United States Department of Agriculture
Natural Resources Conservation Service

A Guide for Design and Layout of Vegetated Wave Protection for Earthen Embankments and Shorelines

Technical Release 56

(210–VI–TR–56, April 2014)

Issued April 2014

Cover photo: Vegetated wave protection on an NRCS dam

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Acknowledgments

Technical Release No. 56, A Guide for Design and Layout of Vegetated Wave Protection for Earth Embankments, dated 1974, was originally developed as a joint effort between the Plant Sciences and Engineering Divisions of the USDA Soil Conservation Service (SCS). This version updates that original work and was prepared by a team led by **Jon Fripp**, Stream Mechanics Civil Engineer, NRCS National Design, Construction and Soil Mechanics Center (NDCSMC), Fort Worth, TX, and **Joel Douglas**, Plant Materials Specialist, Central National Technical Support Center, Fort Worth, TX, under the direction of **Steve Durgin**, National Design Engineer, Washington, DC. Numerous people provided source information as well as expert reviews and comments. NRCS acknowledges the efforts of the following individuals in developing this updated document: **Ruth Book** (Illinois), **Jim Briggs** (Oregon), **Allen Casey** (Kansas), **Andy Deichert** (West Virginia), **Ramona Garner** (North Carolina), **Mari Gilford** (Louisiana), **Coleman Gusler** (Kentucky), **Chris Hoag** (retired wetland plant ecologist), **Claudia Hoeft** (National Hydraulic Engineer), **Paul Larson** (Kansas), **Mark Locke**, (retired National Design Engineer), **Morris Lobrecht** (retired Design Engineer), **Mathew Lyons** (Virginia), **Norman Melvin** (Texas), **Mike Monnin** (Ohio), **John Ramsden** (Wisconsin), **Timothy Ridley** (West Virginia), **Kerry Robinson** (retired hydraulic engineer), **Terri Ruch** (North Carolina), **Heath Sand** (Oklahoma), **Bruce Sandoval** (Idaho), **Don Shanklin** (retired construction engineer), **Dan Vasher** (Michigan), **Karl Visser** (Texas), **Phuc Vu** (Texas), **Richard Weber** (Texas), and **Ken Worster** (Texas).

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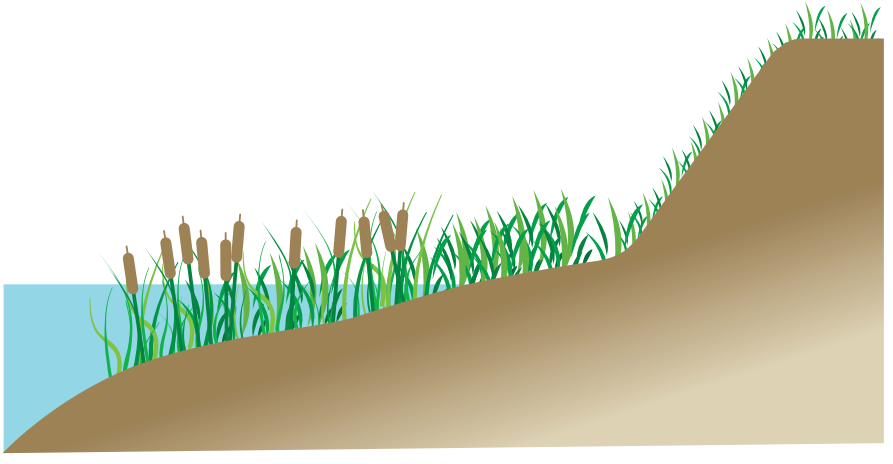
Abstract

Earthen embankments, such as dams, dikes, and levees, and the shorelines of natural and constructed water bodies are often degraded by the erosive action of wind-generated waves and flows. Left untreated, this damage can become severe and endanger structures, cause damage to property, and degrade the ecological functions of shoreline landscapes. Different types of protection can strengthen resistance to wave attack of earthen embankments and shorelines. These protection approaches can range from structural armoring to vegetated wave protection. This technical release provides guidance for the design of vegetated protection berms. The recommendations provided herein are based on peer-reviewed literature as well as empirically developed guidance based on review of vegetated wave protection performance. This technical release presents a simplified approach that is suitable for most small, inland NRCS projects. It is not intended for high-risk projects, large open water, or projects on the coast. Such projects should be designed in accordance with Technical Release 69 or following U.S. Army Corps of Engineers (USACE) guidelines.

Typical vegetated berm profile, showing two-thirds of the berm below the normal pool elevation and one-third of the berm above the normal pool. Calculations to determine these dimensions are provided in this document.



Contents:

Introduction 1
Advantages of vegetated wave protection 2
Limitations of vegetated wave protection 2

Determination of wave height 2
Wind-generated waves 2
Boat-generated waves 8

Determination of wave protection limits 8
Pool elevation 8
Lower elevation of protection 8
Upper elevation of protection 9

Layout of vegetated wave protection berm 10

Selection of vegetation for wave protection 11
Planting and hydrology zones for wave protection 11
Recommended plant species 13
Vendor guide 14
Irrigation 14

Soil bioengineering techniques 19

Maintenance 19

Example problem 20

References 21

Tables

Table 1	Limitations on the use of vegetated berms for embankment protection	3
Table 2	Example calculation of effective reach trial	6
Table 3	Plants for wave erosion control and aquatic functions	15

Figures

Figure 1	Erosion at the toe of an earthen embankment	1
Figure 2	Vegetation incorporated into the habitat and aesthetic features of a reservoir	2
Figure 3	Effective fetch (F_e) calculation. The central radial is line C	5
Figure 4	Maximum wind velocity over land (mph), 50-year recurrence	6
Figure 5	Wind ratio	7
Figure 6	Wave erosion at different pool levels	8
Figure 7	Wave protection berm section	10
Figure 8	Typical vegetated berm profile, showing two-thirds of the berm below the normal pool elevation and one-third of the berm above the normal pool	10
Figure 9	Planting and hydrology zones for vegetated protection	11
Figure 10	Inland saltgrass, suitable for use in the “saturated to permanently ponded” zone	12
Figure 11	Maidencane on a vegetated berm	12
Figure 12	Prairie cordgrass on a vegetated berm	13
Figure 13	NRCS plant distribution regions	13
Figure 14	Example treatment using soil bioengineering	19

A Guide for Design and Layout of Vegetated Wave Protection for Earthen Embankments and Shorelines

Introduction

A great deal of energy can be transported in the form of wind-generated waves. The erosive action of wind-generated waves can degrade the shorelines of natural and constructed water bodies as well as earthen dams, dikes, and levees. The obvious mechanism for causing damage is when the waves dislodge the material on the embankment. As the waves impact the shoreline, the soil is washed away. This is a particular concern for many NRCS projects.

A less evident but often more serious mechanism of wave induced damage results from erosion along the toe of constructed embankments and natural slopes, as shown in figure 1. Scour along the toe effectively steepens the bank and can result in geotechnical slope stability problems for the dam embankment. As material is eroded from the toe or base of the embankment, the resulting steeper embankment experiences a reduction in effective resistant forces. Bank failure results from bank steepening beyond stable geotechnical limits.

Therefore, it is important to be able to provide suitable protection from wave attack. Wave protection can fall in two broad categories.

Armor the bank to resist the energy. Armoring is usually done with rock, soil cement, or other protective structure. Technical Release (TR) 69 addresses the design of structural armor to resist wind-generated erosion.

Figure 1 Erosion at the toe of an earthen embankment

Dissipate the energy before it reaches the embankment. Energy dissipation is typically accomplished with the use of a vegetated gently sloping berm or shaped shoreline. The wave energy is absorbed by passing through this barrier before it can strike the embankment. The energy dissipation approach is the subject of this technical release.

While there is overlap in the suitability of the different protection approaches, they are not interchangeable. The choice of protection approach to utilize can be dependent on a variety of factors including energy that may be applied to the shoreline, fluctuations in pool, adjacent land use, maintenance capacity, tolerance for risk, and local acceptability. While all of these issues can be of critical importance in the planning stages of a design, the focus of this technical release is on designing energy dissipation for wind-generated waves. Therefore, it is important to be able to quantify the amount of energy that may be conveyed by wind to a constructed embankment or shoreline so that suitable wave protection can be designed to resist this energy. This document provides tools for quantifying the energy that is in the form of wind-generated waves and designing **vegetated wave protection to dissipate that energy** before it impacts the embankment or shoreline.

The type of protection described in this technical release has been used on many small NRCS embankment dams or to protect shorelines. These designs were primarily based upon an earlier version of this document, TR–56, dated December 1974. Since the last version of this document, additional wave protection design information has been made available. Recent literature has been reviewed and is incorporated into this document. The guidance presented in this document is simplified from this information. In addition, several empirically derived guidance recommendations on the design of vegetated wave protection berms have been developed and used by different entities. Much of this guidance was developed by examining the performance of different vegetated berms. While empirically derived rules of thumb are not scientific studies, there is remarkable agreement between some of the recommendations across geographic areas.

Advantages of vegetated wave protection

Vegetated shoreline stabilization is considered a "soft" approach. This approach is often less expensive to install and maintain than hard armor (inert) protection. Unlike inert material, vegetation that has been damaged can often reestablish itself.

Vegetation can provide important habitat benefits for both terrestrial and aquatic organisms, as well as nutrient cycling functions for water quality improvement. A gently sloping and vegetated shoreline facilitates recreation uses and is generally considered to be more aesthetically pleasing than hard armor protection. Figure 2 shows a vegetated shoreline and dam.

The sloped berm located in a shallow depth used in vegetated protection also reduces the amount of wave energy that is transferred to the shore. As the water becomes shallow, the wave steepens. The maximum wave height is approximately three-fourths of the water depth. At this point, the wave becomes unstable and breaks. It reforms at a lower height.

