CHAPTER 8

INDIRECT TECHNIQUES FOR EROSION PROTECTION

As in the previous chapter, descriptive information for most techniques presented in this chapter is generally followed by a discussion of advantages, disadvantages, typical applications, and design considerations as appropriate. In order to minimize redundancy, these topics are discussed at the broadest possible level in the hierarchy of the text; in other words, aspects which are shared by all techniques are discussed at the beginning of the chapter; aspects which are shared by a group of techniques are discussed at the group level; aspects that are peculiar to a smaller category of techniques, or to a single technique, are discussed at the appropriate level of specificity.

The extent of the discussion of specific techniques ranges from detailed design guidance to a brief description for some specialized techniques. Therefore, a complete understanding of a specific technique requires perusal of all material at a broader level in the text, as well as material peculiar to that technique.

The following paragraphs outline the general description, advantages, and disadvantages for **most** indirect techniques used in bank stabilization methods:

> Indirect protection structures extend into the stream channel, and redirect the flow so that hydraulic forces at the channel boundary are reduced to a non-erosive level. Indirect protection techniques can be classified as follows:

- Dikes and Retards
  - Dikes
    - Permeable dikes
    - Impermeable dikes
  - Retards
    - Permeable retards
    - Impermeable retards
- Other Flow Deflectors
  - Bendway weirs
  - Iowa vanes

Advantages are: Little or no bank preparation is involved for indirect protection. This reduces costs and riparian environmental impacts, simplifies the acquisition of rights-of-way, eliminates material disposal problems, and usually allows existing overbank drainage patterns to remain undisturbed.

Existing channel alignment and/or geometry can be modified, although the changes may not always be beneficial or predictable.

Indirect approaches usually increase geotechnical bank stability by inducing sediment deposition at the bank toe, although this process may not be rapid or reliable enough to meet project goals.

Disadvantages are: Where geotechnical bank instability or erosion from overbank drainage is a major factor, the fact that indirect protection does not immediately relieve these problems can be a serious and often unacceptable shortcoming.

Because significant changes in flow alignment, channel geometry, roughness, and other hydraulic factors often result from indirect protection structures, special attention must be given to the stream's morphological response.

Some types of indirect protection structures may be a safety hazard if the stream is used for recreation or navigation, and the aesthetics of some types often leave much to be desired, although vegetative growth may ultimately reduce the visual impact in most regions.

Since indirect methods extend into the stream channel, their construction may be difficult, especially during high flow. Also, the structures may be subjected to severe hydraulic conditions throughout their lifespan, and should be closely monitored to insure that maintenance is performed as necessary.

8.1 DIKES AND RETARDS

The following paragraphs outline the general description, advantages, disadvantages, typical applications, and design considerations for **dikes and retards** used in bank stabilization methods:

"Dikes" are defined as a system of individual structures which protrude into the channel, generally transverse to the flow. Other terms which are often used are "groins," "jetties," "spurs," "wing dams," and if they protrude only a short distance into the channel, "hard points." The term "dikes" is also used in some regions to refer to earthen flood-containing structures, which are also called "levees," but that usage is not relevant here.

"Retard" is defined as a continuous structure approximately parallel to the streamflow. It can be a single structure or two, or more, adjacent and parallel structures, in which case the space between may be filled with various materials. Other terms that are sometimes used are "longitudinal dikes," "parallel dikes," "jetties," "guide banks," and "training walls." Most designs have occasional "tiebacks" extending from the bank out to the main structure. These tiebacks have the appearance of dikes. In fact, many retard designs can be viewed as being a dike system with a longitudinal component connecting the ends of the dikes.

Advantages are: Dikes and retards provide a means to modify the channel alignment if that is a project requirement. They are also well suited to the incremental construction approach and are amenable to the establishment of woody vegetation. Also, many designs use locally available material.

Dikes and retards offer the opportunity for incorporating a wide variety of environmental features. They may increase the diversity of aquatic and terrestrial habitat, although subsequent sediment deposition may be detrimental to shallow water habitat. The reduction of water surface area due to deposition within the dike or retard system will reduce evaporation rates, which may be considered to be a benefit in semi-arid areas.

Disadvantages are: Those designs which involve "perishable" materials or mechanical connections are susceptible to gradual deterioration and to damage by debris, fire, ice, and vandals.

Channel capacity at high flow is decreased initially when dikes or retards are constructed, although the channel will usually adjust by forming a deeper, though narrower, cross-section, and the ultimate result may even be an increase in conveyance capacity. However, the extent of the adjustment cannot be always be predicted reliably, even with physical or numerical models. Since conservative assumptions on future deposition and vegetative growth would be necessary, extensive use of dikes or retards must be approached with caution on projects where channel flood conveyance is a concern.

Typical applications are: Dikes and retards can be applied to a wide range of conditions. However, the most common use is on shallow, wide streams with moderate to high transport of suspended bed material, because shallow channel depths reduce the required height of structures, a wide channel provides room for the channel alignment and geometry to adjust, and a heavy supply of suspended bed material accelerates the rate of induced deposition.

Where long-term funding is provided, they are often built in increments in order to reduce costs by modifying the river's form gradually, and taking advantage of subsequent deposition to reduce total project cost.

Dikes and retards are often used on large rivers to increase depth for navigation, in addition to improving the alignment and stabilizing the banks. They can be used to stabilize the channel alignment upstream and downstream of armor revetments in bends, since the shallower depths, moderate velocities, and less concentrated drift loads upstream and downstream of bends are more suitable to in-channel structures than is the bend itself.

Dikes and retards can be used where establishment of riparian vegetation is a high priority. Initial plantings and natural establishment of native species can be supplemented by later plantings on sediments deposited within and behind the structures, or by sloping and vegetating the upper bank slopes once lower bank stability has been attained.

No formal and widely tested design criteria for dikes and retards exist, although design concepts based on experience and model tests have been developed for some applications. A study performed for the U.S. Federal Highway Administration and reported by Brown (1985) is one of the most comprehensive analyses of dikes. That report is based on model tests, a literature review, and a survey of several hundred field installations. Studies by the U.S. Army Corps of Engineers (USACE, 1981) also provide observations on design parameters. Some findings from these and other studies, and from practice, are discussed later under specific headings. The following general concepts apply to the design of both dikes and retards:

(a) Because there are so many variations in design, one must be cautious of becoming so engrossed in the details of materials and construction that the importance of the basic layout is overlooked. If the basic principles in 5.1 and 6.1 are followed, then there are many specific designs that will work equally well, but if basic principles are neglected, the most painstaking attention to detail will be in vain.

