee on Channel Stabilization of the U. S. Army Corps of Engineers.

This document provides guidance for determining potential channel instability in flood control projects. It is intended to facilitate consideration of : the type and severity of erosion and sedimentation problems; the need for and scope of further hydraulic studies to address those problems; and design features to promote channel stability.)

Streubel, D. N., and Griffith, J. S. (1993) "Use of boulder pocket habitat by rainbow trout in Fall River," Great Basin Naturalist 53-2, 194-198.

(Abundance of rainbow trout in relation to characteristics of pockets created by boulders was studied in Fall River, southeastern Idaho. Results showed that maximum water depth and pocket surface area were both positive factors affecting trout density.)

Stream Obstruction Removal Guidelines (1983) Stream Renovation Guidelines Committee, The Wildlife Society and American Fisheries Society and International Association of Fish and Wildlife Agencies.

(The intent of these guidelines is to aid in correcting stream flow problems, caused by obstructions, in an environmentally sound manner and to maintain natural stream characteristics. These guidelines are only applicable to situations where channel blockages result in unacceptable flow problems and where restoration of the natural or former flow capacity of the channel is desired.)

Sylte, T.L., and Fischenich, J.C. (2000). "Rootwad composites for streambank stabilization and habitat enhancement," *EMRRP Technical Notes Collection* (ERDC TN-EMRRP-SR-21), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

(A rootwad composite is a combination of interlocking tree materials where a mass of tree roots, commonly called a rootwad, is utilized with other tree parts and revegetation methods to stabilize streambanks and provide aquatic habitat. Rootwad composites are often a cost-effective bank stabilization and habitat enhancement treatment. Rootwad composites move the current line away from the streambank so that the bank is less susceptible to erosion through hydraulic forces. This, in effect, reduces the energy environment along the streambank/water interface so that riparian vegetation can provide the necessary bank protection and habitat values. Rootwad composites also generate turbulence that creates streambed scour and provides cover and substrate for aquatic organisms. Other streambank stabilization measures generally offer less risk, but rootwad composites offer the following advantages: (1) are typically cost-effective because they utilize natural materials that are often found on or near the site; (2) eventually decompose, thus allowing the restored riparian zone to function naturally, (3) create habitat complexity, hydraulic diversity, and substrate sorting, and (4) induce less local sediment deposition than other flow deflection structures.)

Thorne, C. R., Reed, S., and Doornkamp, J. C. (1996) A Procedure for Assessing River Bank Erosion Problems and Solution, R&D Report 28, National Rivers Authority, Almondsbury, Bristol BS12 4UD.

(The purpose of this report is to provide operational level guidance on the management of river bank erosion problems for individuals concerned with flood defense, land drainage, local drainage, local planning, recreation, conservation, and navigation. Where a structural solution that involves physically protecting the bank is appropriate there is now a wide range of designs and materials that may be used. These range from hard engineering materials to softer materials and combinations of the two.)

U. S. Department of Transportation (1979) Restoration of fish habitat in relocated streams, FHWA-IP-79-3.

This manual provides guidelines for the design and construction of relocated channels, and describes measures that will lead to rapid recovery of new channels by natural processes. Good design, and implementation of these measures can greatly reduce the adverse effects of stream relocation.)

Vaughn, P. L. (1997) "Flood tests stream bank stabilization techniques," Land and Water, 41-3, 32-37.

(Some of the techniques applied included coir fiber logs, coir straw erosion control blankets, jute netting, log crib revetments, meander establishment, root wads, and a variety of bioengineering techniques. Each of these techniques are discussed and their ability to withstand or not withstand a 100 year flood event.)

Wallace, J. B, and Bende, A. C. (1984) "Quantification of wood habitat in subtropical coastal plain streams," Canadian Journal of Fisheries and Aquatic Science, 41, 1643-1652.

(Snag, or woody, habitat is the major stable substrate in these sandy-bottomed streams and is a site of high invertebrate diversity and productivity. Wood is also important to fishes, providing a rich source of invertebrate food, habitat, and cover. The quantification of wood habitat seems mandatory to assess past or potential impacts of snag removal on ecosystem processes in low-gradient streams.)

Wesche, T. A., (1985) "Stream channel modifications and reclamation structures to enhance fish habitat," The Restoration of Rivers and Streams, Chapter 5, Butterworth Publishers.

(Many of the detrimental effects of channelization can be avoided, with little compromise in channel efficiency, by employing channel design guidelines that do not destroy the hydraulic and morphologic equilibria that natural streams possess. These guidelines include minimal straightening; promoting bank stability by leaving trees, minimizing channel reshaping, and employing bank stabilization techniques; and, emulating the morphology of natural stream channels.)

White, D. W., Jr. (1981) "Evaluation of membrane-type materials for streambank erosion protection," U. S. Army Engineer Waterways Experiment Station, Miscellaneous Paper GL-81-4.

(The objective of this study was to investigate new materials and construction techniques for streambank protection by preventing erosion of the banks. Results showed that all membrane materials used performed satisfactorily in protecting streambanks and riverbanks from erosion during normal streamflows as long as the banks remain stable.)

White, R. J. (1991) "Resisted lateral scour in streams-its special importance to salmonid habitat and management," American Fisheries Society Symposium, 10, 200-203.

(The resisted lateral scour forms zones of high shear stress of current against streambanks in association with undercut banks, large bankside rocks, and accumulations of large woody debris. Development and maintenance of the lateral scour pools and related features usually depend on the binding and roughening of banks by abundant riparian vegetation.)

"Waste Tire Problem Becomes Opportunity for Erosion Control," Land and Water 42-2, 36-39.

(Numerous partners in Oklahoma have turned the problem of disposing of waste tires into an opportunity. The alternative: utilizing waste tires to control streambank erosion. Some argue over the integrity of the structures, especially during flooding periods and high water velocity. But with over 18 projects already implemented and the 1st project over 17 years old, several of the projects have already held fast during serious flooding.)