Figure 2 Vegetation incorporated into the habitat and aesthetic features of a reservoir

Limitations of vegetated wave protection

Vegetation has long been used to stabilize shorelines of reservoirs and ponds. However, it is not applicable in all situations. This technical release addresses the design of vegetated shoreline protection where the erosion is caused by wind energy being transferred to the shoreline through the action of waves. The limitations of the vegetated wave berm technique discussed in this technical release are listed in table 1. Suggested course of actions to address these limitations are also included in this table.

Determination of wave height

The design of any protection for a constructed embankment is dependent upon the forces that it must withstand. The energy that is exerted by the waves on protection shore is a function of the wave height. Waves generated by wind are often the most concern for NRCS projects. But designers must keep in mind that waves can also be generated by boat wake.

Wind-generated waves

The mechanics of wind-generated waves and erosive forces caused by these waves are very complex. This technical release provides a simplified analytical design procedure for the assessment of wave attack. This design procedure is based on the following three assumptions:

- The height of the wave is a measure of the energy contained in each wave and of the energy that must be dissipated by the vegetation from each successive wave.
- Wave height is a function of wind direction, wind speed, and fetch length.
- There are no bathymetric limitations on ultimate wave height. This is referred to as the "deep water wave assumption."

These assumptions greatly simplify a complex situation and are generally appropriate for most NRCS projects. For very complex shore protection projects, additional considerations may be taken into account, which is described in detail in USACE Shore Protection Manual (1984).

Table 1 Limitations on the use of vegetated berms for embankment protection

Issue	Concern and alternative
Fluctuating pool level	If the pool elevation fluctuates considerably, the vegetation may not be able to survive without extensive supplemental irrigation or the vegetation could be drowned by prolonged flooding. This is often a concern for irrigation and industrial dams. Extended wave protection berms or inert protection may be necessary if the pool fluctuates significantly.
Arid and semiarid climates	In arid and semiarid climates, the vegetation must be supported by the reservoir pool. Therefore, the accumulative volume of inflow to the reservoir remaining, after seepage and evaporation losses, must be sufficient to maintain the normal pool level within the vertical fluctuation range of the vegetation on the sloping berm. Supplemental irrigation or inert protection may be necessary if the pool fluctuates significantly
Large fetch lengths	Wind traveling across large pools can generate significant waves. When the distance of open water in front of the dam (effective fetch) available to generate waves is in excess of 1,600 feet, the use of vegetation alone may not be sufficient to absorb wave energy. The use of inert material such as rock, soil cement, geogrids, or a combination of inert material and vegetation is typically required to provide effective stabilization.
Geotechnical bank instability	Instability caused by geotechnical or groundwater seepage is not addressed in this guidance document. Generally, such geotechnical problems will need to be approached with a combined use of grading, structures, and vegetation. It should also be noted that vegetation can obscure some geotechnical issues.
Ice and debris	Wind-generated waves can also cause damage to embankments by driving debris and ice into the shore. A structural approach may be necessary if the embankment is in an area where it must resist ice and debris.
Boat wake	Damaging waves can be caused by boat wake. This technical release primarily addresses waves caused by wind. If wake from large craft is a significant issue at the site, inert protection is likely necessary.
Maintenance	Maintenance is required for this approach to be effective. Maintenance and operation may include fencing to prevent damage from grazing animals, fertilizing and supplemental irrigation during plant establishment, and replacement of vegetation that has been destroyed. Care must also be taken to assure that a vegetated berm does not result in woody material growing on the embankment of a dam. If maintenance cannot be performed, then this approach may not be suitable.
Small ponds	This technical guidance is not directed to small farm pond shorelines and embankments. Damage from an extreme event on a small pond is better addressed by routine maintenance.
Conditions for plant growth	For plants to be established and survive, a suitable soil depth, texture, and fertility must be available. Expected rainfall or supplemental irrigation may be required for plant establishment
Tolerance for risk	The vegetated component of the berm or shoreline inherently includes more risk than inert wave protection. Vegetation can also mask slope issues such as borrowing animals and slides. Projects where failure of the protection may result in significant to risk to life and property may not be suitable for the use of vegetated berms to provide wave protection.
Heavy recreation use	Heavy recreational use can damage the protective vegetation on the berm. Foot trails and paths can cause runoff to concentrate and cause erosion. Measures can be taken to protect the vegetation if this is a concern. Heavy bushes and fencing can be used to restrict access. Defined hard fishing access can also be provided in targeted areas.

Simplified procedure for estimation of wind-generated wave height

This simplified procedure calculates wave height as a function of the wind velocity and distance. The energy of wind is conveyed and applied to the embankment by the waves generated by the wind acting on the water surface. This procedure is divided into four basic steps:

Step 1 Determine the effective fetch.

Step 2 Determine the overland wind velocity.

Step 3 Determine the overwater wind velocity.

Step 4 Determine the significant wave height.

These steps are described below in detail as follows:

Step 1 Determine effective fetch (F_e)

The fetch is the distance across open water that the wind blows to generate waves. Direct fetch is the longest uninterrupted distance across the water. In enclosed bodies of water, the fetch is limited by the sides of the reservoir or impoundment. Effective fetch (F_e) is used to take into account the effects of the reservoir shape. This is done by taking into account the energy transferred to the water from wind in all directions within a 90-degree arc centered on the prevailing wind direction (Saville 1954). The assumption behind this approach is that the smaller that the width to length ratio is for the impoundments, the shorter the effective fetch. The following procedure is an approach for computing effective fetch for an impoundment of any shape.

a. Obtain an aerial photograph, USGS quad map, or other plan view of a lake or impoundment pool. The inundated area at normal pool should be indicated on the map. The term "normal pool" as used in this document refers to the still water reservoir elevation during passage of the maximum base flow through the spillway with the reservoir full. The maximum baseflow is the maximum flow into the impoundment that is not related to a specific surface rainfall-runoff event.

b. Approximate the predominant wind direction. This judgment can be based on familiarity with site conditions as well as a review of local climatological data if available. Predominant wind direction information may be available from the National Weather Service. If information of wind directions is not available or not appropriate for the site (for example, a site is in a confined valley), the designer may elect to choose a predominant wind direction that produces the longest fetch.

c. On the plan view of a lake or impoundment pool, draw a "0" (or 0-degree) line from the area of interest at an assumed wind direction that represents the chosen wind direction for this trial. For estimation at dams, this line should extend from the point of greatest vulnerability on the dam through a direction that includes the largest area within 45 degrees of either side of the line. This line is referred to as a "central radial" and is illustrated with line C in figure 3.

d. Draw 14 radial lines at intervals of 6 degrees from the "0" line (seven on each side of the "0" line). Continue to 42 degrees (within 45 degrees from the central radial). Each radial line should be extended to an intersection with the reservoir contour that represents the elevation of the water surface (normal pool) in the reservoir for the fetch being calculated.

e. Measure the length of each line as a distance and record as shown in table 2. Multiply each distance by the cosine of the angle α, measured from the line to the "0" line.

f. Sum the distance multiplied by the cosine of each angle and divide by the sum of the cosines. This calculation of effective fetch is accomplished using the following equation:

$$F_e = \frac{\sum(\text{distance} \times \cos\alpha)}{\sum \cos\alpha} \qquad \text{(eq. 1)}$$

where:
F_e = effective fetch

In the case of the trial 1 example shown in table 2, the effective fetch would be 1,325 feet.

g. Determining prevailing wind direction as well as the main point of intersection at an area of interest can be problematic. To account for uncertainty, choose at least two more central radial wind directions that are reasonable. Consider the longest apparent length for the central radial. Repeat the process for a total of three trials of different wind directions. Chose the largest effective fetch (F_e).

This calculation assumes that there is an uninterrupted line from the shoreline in question across the water surface. If a small promontory or low island obstructs this line or the point in question is around a small bend, the effective fetch calculated

Figure 3 Effective fetch (F_e) calculation. The central radial is line C.