(b) Simplicity should be a design goal. The principles of value engineering are particularly applicable for dikes and retards. Other factors being equal, a design with fewer components and mechanical connections will be more durable and less costly than a more complicated design.

(c) Basic decisions on materials and structural design for a specific project are inherent in the selection process discussed in Chapter 5. Other aspects are covered below under more specific headings. An exhaustive investigation by the engineer of all design alternatives for a specific project is neither practical or necessary. Many of the overwhelming number of possible variations are described by California State Department of Highways (1960) and FHWA (1985). Beyond their practical value, these publications provide testaments to the wide variety of river stabilization problems encountered in practice, and to human imagination in problem solving.

(d) The need for toe and local scour protection may be less obvious than for armoring techniques, but is still important (see 6.3). Using a permanent scour protection material, such as stone, in conjunction with dikes or retards of a less durable material will allow the designer to be less concerned about dike and retard durability, if woody vegetation will eventually provide the same erosion protection to the middle and upper bank as the dikes or retards provided in the beginning.

(e) Since mechanical connections cannot be made underwater, river stages during the construction season will affect some aspects of design, dictating that prefabricated elements or a launchable material such as stone be used for the portion of the structure which will be built underwater.

8.1.1 DIKES

8.1.1.1 Advantages

Advantages of dikes as compared to retards is that they will usually be less expensive for a given situation, and will not interfere with access to the stream. Also, after the stream has adapted to the initial project, dikes can be extended farther into the stream if necessary to fully achieve project objectives, whereas with retards, modification of the initial alignment is likely to be much more expensive.

8.1.1.2 Disadvantages

Disadvantages of dikes as compared to retards is that they will usually be less effective in eliminating bank erosion. Dikes are more vulnerable to floating debris than are retards, since dikes present abrupt obstacles to flow, whereas retards, being approximately parallel to flow, will allow much of the floating debris to pass through the project reach. Also, erosion between the dikes in a system will often be more severe and of longer duration than erosion within a retard system.

8.1.1.3 Typical Applications

Typical application of dikes is in straight reaches and long radius bends, since as bend radius decreases, spacing must decrease, and the required number of dikes soon reaches a point where a retard could be built for the same cost or, if channel realignment is not required, an armor technique could be used.

8.1.1.4 Design Considerations

Design considerations for dikes beyond the general factors discussed in 8.1 is one of the most complex issues in design of erosion protection works. There is general agreement on some aspects, but considerable diversity, even controversy, on others. A complete reading of the Federal Highway Administration report is recommended to obtain full understanding of the complexities involved in dike design (Brown, 1985).

Design involves the following major parameters:

(a) Permeability;
(b) Length;
(c) Spacing;
(d) Angle with respect to flow;
(e) Height;
(f) Bankhead design; and
(g) Structural scour protection.

(a) Since permeability affects some of the other design parameters, it is appropriate to discuss it first. Permeability is defined as the ratio of the area of openings in the dike to the total projected area of the dike, and is expressed as a percentage. If the stream carries only a small amount of debris, or the dikes are low enough that debris will pass over them during most flows, the permeability can be assumed to be the as-built condition. However, if debris loads are moderate to high, then some reduction in permeability with time should be assumed.

FHWA (1985) suggests that where a large reduction in at-bank velocity is required, such as in sharper bends, permeability should not exceed 35 percent. Where a moderate reduction in velocity is sufficient, such as in bends with mild curvature and less easily erodible bank material, permeabilities up to 50 percent can be used. In mild exposures such as straight reaches with low erosion potential, permeabilities up to 80 percent may be successful. However, permeabilities greater than 50 percent are not recommended unless success under conditions similar to the project at hand can be documented.

The U.S. Army Corps of Engineers (USACE, 1981) suggests that permeability should decrease with decreasing size and quantity of sediment carried by the stream in suspension. That is, greater permeability is allowable if a large amount of bed material sediment is carried in suspension, whereas less permeable structures are required if small amounts of sediment, or predominately fine sediment sizes, are transported in suspension.

Permeability and the choice of materials used to construct dikes are interrelated. To achieve a given permeability, there will be more than one possible combination of materials; conversely, a given choice of materials can be used for a range of permeabilities by altering the design details (see 8.1.1).

(b) The length of individual dike structures (from the existing bankline to the riverward end of the structure) is dictated by the desired alignment of channel if the channel is to be realigned. Where stabilization of the existing bankline is the only requirement, then determining the proper length is not so simple, and there is wide variation in practice.

FHWA (1985) states that dike length affects the local scour depth at the tip of the dike, the angle of flow deflection induced by the dike, and the length of streambank protected by each individual dike. Optimum dike length is to some extent a function of dike permeability. Selection of an appropriate dike length is site-specific. However, the following general guidance is provided:

Permeability (percent)	Recommended Projected Length of Dike (percent of channel width)
0-35	15% or less
80	25% or less

For permeabilities between 35% and 80%, linear interpolation between 15% and 25% of channel width can be used to determine maximum allowable length. Channel width is defined as bankfull width, and projected length of dike is measured perpendicular to the main flow direction.

If the dikes are being used to change the channel alignment, then the dike lengths will often exceed these limits, and the length of individual dikes in a system will vary widely depending upon the location of the realigned channel with respect to the existing bankline. These limits basically represent values beyond which additional length is no longer cost-effective, if stabilizing the bank in its present position is the only objective, since difficulties associated with increased scour at the end of the dikes, and other flow anomalies, may more than offset the additional length of bank protected by each dike.

General practice is to define length as the original constructed length, not including any length dug into the bank for scour protection (see “bankheads” below). A very conservative approach for design would be to assume that deposition after construction would effectively move the bankline riverward, and to compute design dike length from that point. Since design dike length would be shorter with this approach, design spacing would be closer (see "spacing below"). The logic for this approach is that the dikes must ultimately protect the newly deposited bankline. The weakness in the logic is that if the dikes ultimately form a new bankline, then they will by definition, also protect it. Therefore, the cost-effectiveness of this very conservative approach may be questionable.

(c) Spacing and length are usually considered to be related, thus much of the literature addresses the ratio of the two rather than separate values. In the absence of a need to construct dikes to a predetermined channel alignment, the optimum length/spacing ratio becomes a site-specific economic determination, involving a trade-off between shorter dikes at a closer spacing against longer dikes at a greater spacing.

