The WRP Notebook

CONTENTS

Userguide for the Wetland Water Budget Model Tutorial

PURPOSE: This technical note provides step-by-step instructions for using a computerized tutorial to help set up, execute, and calibrate the Wetland Water Budget Model, and to help manipulate the model's output using a post-processing program.

BACKGROUND: The Wetlands Research Program has developed a water budget model which can be used to model hydrologic and hydraulic processes in wetlands, and is a useful tool for investigating wetland functions. The model is modular in design, allowing users to run only those modules important to their study. For example, if users are interested in surface water processes, they would run the surface water module. The model also has a horizontal groundwater flow module and a vertical processes module (for precipitation, canopy interception, infiltration, and evapotranspiration). Any combination of the modules can be selected by the user. The number of input files (and the amount of data) needed to run the model depends on which modules are selected. A user could quickly become confused over which input files are needed and what data are required. To eliminate the confusion, a screen-driven, PC-based tutorial was developed to help users select modules, identify all of the necessary input files, and to give users instructions for formatting the data in those input files. The program also provides instructions for calibrating and running the water budget model, and manipulating the model's output.

For more information about the water budget model (including the processes it models, applications of the model, and assessments of the model's capabilities), the tutorial program and a program for manipulating output data, see Walton and Chapman (1993).

OVERVIEW: The computerized tutorial for running the water budget model uses a sequence of screens to prompt users for information they need for their particular model application. The following is an overview of the screens.

<u>SCREEN 1:</u> Provides instructions for using the screens. To move the cursor around a screen, use the **TAB** or **ARROW** keys. To move from one screen to the next, use the **Page Up/Down** keys. Use the **Enter** key to make selections within screens and the **Control_H** keys to obtain "Help" at any time.

<u>SCREEN 2:</u> Permits users to select one or more of the water budget model's modules for their particular application, and allows them to define a **project name** (less than 9 characters) which becomes the "**root**" name for all of the input and output files.

<u>SCREEN 3:</u> Identifies the necessary input files required for the particular application (set of modules) selected by the user. The necessary files are indicated by a "**YES**" appearing in the box next to the file name. Users can view examples of the format for a file's data by selecting (**Enter** key) the file while the cursor is positioned by the file name. The user can also get more information regarding data sources by pressing the **Control_D** keys. The names of the output files that the water budget model will generate are identified by the word "**OUT**" next to the file name. The "**MAKE**

FILE" option will automatically generate a file list (called **"root"**) which the water budget model uses to identify which files are input files and which are output files.

SCREEN 4: Tells the user how to setup the input data, calibrate and run the model, and manipulate the output data. When the user exits this screen, the tutorial ends. The user may also exit the tutorial at any time by pressing the **END** key.

The remainder of this TN concentrates on the module components of the tutorial.

SURFACE WATER MODULE SELECTION: By selecting the surface water module (from SCREEN 2) for their model application, users can simulate surface water processes such as channel flow, overbank wetting and drying, remote-basin inflow, tidal forcing, local rainfall and wind forcing. SCREEN 3 of the program will enable the following file names (i.e. a "YES" will appear next to the file names in SCREEN 3):

root.OUT - general output file to which model input and run information are output.

root.PAR - run parameter file where module selection; simulation start date, duration, time step; print initiation and interval; and echo print options are given.

root.GRD - grid file where the number, location, size, and shape of nodes and links; the linkage between nodes; and link elevation, inverse side slope, and type are defined.

root.ELV - contains the bottom and overbank elevations of each node.

root.PRP - defines link properties such as friction formulation, and weir and culvert coefficients.

root.INI - specifies the initial nodal stages or water elevations above the model datum.

root.BCI - specifies the upstream and downstream boundary conditions (e.g. stage, flow, loop rating, or stage-discharge).

root.HBC - time series of stages or surface water elevations at each head boundary node specified in file "root.BCI."

root.FBC - provides the time series of flows or discharges at each flow boundary node specified in file "root.BCI."

root.MET - contains daily meteorological inputs such as rainfall, temperature, solar radiation and wind speed and direction.

root.HDS - nodal head or elevation output file.

root.FLO - link flow or discharge output file.

root.VOL - nodal volume output file.

root.VEL - link velocity output file.

When in SCREEN 3, examples of the input files may be viewed by moving the cursor to the box next to the file of choice and pressing the **ENTER** key. A sample input file is displayed showing the free-field file format, file delimiters, and a description of each variable within a "Help" window at the bottom of the screen. While a sample input file is being displayed, pressing **Control_D** will display brief information on possible data sources for the necessary file data. The "Make File" option generates a file called "**root**" that contains the file names of all the input and output files required for a surface water module simulation.

Note: While examining the data structure for "**root.GRD**," the user can press the **Control_F** keys to display schematics of the geometry used to describe nodes or links. The figures will be displayed in conjunction with the appropriate line in the data file "**root.GRD**."