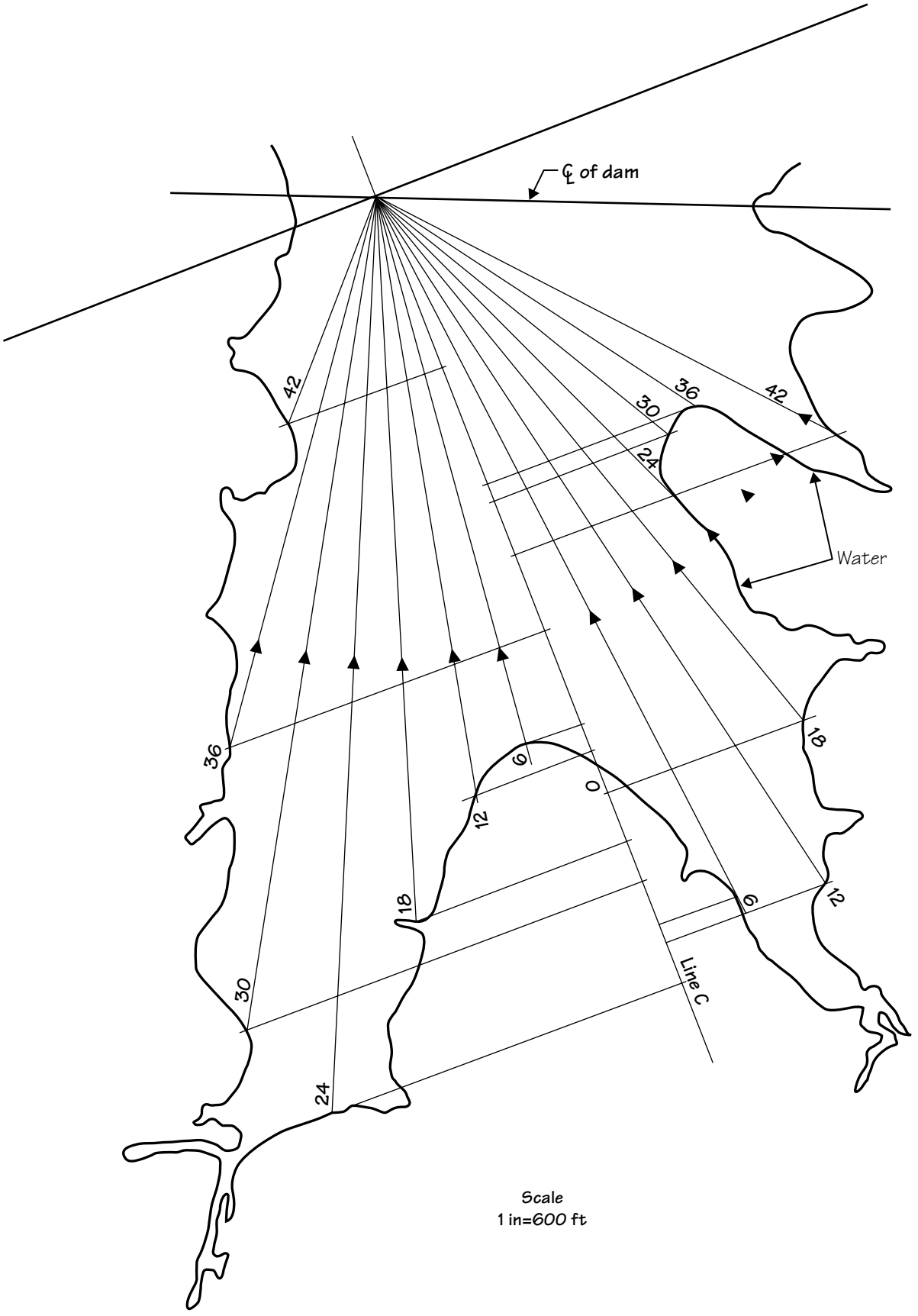


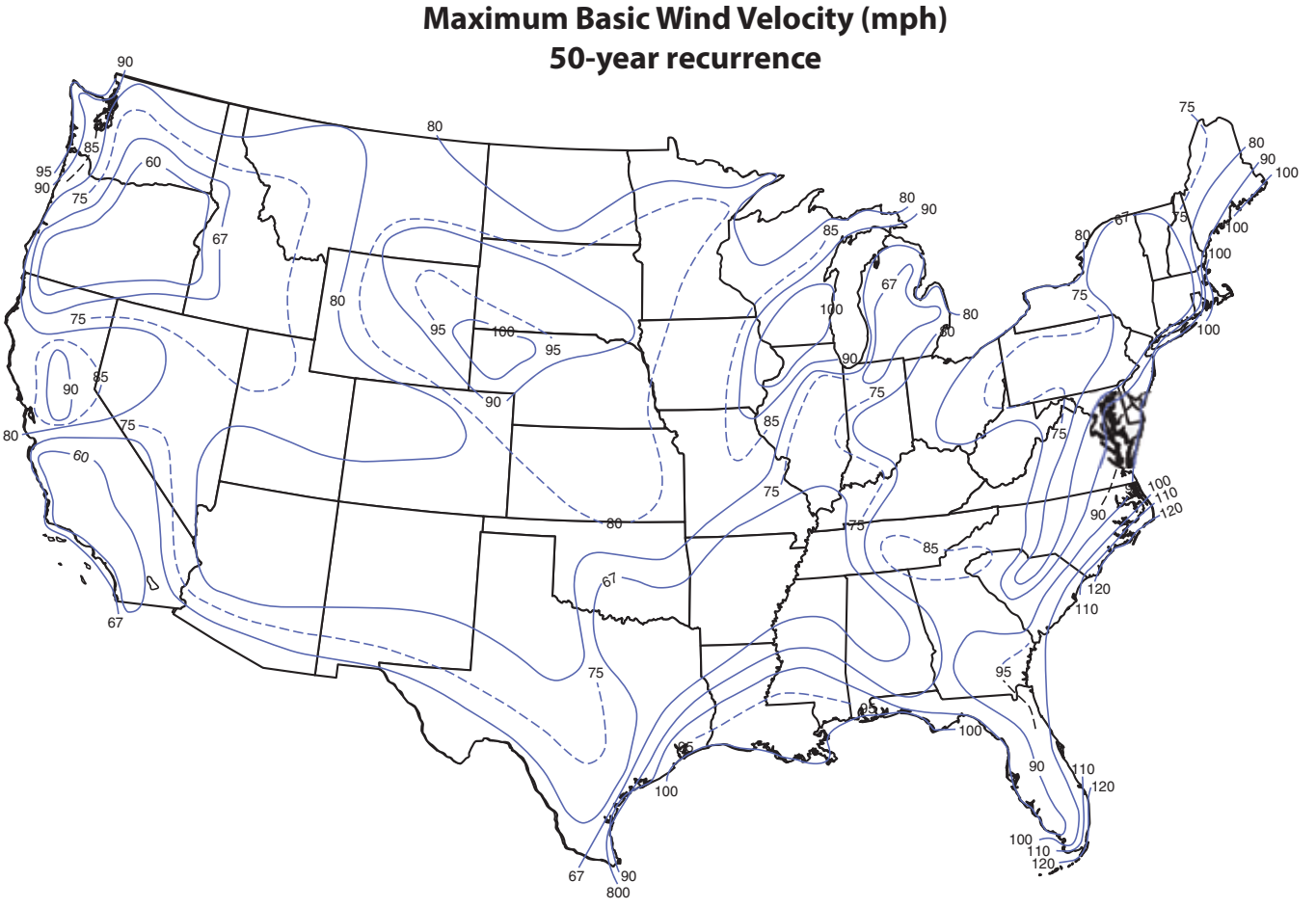
Table 2 Example calculation of effective reach trial

α	cos α	Trial 1 (example)	
		Distance (ft)	Distance × cos α
42	0.743	600	446
36	0.809	1,500	1,214
30	0.866	1,700	1,472
24	0.914	1,800	1,645
18	0.951	1,600	1,522
12	0.978	1,550	1,516
6	0.995	1,500	1,493
0	1.000	1,575	1,575
6	0.995	1,600	1,592
12	0.978	1,650	1,614
18	0.951	1,550	1,474
24	0.914	700	640
30	0.866	600	520
36	0.809	550	445
42	0.743	1,000	743
SUM	13.512		17,909

with this approach could be greatly reduced. In practice, waves refract and diffract around such obstructions. A simplification is to ignore low obstructions but there is some reduction in waves that may result in cost savings for a project. A detailed analysis of such conditions requires additional considerations and analysis. These methods are beyond the scope of this technical release but are available in Reservoir Dams: Wave Conditions and Wave Overtopping (Yarde et al. 1996) and in the USACE Shore Protection Manual (1984).

There is anecdotal evidence that this analysis can result in an underprediction of effective fetch and thus wave height on gently curved or "banana-shaped" impoundments. This can be of particular concern for high-risk sites. For impoundments of this shape, the fetch length should be bent to follow the axis of the reservoir (Yarde et al. 1996). This would reflect a definite worst-case condition and would prevent shorter radial lines on the sides from reducing the final estimated effective fetch when averaged into the total.

Figure 4 Maximum wind velocity over land (mph), 50-year recurrence



Step 2 Determine overland wind velocity (V_L)

The maximum overland wind velocity (V_L) can be estimated using figure 4. This figure contains isolines for maximum wind velocity at 30 feet above the ground at a 50-year recurrence interval (2% probability of occurrence). The user should locate the site on the map and identify the maximum velocity with the isolines.

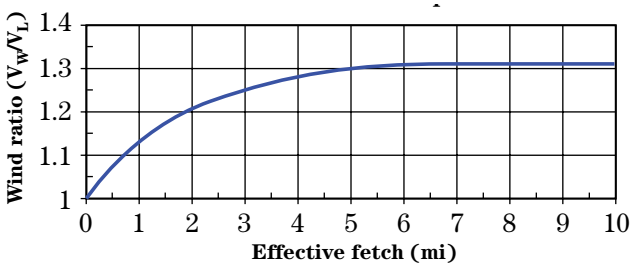
Judgment should be used particularly in mountainous areas where wind velocity can be affected by topography. Coastal areas may also require site specific considerations. Additional guidance is available in the USACE Shore Protection Manual (1984). Alternatively, the designer can use local climatological data if it is available and acceptable. This information may be available from the NOAA National Weather Service.

Step 3: Determine overwater wind velocity (V_w)

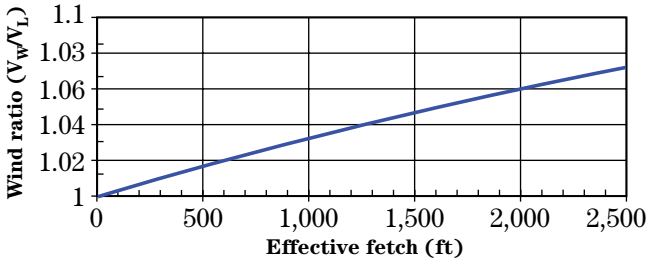
Overwater wind velocities are higher than wind velocities over land. Therefore, it is important to adjust the maximum wind velocity, determined in step 2, to reflect overwater conditions. The effective fetch determined in step 1 is used to identify a wind ratio in figure 5. This is the design wind velocity for shore protection. The overwater wind velocity is calculated using equation 2.

Figure 5 Wind ratio

(a) Wind relationship overwater to overland (miles)



(b) Wind relationship overwater to overland (feet)



$$V_w = \frac{V_w}{V_L} \times V_L \qquad \text{(eq. 2)}$$

where:

V_w = overwater wind velocity (mph)
V_L = wind velocity over land (mph) from figure 4
V_w/V_L = wind ratio from figure 5a or 5b.

The ratios provided in figures 5a and 5b are based on characteristics of reservoirs that are surrounded by terrain of moderate irregularities and surface roughness (USACE 1997).