FHWA (1985) states that although spacing is a function of the length, angle, and permeability of the dikes, as well as channel curvature, a parameter called "expansion angle" may be used to better understand the relationship of these variables. In a straight channel, for short dikes with permeabilities less than 35%, the expansion angle is the same as for impermeable dikes, about 17 degrees. For permeabilities of 35% or greater, the expansion angle increases as permeability or dike length increases.

FHWA (1985) also shows a method of determining dike spacing in a bend by using a projection of a tangent to the thalweg at each dike tip. This procedure gives the maximum allowable spacing, which should be decreased for a more conservative design, particularly if short dikes or highly permeable dikes are used, if the banks are easily erodible, or if the consequences of failure are high. They suggest that the expansion angle be used to determine a prudent decrease in spacing from that which would be used in a straight reach.

USACE (1981) and Copeland (1983) report a range in practice varying from a spacing equal to dike length to a spacing of 6.3 times dike length, and describe USACE model tests at the Waterways Experiment Station, Vicksburg, Mississippi, indicating that the optimum spacing of impermeable dikes in a bend was between 2 and 3 times dike length. However, they caution that those tests should not be applied verbatim to practice, stating that "Spacing-to-length ratios for specific projects are best determined by previous experience in similar circumstances or site-specific model studies." USACE (1981) describes USACE model tests at the Missouri River Division's Mead Hydraulic Laboratory, Nebraska, of very short impermeable dikes ("hard points") in a straight channel, which indicated that flow downstream of each structure expanded at about a 20-degree angle from the main flow, a finding compatible with FHWA guidance. This suggests that a spacing of about 3 times dike length for that type of dikes in a straight reach would be adequate.

A conservative recommendation for dikes in bends would be a spacing equal to dike length. California Department of Highways (1960) also states that spacing should equal dike length unless "scalloping" of the bankline due to erosion between the structures can be accepted. That guidance is then qualified by a recommendation that impermeable dikes not be used in bends. However, that pessimistic viewpoint may have been influenced by unsuccessful use in sharp radius bends, or by failures due to inadequate bankhead design.

Even if one of the approaches discussed above is used to quantify spacing, the location of individual dikes may need to be modified according to site conditions. For example, the project site may have localized "plunge pools" or "shelves" because of variations in bed or bank material, or other local anomalies. If so, dike locations can perhaps be adjusted so that no one dike requires a large volume of material or unusually long piling, or conversely, so that no one dike is built with insufficient volume of material or pile penetration to be stable against future local scour.

If dike spacing is determined by using an approach based on projections of tangents to streamlines or to the thalweg, the engineer should be aware that if the channel upstream of the project is migrating, the alignment of incoming flow and the thalweg may change with time. A conservative approach would be advisable in such cases if the predicted future condition will result in a more direct impingement of flow on the bank which is to be protected.

(d) The optimum angle that dikes should have with respect to the direction of flow is a subject upon which there is much disagreement. The controversy may be due to the influence of less obvious, and perhaps overlooked, factors overriding the effect of angle at a specific site. In the absence of compelling evidence to the contrary, dikes which are constructed on the shortest path from the bankline to the desired new channel alignment will be the shortest, thus the cheapest. Usually, this path will be approximately perpendicular to flow, or the bankline, or a compromise between the two. FHWA (1985) suggests that angle is not critical to permeable dikes, but that better performance may be obtained with impermeable dikes if the upstream dike in a system is constructed at an angle of about 150 degrees, with subsequent dikes having successively smaller angles, reaching a minimum of 90 degrees for the downstream dike. Whether results are better to the extent of outweighing the additional cost for longer structures is a matter for debate.

Permeable dikes are sometimes angled downstream to shed debris and ice, although if debris and ice loads are consistently heavy, permeable dikes may not be the appropriate protection method to begin with. In any event, the "shedding" effect should be considered to be only an additional safety factor, and should not lead to disregarding debris and ice loads in structural design.

Contrary to intuition, dikes angled downstream may form downstream scour holes nearer to the bank than if they were perpendicular to the bank or angled upstream to the flow, because overtopping flows will tend to form an erosive "roller," or plunging flow, immediately adjacent and parallel to the structure, to the detriment of bank stability.

As in determining dike spacing, any future change in alignment of flow due to channel migration upstream should be considered when designing the angle of dikes with respect to flow direction.

(e) General factors affecting the optimum height of erosion protection works were discussed in Section 6.2.5, "Top elevation of protection." Although the term "elevation" is more precise than "height," the term "height" will be used in the discussion below because it is more commonly used in dike design practice.

Height of dikes in a system is often related to bank height which, in turn, can be related to some recurrence frequency of river stage. In humid areas, bank height is often a one or two year return interval for streams that are neither aggrading or degrading. Unfortunately, any design relationship of dike height to bank height is more conceptual than quantitative, and no generally accepted precise guidance can be stated.

In spite of the uncertainties involved, some general guidance can be stated regarding the determination of appropriate dike height. FHWA (1985) states that dikes need be only high enough to protect the bank zone of active erosion, but follows that general axiom with the following three specific guidelines:

> Dike height should be no higher than top bank, but no lower than 3 feet below "design flow."
>
> Impermeable dikes should be submerged 3 feet at the most severe expected flow condition, because the local scour associated with submerged dikes seems to be smaller and located farther from the bank than that associated with unsubmerged dikes.
>
> Permeable dikes should be lower than flow stages that carry significant debris loads.

Application of these guidelines will often result in a fairly conservative design, which is understandable, since the guidelines were developed for application to the protection of highway facilities from channel migration. However, the latitude which exists in the determination of the design flow and the most severe expected flow condition still leaves considerable latitude for the engineer to be more or less conservative as appropriate for a specific project, even if dike height is based on these guidelines.

In practice, the uncertainties of the physical effects of height often become moot, because the economics of dike construction often dictate that dikes be considerably lower than top bank elevation. For permeable dikes, the rapid increase in cost as the height increases is due to structural factors, as discussed below under "permeable dikes." For impermeable dikes, the rapid increase in cost is due to the exponential increase in structure volume as height increases. For a specific project, there will usually be a height beyond which dikes are not economically feasible. Fortunately, that limiting height is often greater than that required for successful performance, since stabilization of the toe and lower bank slopes are the key to success in most applications. Also, the incremental construction approach discussed in 5.3.3 can sometimes be used to reduce the additional cost of increased height.