Step 4: Determine significant wave height (H_s)

Significant wave height is a function of effective fetch and overwater wind velocity. It can be calculated using the following equation:

$$H_s = 0.0232 \times V_w^{1.06} \times F_e^{0.47} \qquad \text{(eq. 3)}$$

where:

H_s = significant wave height (ft)
F_e = effective fetch (miles) from equation 1
V_w = over water wind velocity (mph) from equation 2

It is also important to note that the significant wave height is the average value for the highest one third of the waves. A vegetated berm design based on the average for the highest one third is appropriate for most NRCS applications. However, designers should note that the top 1 percent can be 67 percent higher (USACE 1995) and additional protection may be necessary in for high-risk applications. If this is a concern, the designer is encouraged to consult guidance provided in USACE Shore Protection Manual (1984).

Equation 3 is based on a deep water assumption. This means that the wave length, or distance between the waves, is less than twice the water depth. This is usually the situation adjacent to the embankment for most dams. However, it may not be the case for some shorelines or upper portions of reservoirs. Shallower water cannot support the same wave height as deeper water due to interaction with the bottom. In addition, a dense stand of emergent aquatic vegetation on the fetch will reduce wind velocity and will absorb some wave energy as the wave develops near the shore or embankment. The use of equation 3 for conditions with shallow water design or emergent vegetation growth will typically result in an estimated larger wave height and a conservative design for the protection.

Boat-generated waves

This document addresses waves generated by wind. However, the designer should note that, especially within small impoundments, the waves generated by passing boats can be larger than the waves generated by wind. In some areas, erosion is attributed more to boat-generated waves than from wind-generated waves (MDNR 2004). Calculation of boat-produced waves can be complex and is a function of vessel speed, hull shape, and water depth as well as bathymetry and proximity to shore. In general, boat-generated wave heights for recreational fishing boats average 6 inches, but larger recreational craft can generate waves to a maximum of 2 feet in height (Bhowmik et al. 1991).

For most NRCS impoundments, it is advisable to define a no-wake zone close to the shore. If recreational small craft are expected to travel at speed adjacent to the shore, observations should be made of typical wave height or the rules of thumb indicated above may be used. The estimate for boat-generated waves should be added to the calculation for wind-generated waves. If sustained boat wake (for example, adjacent to a marina) or boat wake from large boats is expected, inert protection is required. Additional guidance is available in the USACE Shore Protection Manual (1984).

Determination of wave protection limits

The portion of an embankment that must be protected is the area that will be impacted by the design wave. The designer must determine both a lower limit of protection and an upper limit of protection. These limits apply regardless of the nature of the protection, whether vegetated or inert.

Pool elevation

Measure the upper and lower limits of protection from the upper and lower potential pool elevation. This is typical of inert protection approaches as well. Normal operation of some municipal, industrial, and irrigation dams often results in significantly fluctuating pool levels. If the dam captures runoff from an arid or semi-arid watershed (where average annual precipitation is less than the average annual evaporation), maintaining a design pool elevation may not be possible. For example, if the pool level is below the face of the berm, nonvegetated portions of the berm may be eroded due to wave attack. If the pool level is above the berm, the wave energy may not be sufficiently absorbed and the area that is being protected may suffer wave-induced erosion. Figure 6 illustrates wave erosion at different pool levels. Extended wave-protection berms or inert protection may be necessary if the pool fluctuates significantly.

The use of water tolerant and aquatic vegetation as a wave barrier on the upstream berm of a dam imposes an additional design requirement. The deviation of the water surface from the design elevation must be of short duration and within tolerable limits to sustain the selected plants. If the pool elevation fluctuates considerably, the vegetation may not be able to survive and the constructed vegetated berm may not provide sufficient protection.

Lower elevation of protection

Design protection must extend into the water below the pool sufficient to absorb wave energy and is set at the lower limit of the wave impact. This is calculated with the following equation:

$$\text{Lower limit of wave impact} = \text{Elev}_L - 1.5 \times H_s \quad \text{(eq. 4)}$$

where:
H_s = significant wave height (ft)

Elev_L is the lowest of the following:

- the normal water elevation for the lowest ungated opening
- the elevation of the lowest controlled outlet

Extending protection to a depth equal to 1.5 times the significant wave height may be impractical or undesir-

Figure 6 Wave erosion at different pool levels

able on some shallow-sloped beaches. An alternative is to install a base apron or rock trench to prevent undercutting of the design protection.

Upper elevation of protection

The vegetated berm should extend to an elevation so that the energy from a wave will be entirely dissipated before striking the embankment. This is equal to the wave runup (R) plus the wave setup (S). The elevation that the wave can reach is provided in the following equation:

$$\text{Upper limit of wave impact} = \text{Elev}_{NP} + R + S \quad \text{(eq. 5)}$$

where:
Elev_{NP} = the normal pool (still water) elevation under normal
R = wave runup (in ft measured vertically)
S = wave setup (in ft measured vertically)

Elev_{NP} is typically the pool elevation (still water) under normal conditions. However if the pool managed to fluctuate considerably, the designer may chose the elevation of the highest controlled outlet.

Wave setup—The wave setup can be approximated with the following equation (USACE 1997):

$$S = \frac{V_w^2 \times F}{1400 \times D} \quad \text{(eq. 6)}$$

where:
S = wave setup (ft)
F = maximum fetch distance along the wind direction (miles). This is longer than the effective fetch
V_w = over water wind velocity (mph)
D = average water depth along the fetch line (ft)

Alternately, a simplification of this calculation that is suitable for most NRCS projects can be made with the following equation:

$$S = 0.1 \times H_s \quad \text{(eq. 7)}$$

where:
S = wave setup (ft)
H_s = significant wave height (ft) calculated from equation 3 to a maximum of 0.5 feet

Wave runup–sloped beach—The wave runup is the vertical height above still water to which the uprush from a wave will rise on the shoreline. It is a function of the wavelength of the waves, the roughness of the embankment, and the geometry of the embankment. This estimation can be calculated with equation 8 (Ahrens and Heimbaugh (1988), USACE 1995):

$$R = H_s \times \left(\frac{A \times \delta}{1 + B \times \delta} \right) \times 1.7 \quad \text{(eq. 8)}$$

where:
H_s = significant wave height (ft) from equation 3
A = a constant (1.286)
B = a constant (0.247)
δ = surf parameter defined as follows in equation 9 from EM 1110–2–1100

$$\delta = \frac{\tan(\theta)}{\sqrt{\frac{H_s}{L}}} \quad \text{(eq. 9)}$$

where:
θ = angle of the embankment slope to the horizontal (for example 1V:10H would be 5.7 degrees)
L = deep water wave length (ft)

L is the deep water wave length of the wind-generated wave. This can be calculated with the following equation:

$$L = 1.24 \times V_w^{0.88} \times F_e^{0.56} \quad \text{(eq. 10)}$$

where:
L = deep water wave length (ft)
F_e = effective fetch (miles)
V_w = over water wind velocity (mph)

This wave runup calculation is based on an assumption that the protected slopes are fairly smooth. Therefore, this equation can be considered to be an upper limit for vegetated protected slopes.

Wave runup–flat berm—Flat berms can be placed in front of embankments to reduce wave energy. While the reduction provided by flat berms in the runup is not large, berms can provide for opportunities to promote edge habitat through a variety of wetland plantings. An estimation of wave runup is still necessary for design. The equation presented in USACE REMR TN CO–RR1.4 (1991) can be simplified to make this estimation as shown in the following equation:

$$R = \frac{H_s}{3.28} \times \exp\left(C_1 + C_2 \times \frac{H_s}{L} + C_3 \times \frac{W_b}{\sqrt{H_s \times L}}\right) \quad \text{(eq. 11)}$$

where:
R = wave runup
C_1 = 0.695
C_2 = –11.269
C_3 = 0.158
W_b = width of berm (ft)

This equation assumes that the top of the berm is at the normal, still-water elevation. It is derived for rock riprap-protected slopes. Additional reduction in wave runup may be expected for a berm that is protected with low vegetation.

Layout of vegetated wave protection berm

The layout of the vegetated berm is critical to the success of the vegetated wave protection. The upper and lower limits of the berm are based on the limits of protection as calculated in the previous section. A hypothetical example is illustrated in figure 7.

Additional guidance for the design of the berm section is offered. This guidance is based upon an examination of the performance of different vegetated berms on NRCS projects.

- berm slope: less than 1V:10H [1/]
- berm width: minimum of 20 feet
- berm elevation: typically two-thirds of the berm is below the normal pool elevation. One third above the normal pool (fig. 8)
- expected low water: when the designer expects the lake pool to drop below the estimated lower limit of wave impact, extend the berm into the pool so it will always be below the water surface. However, the designer should consider that an unvegetated berm extended into the lake may not provide the desired protection and may suffer erosion. Special vegetation selection may be necessary.

1/ In Kansas, it is common practice to select 1V:12H as an ideal slope. Experience in Kansas has shown that steeper slopes are subject to damage from burrowing animals.