As a very broad generalization based on past experience, an acceptable range of dike heights in many situations is between 1/3 and 2/3 of bank height, or in the case of incised streams, 1/3 to 2/3 of the distance between low water elevation and the elevation of a flow with a return interval of one to two years. The lower figure will certainly not be a conservative design, or even as conservative as designing a retard to the same elevation, but dikes are not as suitable as retards for a situation requiring conservative design in any case.

As a design refinement, the height of a dike can vary from the bankhead to the riverward end, i.e., be sloped downward. This provides two advantages:

> It creates less constriction of flow as flow increases, because the riverward portion is submerged at higher flows. This is particularly important for impermeable dikes.
>
> It results in maximum economy, because the structure can then more closely follow the contour of the bank and channel bottom, reducing the required size of structural components of permeable dikes, and reducing the volume of impervious dikes. This in fact is the only feasible approach when prefabricated components of a single size, such as jacks, are used.

A combination of sloped and level profiles is often used when the channel is to be shifted away from the bank significantly.

A dike profile can be "notched" for environmental purposes, allowing some flow to enter the dike system to enhance habitat diversity and water quality, while still diverting sufficient flow to provide erosion protection to the bank.

Physical model studies reported by Franco (1982) indicated that a system of dikes having successively lower elevations in the downstream direction tended to accumulate more deposition than other designs. However, that finding is not usually pertinent to bank protection dikes. The model studies were for long structures in a wide channel, designed to deepen the crossing between two bends. Following that scheme for dikes in a typical eroding channel would require either that the upstream structures be relatively high, or the downstream structures relatively low, choices which would respectively either increase the cost of the upstream dikes substantially, or reduce the effectiveness of the downstream dikes. In a bend, the hydraulics of flow would likely overcome whatever beneficial effect a stepped-down system might have, resulting in the strongest attack on the bank being where the dikes would be the lowest.

(f) Dike bankheads must be designed so that erosion does not flank the structure; that is, disconnect it from the bank. Some local erosion is acceptable, but it must be limited. There are two basic approaches:

(1) Excavate a trench into the bank and extend the dike back into the trench (called the dike "root").

(2) Pave the downstream bank with an armor, and if conservative design is called for, also pave a lesser distance upstream. This usually involves grading the bank and placing riprap.

Specific guidance here is at least as difficult as for other dike design parameters. The best guide, unfortunately, is previous experience in similar circumstances, which is no comfort if similar experience is lacking. The difficulty lies in predicting velocity fields and the depth and precise location of the scour hole which will develop at an unprotected bankhead. For very expensive hydraulic structures, this difficulty is often resolved by large-scale physical models, which is usually impractical for bank protection projects.

The following are "rules of thumb" based on experience, but they cannot be considered formal guidance:

> For dikes in straight reaches, approach (1) above involves extending the dike root into the bank a minimum distance equal to the bank height. If the depth at high flow of local scour holes in the adjacent area, such as around erosion-resistant bank material or other obstructions to flow, can be observed or estimated, a more conservative approach is to extend the root into the bank a distance of the bank height plus that scour depth. If eroded "eddy pockets" downstream of existing protrusions into the channel are observed, the root should be at least as long as the maximum landward extent of those pockets. For areas of severe erosion, such as in bends, the root should be longer. Examples of extremes from practice: A root length of 300 feet is commonly used on Mississippi River dikes, but as little as 10 feet has been successful on very small tributary streams.
>
> USACE Mead Laboratory model tests described in USACE (1981) suggest that lateral erosion between dikes, thus required dike root length for approach (1), is related to stream depth (or bank height), velocity of flow, and dike length.
>
> When using approach (1), backfilling over the dike root, routing surface drainage away from the backfilled area, and vegetating the disturbed area will help prevent post-construction erosion and will improve the aesthetics of the project. Design of the backfill can be simple or sophisticated, depending upon specific site conditions. The simplest approach is simply to replace the excavated material in the most expeditious way (with due

allowance for subsequent settlement of the backfill) then letting nature take its course afterwards. The most sophisticated approach is to fill all voids in a stone root to the extent possible by flushing sand into the voids, then placing engineering fabric over the top of the stone and sand, then completing the backfill with compacted lifts of silt or clay, then vegetating the backfill and adjacent disturbed areas.

Bank height or bank height plus a scour allowance can also be used as a starting point for designing approach (2) above. The length of armor downstream of a dike should be a multiple, perhaps three for average conditions, of that dimension. Upstream paving is optional, but the distance need not exceed bank height. Normally, the bank toe just upstream of a dike is a depositional area. For designing stone paving, the guidance in Appendix A can be referred to, but because that guidance is not intended for application to highly turbulent situations, stone size and thickness should be greater than that which would be designed for a riprap blanket not adjacent to a dike, perhaps a multiple of 1.5 or 2.

Stone is an excellent choice for a root dike material, even if the dike itself is of other materials, because in other than mild erosion situations, the ability of the dike root to adjust to scour is critical.

In severe conditions, dike roots or armoring of bankheads can become large cost items, which is part of the reason why dikes can be more expensive than conventional bank armoring in those cases.

(g) Structural scour protection prevents undermining and failure of rigid dikes, and fortifies dikes of an adjustable material such as stone against unacceptable loss of elevation or length.

Alternative approaches to structural scour protection are to:

Place a blanket (sometimes called an “apron”) of adjustable armor or a flexible mattress on the bed under and adjacent to the dike. As with bankhead armor, this blanket or mattress should be of a stronger design than if it was being used at the same site not adjacent to a structure. USACE (1981) found that an apron of stone or gabion mattress did not reduce the depth of scour at the tip of a dike, but did enhance the stability of the structure by moving the scour away from it.

Place extra material at the end and on the side slopes of the dike. The extra material will launch into a scour hole and limit its extent, thus leaving the dike length and elevation intact. This approach is simpler to construct than an apron, but allows the scour to approach close to the dike. For a stone dike, it would consist of a crown wide enough for stone to launch into the scour along the face of the dike without breaching the crest elevation, and a slope at the end of the dike which is significantly flatter than the slope of natural repose of stone.

Specify extra penetration for pile structures so that scour will not fail the piling. However, unless the facing of the dike can adjust downward with the scour, or the dike is constructed entirely of driven piling this approach detracts from performance, since the total permeability of the structure is increased as the bed beneath the structure erodes. More flow is allowed to pass through the structure, and the scour may endanger bank stability. This is likely to be an expensive approach as well. For example, required pile penetration for one dike design on the Sacramento River was computed to be 13 feet if protected from scour, 34 feet if unprotected. Even if the dikes are constructed with adjustable facing which displaces downward with bed scour, maintenance of the design elevation by adding more facing will be required, unless the original design provided for lowering of the effective height of the structure.

Add structural features such as an L-head, "hockey stick," or T-head (sometimes called "hammerhead"), in order to move the scour away from the dike proper. This approach actually coalesces into a retard design if carried to the extreme of affecting overall flow rather than just local scour. Also, the scour around the added feature itself must still be addressed by one of the other approaches. A similar approach was used on some Mississippi River stone dikes in the 1960's, in the form of stone "rib spurs" built intermittently along the upstream face of dikes which were experiencing loss of stone due to launching into the scour hole caused by lateral flow along the upstream face. There was no conclusive evidence that this attempt to move the scour away from the dike was more cost-effective than simply adding additional stone to the dike cross-section to compensate for the launching, and the practice was soon discontinued.

Use a dike design that will maintain contact with the bed as scour occurs. Examples of this approach are jacks, "Palisades," tire-post dikes, and anchored trees.

Use a hydraulically smooth design for the end of impermeable dikes, and round structural members for permeable dikes (FHWA, 1985). However, this alone is not likely to be sufficient if the dike intercepts much flow.

A safety factor is sometimes added by using two or more of the above approaches in combination. Examples are a dike structure designed to maintain bed contact, along with armor or mat to limit scour; or extra pile penetration at the end of the dike, along with armor or mat for the full length of the dike as well as beyond the tip.

8.1.2 PERMEABLE DIKES

8.1.2.1 Advantages

The advantages of permeable dikes as compared to impermeable dikes are that they are equally, if not more effective when used on streams with relatively high concentrations of suspended sediment, and are often less costly.

8.1.2.2 Disadvantages

The disadvantages are that they are less durable than stone dikes and some other impermeable dike materials, and are usually considered less aesthetic, although the visual impact may ultimately be lessened by the growth of vegetation.

8.1.2.3 Design Considerations

Design considerations beyond those general considerations discussed previously for dikes involve materials, structural design, and miscellaneous items.

(a) Posts and piles for permeable dikes, and the main members of jacks, may be wood, steel, or concrete. The economic feasibility of using treated wood for decay prevention is a project-specific decision, as discussed by Petersen (1986). However, water quality considerations may preclude the use of some preservatives. Some early jack designs were patented, and although their use has become practically generic, the present legal status of these patents is unclear. Other shapes, such as tetrahedrons, are sometimes used. The function of tetrahedrons is identical to jacks, but they are stronger and more expensive than jacks made of the same components.

    At least one proprietary design of permeable dikes exists, called “Palisades.” They are constructed of panels of synthetic netting attached to pipes driven into the stream bank and bed. The panels can slide down the pipes to adjust to changing contours of the bank and bed.

    Anchored trees or brush provide an “all-in-one material.” The primary shortcomings are durability, and in some regions, availability.

    The most common facings are boards and wire fencing of various types. For pile dikes in deep streams, the piles are closely spaced without a separate facing material (Peterson, 1986). This design retains the original permeability ratio even if the bed beneath a dike scours, as long as the dike does not fail from loss of pile penetration, and it also makes construction of a permeable dike practical even in fairly deep water.

Hardware and fasteners, such as nails, bolts and cable, will be largely dictated by the choice of other materials. Corrosion resistant hardware must be used unless the work is temporary.

(b) Structural design is an iterative process. The goal is to achieve the required height and permeability in the most economical way, considering the cost of materials and the construction techniques that will be used. The variables for fence-type permeable dikes are:

Lateral loads (drag force of current, impact of debris);
Spacing, size, and penetration of piles;
Size of sub-components (boards, fencing, cables, anchors); and
Supplementary bracing.

The vulnerability to failure from lateral loads increases with dike height, since the moment arm of the force is greater, and the amount of debris carried by the stream, as well as the speed of impact, is likely to increase as river stage increases. As the height of the dike increases, this combination dictates an increase in the size of the structural members, as well as an increase in pile penetration for those designs using driven piles. These factors cause the cost to increase dramatically as the dike height increases.

Typical practice for penetration of piles or posts is that at least 1/2 to 2/3 of the total length should be in the ground. Factors that influence required penetration are the nature of the bed and sub-bed material, the potential for scour, and anticipated lateral loads from hydraulic loading and floating debris or ice. The nature of the material through which the piles or posts are to be driven must be known in order to determine if driving will be feasible. Encountering unanticipated difficulties during the driving operation may cause contractual difficulties as well as perhaps necessitating redesign of the work.

If previous experience has developed a design that has been successful in applications similar to the project at hand, it is more prudent to apply that experience rather than over-extending the safe bounds of theory with numerical structural analysis using imprecise assumptions. Figure 8.1 shows some typical designs of permeable dikes.

(c) Some miscellaneous design considerations are as follows:

The facing material should be attached to the upstream side of dikes.

Large trees which may be undermined and fall onto the dikes should be removed. Otherwise, existing vegetation should be preserved to the greatest extent possible. If clearing of the bank is necessary to provide construction access, stumps should be left in the ground, since regrowth of some species will occur.

Cuts made in treated wood members should be recoated with a preservative.

8.1.3 IMPERMEABLE DIKES

8.1.3.1 Description

The relative merits and faults of impermeable dikes as compared to permeable dikes were discussed in 8.1.2. Impermeable dikes can be built of the following materials:

Stone;
Gabions;
Earth, sand, or other material faced with armor;
Bags or tubes filled with sand or grout;
Walls of steel, wood, or concrete piling;
Wooden cribs filled with earth or stone;
Asphalt; and
Masonry.

Stone and gabions are the most commonly used of these materials. Although some of these materials are not truly impermeable, dikes constructed of them have permeabilities low enough that the amount of flow which passes through the structure is negligible. Discussion of the general characteristics of most of these materials is provided in Chapter 7. Typical impermeable dikes are shown in Figure 8.2.

(a) Palisades

(b) Board Fence Dikes

Figure 8.1 Typical Permeable Dikes

8.1.3.2 Design Considerations

Design considerations for impermeable dikes beyond the general factors discussed previously for dikes are as follows:

(a) Stone gradation for stone dikes is less critical than for riprap armor, which is fortunate, because there is no widely accepted method for designing stone gradation for dikes. Stone displacement due to scour will tend to be self-healing if the maximum stone size is adequate, and enough stone is present.