Figure 8 Typical vegetated berm profile, showing two thirds of the berm below the normal pool elevation and one-third of the berm above the normal pool

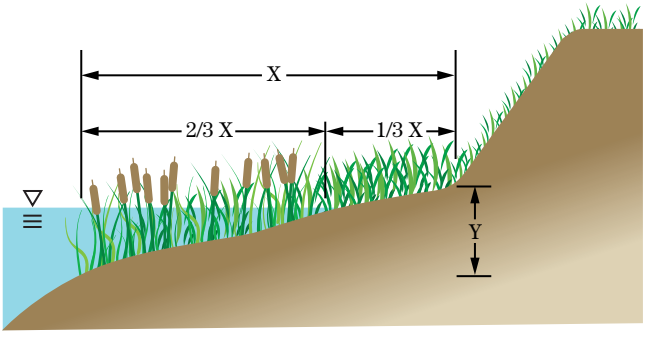
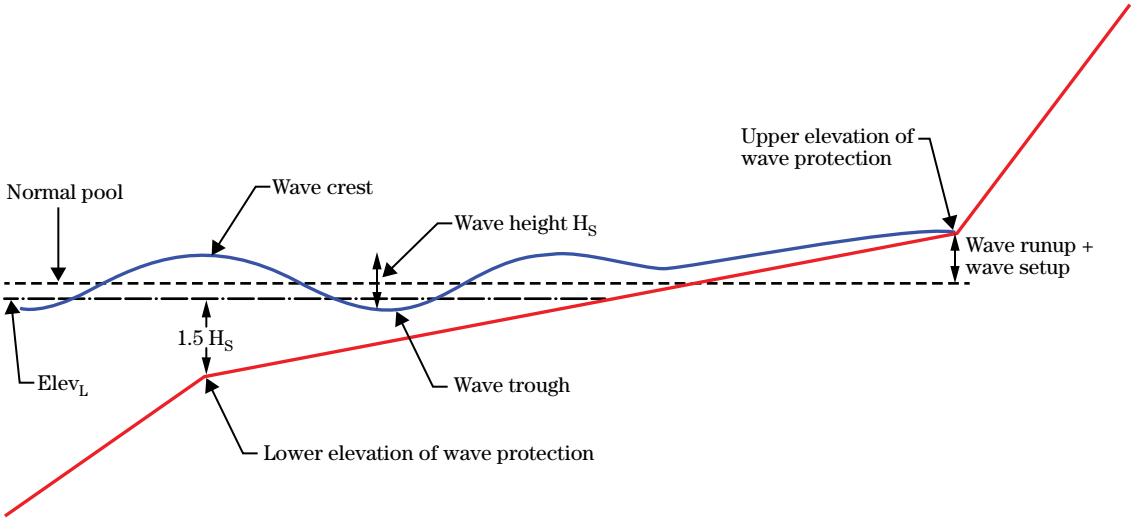


Figure 7 Wave protection berm section



Selection of vegetation for wave protection

Traditionally, only herbaceous species have been established on embankments. The potential damage caused by tree root channels and wind throw (uprooting of trees by wind) is a known hazard to the integrity of embankments. However, certain shrubs and trees suited to grow in wetland conditions have shallow root systems, limited growth potential, and most are unable to propagate outside of the wet hydrologic zones. On shorelines, woody hydrophytes (trees) can reduce the wind velocities over long fetch lengths.

Hydrophytic plants grow in soil that is at least partially deficient in oxygen as a result of excessive water inundation. This vegetation is uniquely adapted to survive in saturated soil conditions where no oxygen is present during large parts of the growing season. This does not mean that they will not survive during periods where oxygen is present, however. Because they can live under conditions where nonhydrophytic conditions cannot, they successfully out-compete nonhydrophytes.

Since hydrophytic vegetation is adapted to saturated soil conditions, it can be used for the protection of constructed embankments and shorelines. These environments are similar to the conditions of the wetlands where they grow under natural conditions. However, the wave energy that causes damage to shorelines is not necessarily the same as those found in their natural environment. In addition to thriving under saturated soil conditions, plants selected for shoreline protection must also have a dense root mass that can resist erosion, as well as strong, thick stems and leaves.

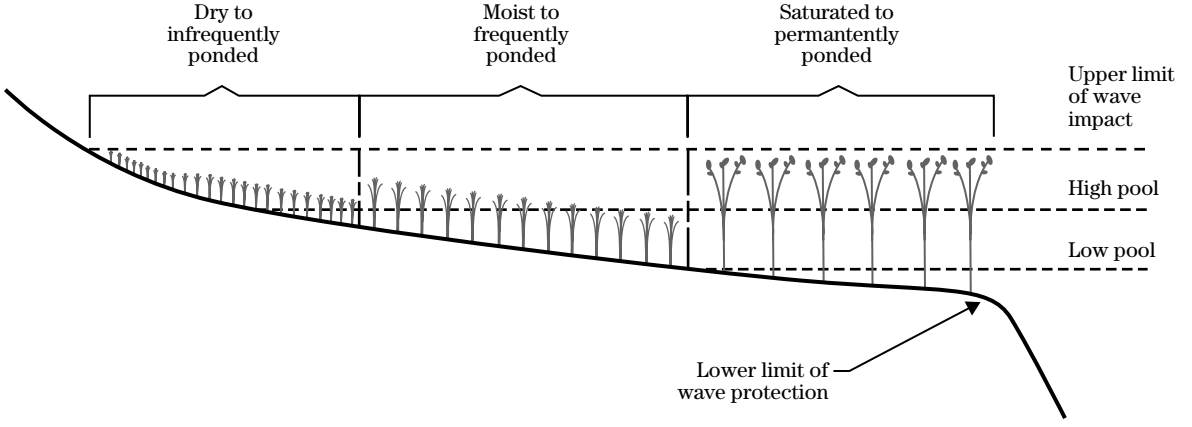
In arid climates where the average annual evaporation exceeds the average annual rainfall, the drastic fluctuation of water levels creates conditions where hydrologic zones are not permanent enough for the establishment of any hydrophytic vegetation. In these cases, the only option is the establishment of upland vegetation, and reestablishment after infrequent high intensity flood events that drown out the vegetation. This condition can be observed in playa wetlands on the high plains, where short-term inundation precludes the growth of upland plants, but does not persist long enough for permanent hydrophytes to become established.

Planting and hydrology zones for wave protection

The success of vegetated protection is dependent upon the establishment of plant species. The establishment of aquatic and riparian plant species is, in turn, dependent upon their location relative to the water (Hoag 2001). Plants used for wave protection should be from the same hydrologic regime as their native environment. To assist with locating planting regimes, this document defines three hydrology zones along the wave protection berm in terms of the general types of expected plant communities. This is illustrated in figure 9.

Plant selection is based on species suitability for the hydrologic regime on the shoreline. It is important to recognize that the hydrologic conditions change in a continuum from wet to dry across a slope. Permanently ponded conditions exist at the lower end. Plants suitable for this zone are referred to as “emergent aquatic vegetation” and the zone is referred to as “saturated to permanently ponded.” At the highest

Figure 9 Planting and hydrology zones for vegetated protection



"dry to infrequently ponded" zone, where ponding is infrequent and of short duration, only upland vegetation is suitable. In between these zones, various combinations of ponding duration and frequency exist in a zone broadly shown in figure 9 as "moist to frequently ponded."

Figure 9 illustrates an idealized representation of the zones. There is often not a sharp demarcation between each of the zones. This idealized representation is a tool for selecting plant species and any uncertainty in the estimation of water level will have to be a consideration. For example, it is acceptable to establish a plant community for a single planting zone where water level fluctuations are small. But where the hydrologic regime changes significantly from high to low elevations, it is desirable to establish multiple plant communities. Place drier regime plants at the higher elevations and wetter regime plants at the lower areas as indicated in each zone. A brief description of planting zones is provided.

"Saturated to permanently ponded" zone—Hydrophytic vegetation is adapted to growing in conditions of permanent to semipermanent inundation. These plants provide excellent wind velocity reduction in shallow offshore areas, as well as wave energy reduction in the near shore area. An example of vegetation suitable for this zone is shown in figure 10.

While the wave protection design procedures described previously cannot account for the benefits of emergent vegetation in this zone, the benefits should not be overlooked. In addition, emergent aquatics can provide some valuable ecosystem benefits such as aquatic organism habitat and nutrient cycling. Planting desirable emergents can also prevent the ultimate establishment of undesirable plants in the same zone. The selection of the upper shoreline elevation for this zone should be based on a careful evaluation of the pool fluctuations. For areas where probability-duration maps have been developed for surface runoff, it is recommended that the upper boundary be set at no higher than the 80-percent chance annual runoff probability line. If pool level analysis is made using the soil-plant-air-water (SPAW) model, the upper boundary can be set at 1 foot above the 80-percent probability of continuous inundation during the growing season. The lower boundary is dependent on the plant species. However, depths greater than 3 feet can usually be considered to be a practical lower limit for most emergent plant communities.

"Moist to frequently ponded" zone—Hydrophytes that thrive in the saturated to semipermanently inundated zone are often referred to as "wet prairie" or "moist soil" plants and can survive short to long periods of dry conditions. Nonhydrophytes or "upland" plants can tolerate only short periods of inundation. If reservoir routing techniques are used to determine this zonal boundary, the upper elevation can be set at the water surface with a 50-percent chance annual exceedence probability (2-year return period). If a hydrologic water budgeting model (such as the SPAW model) is used, the boundary should be set at the 50-percent chance, 15-day duration for periods during the growing season. An example of vegetation suitable for this zone is shown in figure 11.