A larger maximum stone size required for dikes than would be used for riprap armor on the same stream, because turbulence and local acceleration of flow adjacent to the dike creates large hydraulic forces. Also, if stone is being placed in large depths and/or high velocities, larger sized stones will suffer less displacement as they fall through the water column, thus control of placement is easier and the amount of stone which falls outside the design cross-section will be reduced. The range of maximum stone sizes commonly used in practice is from 200 pounds to 5,000 pounds, depending on the depth of water, velocity of flow, and the amount of flow being intercepted by the structure, all of which influence the displacement forces on the stone and the amount of scour which will occur during and after construction.

The gradation of stone below the maximum size is dependent to a large degree on the economics of quarrying and handling the stone. Ideally, stone will be well graded, with a low percentage of spalls and waste particles. However, too restrictive a gradation will increase the cost of quarrying beyond the benefits gained. In general, the higher the cost of transporting the stone to the project site, and the more severe the hydraulic conditions, the more justified a strictly controlled gradation, since transportation costs for "waste" material in the stone is the same as for the high-quality stone.

(b) The crown width of stone dikes depends primarily on the amount of anticipated scour adjacent to the structure (see "Structural scour protection" in 8.1.1 above) and the height of the structure. As a practical matter, a crown width of about 2 feet is the smallest that can feasibly be constructed, while still providing a minimal amount of stone to launch into any scour that may occur. Crown width should be increased beyond that if the maximum stone size is larger than 2 feet, or if significant scour adjacent to the structure is expected and the height of the dike is so small that the amount of stone available to launch off the downstream side slope will be insufficient to retain an effective dike height.

Figure 8.2 Typical Impermeable Dikes

The method to be used to construct the dikes may also influence the choice of crown width. If land-based equipment is to be used, but the area where a dike is to be constructed is underwater or otherwise impassable, specifying a crown wide enough for the operation of hauling and handling equipment should be considered, since the additional crown width will strengthen the dike as well as expediting construction. Whether this is cost effective for a given structure will depend on the capabilities of the work force, the cost of stone, and the height of the structure, since the additional volume of stone required for a wider crown will increase exponentially with the height of the structure.

(c) The slope of natural repose can be specified for side slopes of stone dikes. Providing extra stone to launch into any scour hole that may occur adjacent to the structure can be accomplished more efficiently by increasing the crown width, as discussed in "Structural scour protection" in 8.1.1 above, than by attempting to construct a flatter side slope to accomplish the same purpose. Specifying the slope of natural repose simplifies construction, because then only the elevation and crown width of a dike require control in the latter stages of construction, which is especially advantageous if the side slopes of a dike are underwater. For pre-construction estimates of stone quantities, the slope of natural repose is commonly assumed to be 1 vertical on 1.5 horizontal, although some variation can be expected depending on stone gradation, construction procedures, and site conditions.

(d) The slope of the riverward end of a stone dike is often designed flatter than the slope of natural repose, as discussed in "Structural scour protection" in 8.1.1.

(e) Dikes with a core of earth or other material, with an armor on the surface, are not commonly used because they provide a smaller factor of safety against unanticipated scour and other severe hydraulic conditions than do sturdier structures. Baird and Klumpp (1992) report scour problems with such dikes on the Rio Grande River. A filter of some type between the core material and the armor is likely to be required, which increases the cost. Also, construction of this type of dike underwater is not usually practicable. In spite of these shortcomings, the potential for cost savings may be considerable if the cost of stone or other conventional dike materials is very high.

8.1.4 RETARDS

The relative advantages and disadvantages of retards were compared to dikes in Section 8.1.1.

8.1.4.1 Typical Application

The typical application of retards is where the channel is to be realigned, but the bend curvature, bank erodibility, debris load, or hydraulic conditions are too severe for dikes to be effective or economical. In some cases where channel realignment is not a factor, retards may be the preferred method if less expensive than bank armoring.

8.1.4.2 Design Considerations

Design considerations for retards beyond those discussed in Section 8.1 involve location, height, and tiebacks.

(a) If a change in channel alignment is not required, the preferred location for the retard from the standpoint of economy and efficiency is at a point slightly riverward from the toe of the bank slope. The location of the retard in plan view is determined by identifying that point on surveyed bank cross-sections, then plotting on a plan view that point's location at each cross-section. A smooth alignment can then be drawn through those points which "control" the overall alignment. Those points will be the ones which are farthest out in the channel. If the existing bank alignment is fairly smooth, then the retard alignment will pass through or near all the "preferred" points. However, if the existing alignment is irregular, then the retard alignment must necessarily lie riverward of many of the preferred points. If a pronounced single irregularity causes the retard to be located unacceptably far out in the channel upstream and downstream of the irregularity, then the alternative is to smooth the bankline irregularity by excavation.

(b) The height, or elevation, of the retard is determined by considering the factors discussed previously for dikes. The elevation of the retard can be varied around a bend as the attack against the bank and/or as the erodibility of material varies. This complicates design and construction somewhat, and is seldom done, but does have the potential to increase the efficiency of the design. The United Nations (1953) described some European work as having the retard highest at the apex of the bend, sloping downward to a minimum elevation at the upstream and downstream ends. A concern about that approach, however, would be that the downstream limb of a bend is often where the attack against the bank is greatest at higher flows, and the risk of a low elevation there is greater than for a low elevation at the upstream end. This is especially true after the work has been in place long enough for the normal downstream movement of scour pools and bars to have increased the hydraulic forces along the downstream portion of a retard in a bend.

(c) Tiebacks (sometimes called "baffles") are mandatory where the retard is located well in front of the bank and in short radius bends, and are recommended in all cases. For simplicity of design and construction, they are often of the same structural design as the retard, but can be of a less costly design if site conditions permit a less conservative approach. The length of tiebacks is determined by the distance from the bank to the retard. The top elevation of tiebacks is commonly made the same as the retard, although a lower elevation can be used for a less costly, but less conservative, design.

The spacing of tiebacks can be designed according to the concepts discussed previously for spacing of dikes. However, such a design would often be overly conservative, since the tiebacks are simply used to reinforce the main protection device, the retard itself. The permissible increase in spacing can be determined for a specific site only by applying judgement, experience, and the factors discussed in 6.6, "Safety factor."

General practice is to place tiebacks on the shortest line from the retard to the bank. This is the least costly approach, and provides a compromise between them being perpendicular to the realigned flow and perpendicular to the existing bankline. The lack of agreement regarding the optimum angle that transverse structures should have with respect to direction of flow is less troubling for tiebacks than for dikes, since the tiebacks are not the primary component of the work.