"Dry to infrequently ponded" zone—While only upland plants can be expected to thrive in this zone, they should be selected based on known tolerance for infrequent flooding. The upper boundary of this zone can be set at the design slope break for a wave protec-

Figure 10 Inland saltgrass, suitable for use in the "saturated to permanently ponded" zone

Figure 11 Maidencane on a vegetated berm

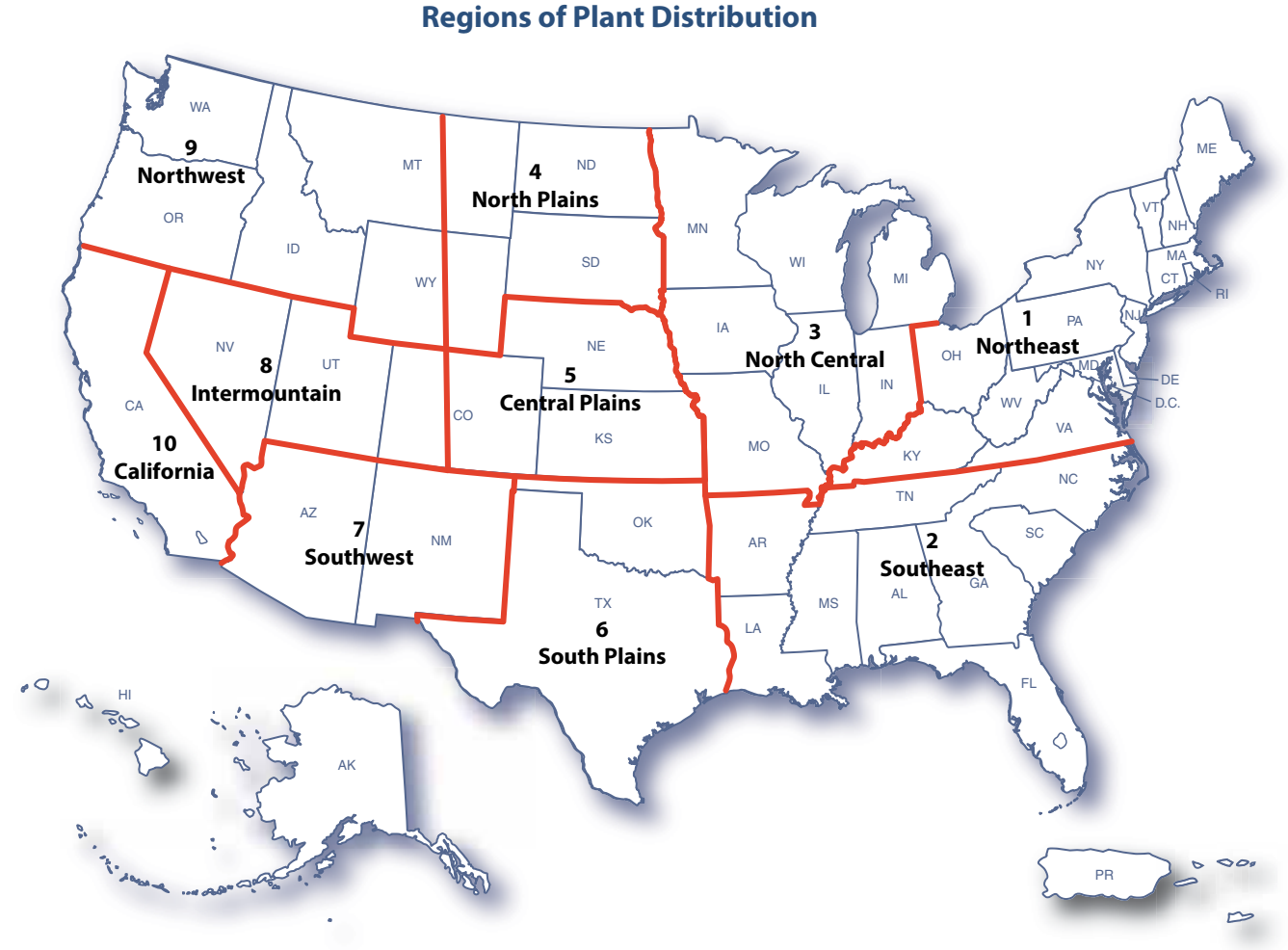
tion berm on embankments, or the 10-percent chance annual exceedence probability (10-year return period) water surface on flat shorelines. High levels in flood control reservoirs tend to be fairly short-term events, where the level is drawn back down to normal pool within approximately 10 days, and many upland plant species can survive this short-term, infrequent inundation. An example of vegetation suitable for this zone is shown in figure 12.

Figure 12 Prairie cordgrass on a vegetated berm

Recommended plant species

Table 3 contains a partial list of plants recommended for wave erosion control along shorelines of water impoundment structures and other aquatic functions. The list includes grass, grass-like, shrub and tree species adapted to the 10 Plant Distribution Regions identified by NRCS (fig. 13). A partial listing of

Figure 13 NRCS plant distribution regions



common and prevarietal sources and cultivars for each of the species is included in table 3. The named sources of herbaceous and woody plants should not be misconstrued as an endorsement of the product by the U.S. Government. No discrimination against other suitable sources is intended. The term "common" refers to local or unnamed sources that may be available for those who prefer to use them rather than cultivars or prevarietal releases. For additional information on the plants or named sources contact the plant materials center or plant materials specialist serving your State (http://www.nrcs.usda.gov/wps/portal/nrcs/site/plantmaterials/home/). Designers are encouraged to consult with local plant materials and wetland vegetation specialists to select native hydrophytes that most closely match the hydrologic regime on the project site.

References to the wetland indicator status for plants can provide some general guidance on plant selection. These indicator labels range from Obligate (OBL) to Upland (UPL). It should be noted that the wetland plant status does not define the best planting zone. In other words, a status of Facultative Wetland (FACW) does not mean that a plant will grow in wetter soil than a Facultative Upland (FACU). The indicator label only means that it is more likely to be found naturally under any wetland conditions. For instance, many plants with FACW status will only thrive in moist soil conditions, but will not tolerate inundation. However, FACW plants will be more suitable for all of the planting zones than a FACU plant.

Plant information contained in this publication is based on current information for the species adaptation and growth under normal growing conditions. Plant persistence following extended periods of drought or inundation during the growing season and beyond the hydrology zones identified in the table is unknown. Species names in the publication were derived from the PLANTS database (http://plants.usda.gov).

Vendor guide

For information on vendors of herbaceous and woody plants stated in this publication, contact the local NRCS field office. The links below provide a sample of vendors of herbaceous and woody plants listed in table 3. This is not intended to be a complete listing. The mention of any vendor does not indicate endorsement by NRCS, nor does NRCS guarantee availability or quality of seeds and plants produced by the vendor.

http://plant-materials.nrcs.usda.gov/technical/publications/wetlandvendors.html

http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmstn10795.pdf

http://www.plant-materials.nrcs.usda.gov/pubs/orpmctn9149.pdf

http://www.plant-materials.nrcs.usda.gov/pubs/nypmcbr7345.pdf

Irrigation

Applying the proper amount of supplemental water is essential during the first year for accelerating establishment of desirable plants for dissipating wave action along the shoreline and reducing damaging erosion. Follow local watering regimes and recommendations for establishment of shrubs, herbaceous plants, and other rootstock (i.e., rhizomes, sprigs). Avoid overwatering. Overwatering causes plants to develop roots in the irrigation zone and prevents them from exploring for moisture deeper into the soil profile. Plants that fail to develop an extensive root system are vulnerable to wave action destruction and drought. It is highly recommended that the person responsible for designing the impoundment consult planting guides for information on establishing and managing the plants of interest and incorporate local knowledge when designing an irrigation system.

Table 3 Plants for wave erosion control and aquatic functions

	Regions of Plant Distribution[1/]										Hydrology Zone[2/]			Wetland Indicator[3/]	Drought Tolerance			Established by		Plant Guide
	1	2	3	4	5	6	7	8	9	10	SAT-SF	FF	P-SM F	Status	good	fair	poor	Seed	Veg	
Grass																				
Maidencane (*Panicum hemitomon)*														FACW+ OBL						http://plants.usda.gov/plantguide/pdf/pg_pahe2.pdf
Citrus Germplasm		x																		http://www.plant-materials.nrcs.usda.gov/pubs/flpmstn7478.pdf
											x	x	x			x			x	
Halifax	x	x				x					x	x	x			x			x	
Common[4/]	x	x				x					x	x	x			x			x	
Switchgrass (*Panicum virgatum*)														UPL, FACW		x				http://plants.usda.gov/factsheet/pdf/fs_pavi2.pdf
Alamo																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/txpmcrb11189.pdf
		x				x					x	x				x		x		
Kanlow																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/kspmcrb10373.pdf
					x	x					x	x				x		x		
High Tide Germplasm																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/njpmsrb7506.pdf
	x	x									x	x				x		x		
Miami	x										x	x				x			x	
Stuart	x										x	x				x			x	
Wabasso																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/flpmcrb5447.pdf
	x										x	x				x			x	
Common (lowland types only)	x	x	x	x	x	x	x	x	x	x	x	x				x		x	x	
Prairie cordgrass (*Spartina pectinata*)											x	x		FACW, OBL						
Red River Germplasm			x	x	x						x	x					x	x	x	http://plants.usda.gov/plantguide/pdf/pg_sppe.pdf
Atkins Germplasm					x						x	x					x		x	
Common	x	x	x	x	x	x			x		x	x					x	x	x	
Giant cutgrass (*Zizaniopsis miliacea*)												x	x	OBL						
Common	x	x	x			x					x	x	x				x		x	http://plants.usda.gov/factsheet/pdf/fs_zimi.pdf
Muhlenberg maidencane (*Amphicarpum muehlenbergianum*)														FACW						
Gator Germplasm																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/flpmcpg10200.pdf
		x									x	x				x			x	
Common		x									x	x				x			x	
Marshhay cordgrass (*Spartina patens*)														FAC, OBL					x	
Sharp		x				x					x	x	x			x			x	
Avalon	x	x									x	x	x			x			x	http://plants.usda.gov/factsheet/pdf/fs_sppa.pdf
Gulf Coast		x				x					x	x	x			x			x	
Flageo		x				x					x	x	x			x			x	
Common	x	x				x			x	x	x	x	x			x			x	
Tufted hairgrass (*Deschampsia cespitosa*)[5/]														FAC, FACW+						(Meadow barley) http://plants.usda.gov/factsheet/pdf/fs_hobr2.pdf
Peru Creek							x		x		x	x					x	x		
Tallamook Germplasm																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpg10224.pdf
									x	x	x	x					x	x		
Willamette Germplasm																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ormcrb11945.pdf
									x	x	x	x					x	x		
Common	x		x				x	x	x	x	x	x					x	x		
Beardless wildrye (*Leymus triticoides*)														FACU, FAC+						
Rio										x	x	x					x	x	x	http://plants.usda.gov/plantguide/pdf/pg_letr5.pdf
Common				x	x		x	x	x	x	x	x					x	x	x	
Manystem wildrye (*Leymus multicaulis*)														FACU, FAC+						http://plants.usda.gov/plantguide/pdf/pg_letr5.pdf
Shoshone				x				x			x	x					x	x	x	
Eastern gamagrass (*Tripsacum dactyloides*)														FAC, FACW						http://plants.usda.gov/plantguide/pdf/pg_trda3.pdf
Pete	x		x		x						x	x				x		x		
Highlander																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/mspmcpg6132.pdf
		x	x								x	x				x		x		
Meadowcrest	x										x	x				x		x		
Bumpers		x	x								x	x				x		x		
Martin Germplasm																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/flpmcrb5450.pdf
		x									x	x				x			x	
St. Lucie Germplasm		x									x	x				x			x	
Common	x		x		x	x					x	x				x		x	x	

Table 3 Plants for wave erosion control and aquatic functions—continued

	Regions of Plant Distribution[1/]										Hydrology Zone [2/]			Wetland Indicator [3/]	Drought Tolerance			Established by		Plant Guide
	1	2	3	4	5	6	7	8	9	10	SAT-SF	FF	P-SM F	Status	good	fair	poor	Seed	Veg	
Western wheatgrass (*Pascopyrum smithii*)														UPL, FAC-						http://plants.usda.gov/plantguide/pdf/pg_pasm.pdf
Arriba					x		x				x	x			x			x		
Flintlock					x						x	x			x			x		
Barton					x	x					x	x				x		x		
Recovery								x			x	x				x				
Rodan																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ndpmcrb11299.pdf
				x							x	x				x		x		
Rosana				x				x			x	x				x		x		
Common	x		x	x	x	x	x	x	x	x	x	x				x		x		
Inland saltgrass (*Distichlis spicata*)														FAC+, FACW+						
LK517f Germplasm										x	x	x				x		x	x	http://plants.usda.gov/plantguide/pdf/pg_disp.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x				x		x	x	
Rice cutgrass (*Leersia oryzoides*)[6/]														OBL						http://plants.usda.gov/factsheet/pdf/fs_leor.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x			x		x	x	
Grass-like Plants																				
Alkali Bulrush (*Schoenoplectus maritimus*)														OBL						http://plants.usda.gov/plantguide/pdf/pg_scma8.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	
American bulrush (*Schoenoplectus americanus*)														OBL						http://plants.usda.gov/plantguide/pdf/cs_scam6.pdf
Common		x				x	x	x	x	x	x	x	x				x		x	
Hardstem bulrush (*Schoenoplectus acutus*)														OBL						http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpm
Common	x		x	x	x	x	x	x	x		x	x	x			x			x	
Softstem bulrush (*Schoenoplectus tabernaemontani*)														OBL						http://plants.usda.gov/plantguide/pdf/cs_scta2.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	
California bulrush (*Schoenoplectus californicus*)														OBL						
Bayou Lafourche Germplasm		x				x					x	x	x				x			http://plants.usda.gov/plantguide/pdf/cs_scca11.pdf
Common		x				x	x			x	x	x	x				x		x	
Beaked Sedge (*carex rostrata*)														OBL						
																				http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmctn380201.pdf
Common			x					x	x		x	x	x				x		x	
Nebraska sedge (*Carex nebrascensis*)														OBL						http://plants.usda.gov/plantguide/pdf/pg_cane2.pdf
Common				x	x		x	x	x	x	x	x	x				x		x	
Baltic Rush (*Juncus arcticus*)														FACW, OBL						http://plants.usda.gov/plantguide/pdf/pg_juar.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x		x				x	
Softstem bulrush (*Juncus effusus*)														FACW+, OBL						http://plants.usda.gov/plantguide/pdf/cs_juef.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	
Torrey's rush (*Juncus torreyi*)														FACW, FACW+						Planting guide not available
Common	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	
Water sedge (*Carex aquatilis*)														OBL						http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpg10239.pdf
Common	x		x	x	x		x	x	x	x	x	x	x				x		x	
Creeping Spikerush (*Eleocharis palustris*)														OBL						http://plants.usda.gov/plantguide/pdf/pg_elpa3.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x				x		x	
Common threesquare (*Schoenoplectus pungens*)														FACW+, OBL						http://plants.usda.gov/plantguide/pdf/cs_scpu10.pdf
Common	x	x	x	x	x	x	x	x	x	x	x	x	x		x				x	http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpg11463.pdf
Shrubs																				
White alder (*Alnus rhombifolia*)														FACW						Planting guide not available

Table 3 Plants for wave erosion control and aquatic functions—continued

	Regions of Plant Distribution[1/]										Hydrology Zone[2/]			Wetland Indicator[3/]	Drought Tolerance			Established by		Plant Guide
	1	2	3	4	5	6	7	8	9	10	SAT-SF	FF	P-SM F	Status	good	fair	poor	Seed	Veg	
Common				x				x	x	x	x	x	x				x		x	
False indigo bush (*Amorpha fruticosa*)														FACU-, FACU						
Survivor				x	x						x	x	x			x		x	x	http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ndpmcrb6148.pdf
Iowa Covey Germplasm			x								x	x	x			x		x	x	http://www.plant-materials.nrcs.usda.gov/pubs/mopmsrb6769.pdf
Missouri Covey Germplasm			x								x	x	x			x		x	x	
Common	x	x	x	x	x	x	x	x	x	x	x	x	x			x		x	x	
Button bush (*Cephalanthus occidentalis*)														OBL						
Keystone	x	x									x	x	x			x			x	http://plants.usda.gov/plantguide/pdf/pg_ceoc2.pdf
Common	x	x	x		x	x	x			x	x	x	x			x			x	
Black twinberry (*Lonicera involucrata*)											x	x		UPL, FAC						
Common							x	x	x	x	x	x					x		x	http://plants.usda.gov/plantguide/pdf/pg_loin5.pdf
Redosier dogwood (*Cornus sericea*)														FAC, FACW+						http://plants.usda.gov/plantguide/pdf/cs_cose16.pdf
Ruby	x		x								x	x	x				x		x	
Cheney Selection									x		x	x	x				x		x	http://www.plant-materials.nrcs.usda.gov/pubs/wapmcrbcoseochen.pdf
Harrington Germplasm								x	x		x	x	x				x		x	http://www.plant-materials.nrcs.usda.gov/pubs/wapmcrbcoseswall.pdf
Wallowa Selection								x	x		x	x	x				x		x	
Common	x		x	x	x		x	x	x	x	x	x	x				x		x	
Silver buffolaberry (*Shepherdia argentea*)														FACU[4/]						
Sakakawea						x	x				x	x				x			x	http://plants.usda.gov/plantguide/pdf/pg_shar.pdf
Common			x	x	x		x	x	x	x	x	x				x			x	
Willows																				
Booth's willow (*S. boothii*)														OBL						
Common							x	x	x	x	x	x	x				x		x	http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpu7428.pdf
Dwarf willow (*S. X cottetii*)														Unknown						
Bankers	x	x	x								x	x	x				x		x	http://plants.usda.gov/factsheet/pdf/fs_saco28.pdf
Drummond willow (*S. drummondiana*)														FACW, OBL						
Curlew								x	x		x	x	x				x		x	http://plants.usda.gov/plantguide/pdf/pg_sadr.pdf
Common							x	x	x	x	x	x	x				x		x	
Missouri river willow (*S. eriocephala*)														FACW					x	
Placer									x	x	x	x	x							http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/orpmcrb11957.pdf
Common	x	x	x	x	x	x					x	x	x				x			
Coyote willow (*S. exigua*)														FACW, OBL						
Silvar								x	x		x	x	x			x			x	http://plants.usda.gov/plantguide/pdf/cs_saex.pdf
Common						x	x	x	x	x	x	x	x			x			x	
Geyer willow (*S. geyeriana*)														OBL, FACW+[4/]						http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpu7428.pdf
Common							x	x	x	x	x	x	x				x		x	
Hooker willow (*S. hookeriana*)														FACW-, FACW						
Clatsop									x	x	x	x	x				x		x	http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/orpmcrb11958.pdf
Common									x	x	x	x	x							
Sandbar willow (*S. interior*)														FACW[4/]						http://plants.usda.gov/factsheet/pdf/fs_sain3.pdf
Silver Sands Germplasm			x	x	x						x	x	x				x		x	http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ndpmcrb6148.pdf
Common	x	x	x	x	x						x	x	x				x		x	

Table 3 Plants for wave erosion control and aquatic functions—continued

	Regions of Plant Distribution[1/]										Hydrology Zone [2/]			Wetland Indicator [3/]	Drought Tolerance			Established by		Plant Guide
	1	2	3	4	5	6	7	8	9	10	SAT-SF	FF	P-SM F	Status	good	fair	poor	Seed	Veg	
Pacific willow (*S. lucida*)														FACW-, FACW+						
Nehalem									x		x	x	x				x		x	http://plants.usda.gov/plantguide/pdf/cs_salul.pdf
Common							x	x	x	x	x	x	x				x		x	
Yellow willow (*S. lutea*)														FACW+, OBL						http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpu7428.pdf
Common			x	x	x	x	x	x	x	x	x	x	x				x		x	
Tea leaf willow (*S. planifolia*)														FACW, OBL						http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/idpmcpu7428.pdf
Common					x		x	x	x	x	x	x	x				x		x	
Columbia River willow (*S. sessilifolia*)														FACW						
Multnomah									x		x	x	x				x		x	http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ormcrb11959.pdf
Common									x	x	x	x	x			x			x	
Sitka willow (*S. sitchensis*)														FAC, FACW+						http://plants.usda.gov/plantguide/pdf/cs_sasi2.pdf http://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/ormcrb11960.pdf
Plumas									x	x	x	x	x				x		x	
Common									x	x	x	x	x				x		x	

1/ See attached map for regional distribution definition.