Tieback bankhead design should follow the same principles as for dike bankheads, but can be less conservative in many cases since the retard itself will usually decrease erosive forces at the tieback bankhead.

8.1.5 PERMEABLE RETARDS

The advantages of permeable retards as compared to impermeable retards are that they are equally, if not more, effective when used on streams with relatively high concentrations of suspended sediment, and are often less costly to construct, since materials are usually available locally. Typical permeable retards are shown in Figure 8.3.

The disadvantages are that they are less durable than stone retards and some of the other impermeable retard materials, and are usually considered less aesthetic. They also interfere to a greater degree with access to the stream channel.

Most aspects of materials and structural design are the same as for permeable dikes (see 8.1.2). Other design considerations beyond those discussed previously for retards are as follows:

(a) Double-row retards are sometimes used to increase structural stability and to further reduce flow behind the retard. A double-row design also gives the impression of better toe protection, but that may be illusory for rigid retards, since if the first row fails from toe scour, the second row is likely to fail eventually also. However, the outer row of flexible double-row retards, such as jacks, can displace downward into a scour hole and still provide protection to the inner row.

(a) Board Fence Retard

(b) Jack Field

Figure 8.3 Typical Permeable Retards

Rigid double-row retards are sometimes used as "cribs," filled with various materials to further reduce velocities behind the retard. This is a site-specific decision, dependent on the economics of filling versus using a less permeable facing design, and on the durability required of the filling material. Using local material such as hay or brush reduces permeability at low cost, but at the expense of durability, and relies on future deposition and vegetation for permanent velocity reduction. A stone filling provides permanent toe protection as well as permeability reduction, but requires a substantial facing to retain the stone, and will add substantially to the cost. Used tires (perforated to reduce buoyancy) provide an inexpensive and durable filling, if regulations permit such use. However, undermining or deterioration of the crib may result in an unsightly redistribution of the tires along downstream river banks, adding environmental insult to the injury of a failed structure.

(b) Some designs, such as fence-type retards, require that the bottom member be approximately horizontal. Therefore, some leveling of the streambed along the line of the structure may be required during construction, which limits the use of these designs to ephemeral streams and minor scour situations, unless a material such as stone is used to build up the base. In that case, the stone will also serve as toe protection. Otherwise, any leveling of the streambed to expedite construction must be considered as being temporary, lasting only until the first flow event.

(c) Carlson and Dodge (1962) present a method for determining the suitability of jack retards for a given situation, and for estimating the amount of deposition likely to be induced by them.

8.1.6 IMPERMEABLE RETARDS

The relative advantages and disadvantages of impermeable retards as compared to permeable retards were discussed in 8.1.5. Most aspects of materials and structural design are the same as for impermeable dikes (see 8.1.3). An impermeable retard of stone can be considered to be a form of longitudinal stone toe, discussed in 7.1.4 and most aspects of design discussed there are applicable to stone retards.

8.2 OTHER FLOW DEFLECTING METHODS

Structures other than dikes and retards may provide a means of altering hydraulic conditions in order to resist bank erosion in bends. One of the most intractable problems of river engineering is posed by the coupled processes of deposition of sediment on point bar faces and scour in the thalweg of bends. Several approaches have successfully addressed these coupled processes in some cases. These approaches alter secondary currents so that sediment transport away from the toe of the bank is reduced. This results in a more uniform cross-section shape, with shallower thalweg depths and a wider channel at low flow. These approaches include Iowa vanes, bendway weirs, and sills.

8.2.1 IOWA VANES

The technique called "Iowa vanes" originated from physical model tests performed by the Iowa Institute of Hydraulic Research for the U.S. Army Corps of Engineers (Odgaard and Kennedy, 1982). The purpose of the model study was to define a bank stabilization technique for the Sacramento River which would be both effective and environmentally sound although the proposed solution was not actually implemented. The first field application was sponsored by the Iowa Department of Transportation in 1985 on the East Nishnabotna River near Red Oak, Iowa. Subsequent development of the technique has led to it being patented. At present, the primary use of Iowa vanes is on bank stability problems on small rivers and on local sedimentation problems, such as at water intakes, on larger rivers. Results from these works may in time identify broader applications.

Iowa vanes are fully submerged during high flows, but are above the water level at low flows. The location and orientation of the vanes with respect to flow is critical to success. Also, because success depends upon the structures having a precise effect on the velocity vectors in the bend, stabilization of the upstream bend is recommended if upstream channel migration is likely to change the flow patterns entering the vane system.

Initial evaluation of the East Nishnabotna installation indicated that flowlines through the project reach were not affected by the structures (Odgaard and Mosconi, 1987).

8.2.2 BENDWAY WEIRS

Bendway weirs were developed by the U.S. Army Corps of Engineers as a method to increase channel width in bends on the Mississippi River in order to improve navigation conditions and reduce maintenance dredging requirements (Derrick et al., 1994). They also induce deposition in the thalweg of the bend, which should enhance bank stability and reduce the tendency for scouring velocities in the overbank area during floods. The success of bendway weirs is based on the premise that the flow over the weir is redirected at an angle perpendicular to the weir. When the weirs are angled upstream, the water is directed away from the outer bank and towards the inner bank, or point bar.

The weirs on the Mississippi River are level-crested stone structures angled upstream, with a crest elevation about 15 feet (4.5 meters) below low water. The design is based on physical model studies at the Waterways Experiment Station, which indicated that a pronounced upstream angle was required for the structures to function properly. The first system was installed in 1990 on the Mississippi River upstream of the mouth of the Ohio River, and is performing well. That installation and several subsequent ones are being monitored, and other installations are planned.

Environmental aspects of bendway weirs appear to be favorable. Since they are submerged well below low water level, the detrimental impacts on esthetics and safety which are associated with most other indirect protection techniques are eliminated. Also, by providing a rocky substrate for benthic organisms and cover for fish, and by altering the velocity distribution across the cross-section and in the vertical, they improve habitat conditions for some species of aquatic life. Whether detrimental effects would accompany these beneficial effects in other applications would depend upon the environmental context of a specific application.

In recent years, bendway weir theory has been applied to small stream applications as a streambank protection measure (Figure 8.4). The first small stream application was in 1993 on Harland Creek near Tchula Mississippi where fifty-four bendway weirs were constructed (Derrick, 1997a). Since that time, bendway weirs have been built on numerous small streams throughout the country. Some of theses projects have used low-cost, hand placed stone weirs, and weirs constructed of tree trunks and geobags to protect farmland (Derrick, 1997b). Because this is a recently developed technique, the long term success of these structures as a bank stabilization scheme is not known. Further research and monitoring of existing structures is needed to document the long-term performance and to develop more definitive design criteria.