2/ Hydrology Zone - Saturated to Seldom Flooded (SAT- SF); Frequently Flooded (FF); Permanent- Semi Permanently Flooded (P-SP).

3/ Wetland Indicator Status - Derived from the National Plants Data Center (http:/plants.usda.gov) and based on "National List of Plant Species that Occurs in Wetlands", US Fish and Wildlife Service, 1988.

4/ "Common" refers to common or local source(s).

5/ Add 5-10% meadow barley with the recommended planting rate of tufted hairgrass for shoreline protection in the Western States.

6/ Species not reliably hardy (perennial) in the Northern States.

Soil bioengineering techniques

Soil bioengineering is the use of living and inert materials to stabilize eroding banks (USDA, 1996). This broad category of techniques includes plants, grading, and inert materials. Soil bioengineering provides not only stability and aesthetic benefits but also both terrestrial and aquatic benefits. "Streambank" soil bioengineering is a commonly used technique in stream restoration projects (Hoag and Fripp 2002). Many of these are well documented in a variety of sources including Title 210, National Engineering Handbook (NEH), Part 654, Chapter 14. Several techniques have been adapted for lake shore protection. A sketch of one such example is the use of a vegetated coir log as shown in figure 14.

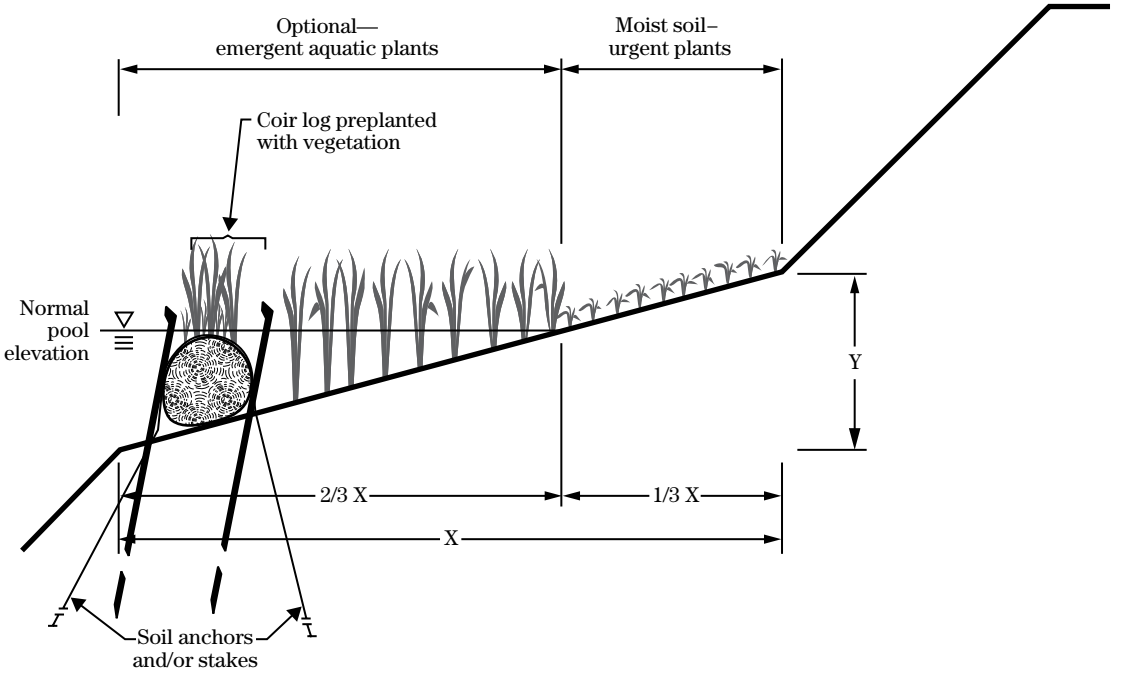
Streambank soil bioengineering can be broadly classified as either structural based or plant based, depending on the resulting flexibility of the project (Fripp et al. 2008). Structural based approaches typically include more reliance on inert materials while plant based approaches rely on vegetation almost exclusively. Both approaches are often chosen because they provide aesthetic and basic habitat benefits. The difference is that a successful structural-based approach results in a static bank line while the bank treated with plant-based approaches can move. In most situations, the structural-based treatments will be more suitable to high-risk areas, while the plant based are more suitable for lower-risk sites.

A great deal of design guidance is available for stream bank soil bioengineering practices (210–NEH, Part 654, Chapter 14). Some of this guidance is applicable to soil bioengineering on lake shores. However, most of the limiting criteria are expressed in velocity or shear exerted by flowing fluvial systems. Little guidance is available for a designer to calculate the required treatment for wave energy. Designers who adapt streambank soil bioengineering techniques to lake shore conditions will have to rely on judgment and local examples of successful approaches.

Maintenance

Operators and designers are cautioned to not underestimate the importance of maintenance. Wave damage is not usually the result of a single, major storm event. Rather it is the result of continuing wave action over several years. Responsible local officials or individual owners and operators should enter into a binding, written agreement to properly operate, manage, and maintain the total structure. The agreement should address such items as irrigation during establishment, fertilization, and reestablishment of vegetation as needed; fire prevention; exclusion of grazing by domestic animals; control of fishing and boating from the dam; control of rodents; and cutting and killing of tree species that could grow tall and shade out the desirable wave protection grasses or shrubs.

Figure 14 Example treatment using soil bioengineering



Example problem

Given: Multipurpose reservoir planned for construction in the Fort Worth, Texas, area.

Elevation of lowest ungated opening is 650 ft. Elevation of normal pool is 651 feet.

Assume shape provided in figure 3.

Find: Layout of vegetative wave protection berm

Calculate wind-generated wave height using simplified procedure:

Step 1 Calculate effective fetch (F_e) as shown in table 2.

Assume analysis indicates 900 feet

Confirm below 1,600 feet per table 1

Step 2 From figure 4, the maximum 50-year velocity is 67 miles per hour.

Step 3 Wind ratio from figure 5b is 1.04.

Overwater wind velocity (eq. 2)

$1.04 \times 67 = 70$ mph

Step 4 Significant wave height (eq. 3)

$0.0232 \times 70^{1.06} \times (900/5280)^{0.47} = 0.91$ ft

Boat-generated waves

Define a no-wake zone close to the shore.

Calculate the lower limit of protection

Using equation 4:

$650 - 1.5 \times 0.91 =$ **<u>648.6</u>**

Calculate the upper limit of protection.

Wave setup (eq. 7)

$0.1 \times 0.91 = 0.1$ ft

Deep water wave length (eq. 10)

$1.24 \times 70^{0.88} \times (900/5280)^{0.56} = 19.4$ ft

Surf parameter (equation 9)

$\tan (5.7)/(0.91/19.4)^{1/2} = 0.46$

Wave runup (equation 8)

$0.91 \times (1.286 \times .46)/(1+0.247 \times 0.46) \times 1.7 = 0.8$ ft

Upper limit of wave impact (equation 5)

$651 + 0.8 + 0.1 =$ **<u>651.9</u>**

Calculate the width of berm

Using a 1:10 slope, the width is:
$10 \times (651.9 - 648.6) =$ **<u>33 ft</u>**

Confirm that dimensions for this size of berm are allowable for the design pool. Check possible limitations as indicated in table 1. Contact plant material specialist with expertise in Region 6 (fig. 13) for aid in selecting appropriate plant species. Confirm appropriate maintenance can be accomplished to establish and maintain vegetation.

References

Ahrens, J.P. 1981a. Design of riprap revetments for protection against wave attack. CERC Technical Paper 81–5, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

Ahrens, J.P. 1981b. Irregular wave runup on smooth slopes. CERC Coastal Engineering Technical Aid 81–17, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

Ahrens, J.P., and M.S. Heimbaugh. 1988. Approximate upper limit of irregular wave runup on riprap. Technical Report CERC–88–5, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

Bhowmik, N.G., T.W. Soong, W.F. Reichelt, and N.M.L. Seddik. 1991. Waves generated by recreational traffic on the Upper Mississippi River system. Illinois State Water Survey, Champaign, Research Report 117.

Fripp, J.B., J.C. Hoag, and T. Moody. 2008. Streambank soil bioengineering: A proposed refinement of the definition riparian/wetland project Information Series No. 23. Plant Materials Center, USDA–NRCS, Aberdeen, ID.

Hoag, J.C., and J.B. Fripp. 2002. Streambank soil bioengineering field guide for low precipitation areas, Interagency Riparian/Wetland Project. Plant Materials Center, USDA–NRCS, Aberdeen, ID.

Hoag, J.C. 2001 (revision). Riparian planting zones. USDA–NRCS Plant Materials Center. Riparian/Wetland Project Information Series #16, Plant Materials Center, USDA–NRCS, Aberdeen, ID.

Minnesota Department of Natural Resources. 2004. Shoreline and water quality impacts from recreational boating on the Mississippi River. Mississippi River Landscape Team.

Saville T. 1954. The effect of fetch width on wave generation. Tech. Memo No. 70. U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers. 1984. USACE Shore Protection Manual. U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers. 1991. USACE REMR TN CO–RR1.4, Performance of Bermed Revetments. U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers. 1995. USACE EM 1110–2–1614, Engineering and Design—Design of Coastal Revetments, Seawalls, and Bulkheads, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers. 1997. USACE–EM 1110–2–1420, Engineering and Design—Hydrologic Engineering Requirements for Reservoirs, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1996. Title 210, National Engineering Handbook, Part 650, Chapter 16 Streambank and Shoreline Protection. Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service. 2007. Title 210, National Engineering Handbook, Part 654, Stream Restoration Design. Washington, DC.

Yarde A.J, L.S. Banyard, and N.W. Allsop. 1996. Reservoir Dams Wave Conditions, Wave Overtopping and Slab Protection, HR Wallingford Report Report SR 459.