(a) Bendway Weirs on Harland Creek

(b) Bendway Weirs in Combination with Longitudinal Peaked Stone Toe Protection

Figure 8.4 Bendway Weirs on Small Streams

CHAPTER 9

VEGETATIVE METHODS FOR EROSION PROTECTION

The two previous chapters addressed structural approaches to erosion protection, in the form of surface armor and indirect techniques. Vegetation's great potential for use in erosion protection, and the requirement that it be carefully planned and designed using skills not usually included in traditional engineering knowledge, merits separate discussion. This chapter is not an exhaustive treatment, but does present a rational overview of the subject. The latest U.S. Army Corps of Engineers guidance for bioengineering for streambank erosion control is discussed in Appendix B.

9.1 OVERVIEW

Vegetation is the basic component of what is known as "bioengineering" (Schiechtl 1980) or biotechnical engineering (Gray and Leiser, 1982; Gray and Sotir, 1996). Schiechtl (1980) states that bioengineering requires "the skills of the engineer, the learning of the biologist, and the artistry of the landscape architect." The concept of bioengineering is ancient, but there has been much recent research and documentation of the topic. The publications just cited, as well as Coppin and Richards (1990), provide comprehensive coverage, and many other works provide discussion of specialized aspects of the subject.

9.1.1 FUNDAMENTAL CONCEPTS

Vegetation can function as either armor or indirect protection, and in some applications, can function as both simultaneously. Grassy vegetation and the roots of brushy and woody vegetation function as armor, while brushy and woody vegetation function as indirect protection. The roots of vegetation may also add a degree of geotechnical stability to a bank slope through reinforcing the soil.

Some factors which affect the success of a bioengineering approach, such as weather and the timing and magnitude of streamflows, are beyond the designer's control. Therefore, expert advice, careful planning, and attention to detail are critical to maximizing the probability of success.

Many streambank protection projects include vegetation without conscious thought by the designer, since native vegetation often establishes itself once the processes of bank failure are stopped by structural means. However, if the potential for utilizing vegetation is considered from the beginning, then the effectiveness, environmental aspects, and economy of a project can often be significantly improved.

The general principles of erosion protection discussed in Chapter 6 are fully applicable to vegetative work. In fact, because vegetative works are generally more vulnerable than structural works, particular care must be taken to insure that the overall approach is sound. Beyond those general principles, the details of successful use of vegetation are even more site-specific than for structural bank protection. The terminology of the details can sometimes be confusing, because the technology developed somewhat independently from region to region over a long time period, whereas widespread interdisciplinary interest in the subject, and broad dissemination of the technology, is fairly recent. Also, the many variations on the basic techniques add some confusion to the terminology. However, the basic concepts are straight-forward, and have international and timeless application.

9.1.2 ADVANTAGES

The two obvious advantages of vegetation as erosion protection are its environmental attractions and its relatively low cost. A third and less obvious attraction is that it can increase the safety factor of structural protection by enhancing the level of performance. Because many types of vegetative treatment are labor intensive, the cost advantage will be especially prominent in regions where labor is inexpensive, skilled in agriculture, and conscientious.

9.1.3 DISADVANTAGES

Some characteristics which make vegetation effective and desirable in most situations may be disadvantages in other situations. However, many of the following concerns will either not be applicable for a specific project, or will be acceptable as compromises in light of vegetation's merits.

The most serious shortcoming is that even well executed vegetative protection cannot be planned and installed with the same degree of confidence, or with as high a safety factor, as structural protection. This is not to say that vegetation will not be adequate, or will not be more cost effective than structural protection in a specific situation, but is rather an acknowledgement that structural protection can be designed to function under more severe conditions of hydraulic and geotechnical instability than can vegetation. Vegetation is especially vulnerable to extremes of weather and inundation before it becomes well established.

Quantitative guidance for the use of vegetation in streambank protection is limited, although there has been progress through recent research.

Most vegetative measures have constraints on the season of the year that installation can be performed. This shortcoming can be mitigated to some degree by advance planning or by developing more than one option for vegetative treatment.

Vegetative treatments often require significant maintenance and management in order to prevent the following problems:

> Growth of vegetation causing a reduction in flood conveyance or causing erosive increases in velocity in adjacent unvegetated areas.
>
> Deterioration of the environmental function of the vegetation due to mismanagement by adjacent landowners, vandalism, or natural causes.
>
> Trunks of woody vegetation or clumps of brushy vegetation on armor revetment causing local flow anomalies which may damage the armor.
>
> Large trees threatening the integrity of structural protection by root invasion or by toppling and damaging the protection works, or by toppling and directing flow into an adjacent unprotected bank.
>
> Roots infiltrating and interfering with internal bank drainage systems, or causing excess infiltration of water into the bank.
>
> In arid regions, vegetation's ability to reduce soil moisture may be a concern. However, this is not likely to be a serious concern if the native plant ecosystem was considered in the initial selection of vegetative species. In any event, a riparian strip of vegetation is not likely to harm the groundwater resource enough to outweigh the positive values of the vegetation.
>
> Many of these problems may be avoided through selection of the appropriate type, and species or clone of vegetation for the purpose. However, designers rarely have the practical experience or formal training in biotechnology to make such selections and expert advice must be obtained from qualified individuals in plant biology and bioengineering.

9.1.4 TYPICAL APPLICATIONS

Vegetation is most often used in conjunction with structural protection. Exceptions may be made for very small waterways, for areas of low erosion activity, or for situations where the consequences of failure are low and there is provision for rehabilitation in case of failure. Vegetation can have a particularly important role in the stabilization of upper bank slopes.

Vegetation is especially appropriate for environmentally sensitive projects, whether benefits to recreation, esthetics, or wildlife is the object.

Vegetation is well-suited for incremental construction, either to wait for more favorable planting conditions for specific types of vegetation or to wait for deposition of sediments in the area to be planted. Vegetation is also suitable for inexpensive reinforcement or repair of existing erosion protection works in some situations.

Woody vegetation is useful in preventing or repairing scour at or behind top of bank, especially if the scour resulted from an infrequent flood event which is not likely to recur before the vegetation becomes effective.

Woody vegetation is sometimes used to prevent floating debris from exiting the channel during floods and becoming a nuisance in the floodplain.