VERTICAL PROCESSES MODULE SELECTION: By selecting the vertical processes module (from SCREEN 2) for the model application, users can simulate processes such as canopy interception, ET, and infiltration. To prescribe inputs and boundary conditions for these processes, the following files are enabled (i.e. a "YES" will appear next to the file names on SCREEN 3).

root.OUT - general file to which input and run information are output.

root.PAR - run parameter file where module selection; simulation start date, duration, time step; print initiation and interval; and echo print options are specified.

root.GRD - grid file where the number, location, size, and shape of nodes and links as well as the linkage between nodes are defined.

root.ELV - bottom and overbank elevations of each node, and the elevations of the bottoms of each layer at each node.

root.NOD - canopy and soil types used in each node layer at each node.

root.CAN - canopy type in terms of drainage parameters and monthly values of leaf area index (LAI).

root.SOL - soil type in terms of moisture parameters, hydraulic conductivities, and the power function relationship to soil moisture tension.

root.INI - initial nodal water surface elevations and groundwater heads in each layer, with respect to the model datum.

root.MET - daily meteorological inputs such rainfall, temperature, solar radiation, and wind speed and direction.

root.HDS - nodal surface water head output file.

root.GWH - nodal groundwater heads output file.

root.SMC - nodal soil moisture content output file.

root.SUM - vertical water mass balance file.

When in SCREEN 3, examples of the input files may be viewed by moving the cursor to the file of choice and pressing **Enter**. A sample file will appear showing the free-field file format, file delimiters, and a description of each variable within a "Help" window at the bottom of the screen. While the sample input file is displayed, pressing the **Control_D** keys will show some general information on possible sources for the necessary file data. The "**Make File**" option generates a file called "**root**" that contains the file names of all of the input and output required for a vertical processes module simulation.

HORIZONTAL GROUNDWATER FLOW MODULE SELECTION: By selecting the horizontal groundwater flow module, users can include that hydrologic process in their application. The module can be used alone to simulate depth-averaged groundwater flow, although it is important to remember that the module is based on variably saturated groundwater flow theory. More commonly, the module would be used with the vertical processes module (described above) to simulate three-dimension groundwater flow and surface exchanges. In order to prescribe inputs and boundary conditions for these processes, the files "**root.OUT,**" "**root.PAR,**" "**root.GRD,**" "**root.ELV,**" "**root.NOD,**" "**root.SOL,**" "**root.INI,**" "**root.GWH,**" and "**root.SMC**" are enabled (i.e. a "YES" will appear next to the file names in SCREEN 3) as described above for the vertical processes module. In addition, SCREEN 3 enables "**root.BCI**" which specified fixed head boundary conditions and the location of wells.

MODEL EXECUTION: Once the necessary input data files are created, the selected modules are executed by typing "**WWBM**" followed by **Enter** at the DOS prompt. (Note: the prompt must be in the directory where the swamp program resides or the directory must be in the PC Path [see DOS manual].) At the program prompt, enter the 'control' file name: "**root**" followed by **Enter**. The program will echo the input and output file names and grid manipulation operations as they are completed. During the model simulation, the program prints a message to the screen each time output data are written. When "SIMULATION COMPLETED" appears on the screen, execution ends.

OUTPUT MANIPULATION: A post-processing program (called **WWBMAID**) is available with the water budget model. The program allows users to customize the output data from the surface water module output files. After starting the **WWBMAID** program, the following data manipulation options are displayed:

1. Create file with specified node numbers
2. Compare computed and observed heads
3. Compare computed and observed flows
4. Select a node or link for graphics
5. Edit heads for initial conditions
6. Convert grid files to new datum and units
7. Hydroperiod statistics
8. Water surface profiles
9. Add more columns of data to file
10. Groundwater heads for graphics
11. Calculate head from soil moisture content
99. EXIT

Enter selection:

CONCLUSION: A computerized tutorial is available to help users setup, calibrate, and run the Wetland Water Budget Model that simulates wetland hydrologic and hydraulic processes. The tutorial also explains how to use a post-processing program to manipulate the model's output data. The tutorial program, the Wetland Water Budget Model, and the post-processing program are available through the WES Engineering Computer Programs Library, Attention Gloria Naylor at (601) 634-2581. The programs' reference number is 722-PD-R0008.

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Hydraulic Structures for Wetlands

PURPOSE: This technical note examines hydraulic structures presently being used in wetland design. The examples given will provide insight to structure types being used in the field and how well they are succeeding.

BACKGROUND: The design and construction of a wetland site requires knowledge of the wetland type or functions that are to be achieved by the project. Examples of functional objectives include: waterfowl habitat including food and nesting sites, flood storage, water treatment to remove undesirable materials, sediment trapping, and ground water recharge. Also required is a knowledge of the operation, management and maintenance resources that will be available during the life of the project. Basic hydrologic data are required to determine the potential flows and water properties to which any hydraulic structures associated with the project will be subjected.

Hydraulic structures for wetlands generally fall into one of two categories: **water containing structures**, which are generally referred to as dikes, levees, or embankments, and **water control structures** of which there are a multitude of types and designs. In this technical note, dikes, levees, and embankments are collectively referred to as dikes.

DIKES: Dikes are structures constructed of earth or other suitable materials designed to contain water or protect lands against overflows from lakes, streams, and tides. Dikes, often a major component of wetland restoration, enhancement, or creation, can be effectively used in a wetland system to control flow paths and to minimize short-circuiting. Usual causes of dike failure are overtopping, undermining, sloughing, piping, or seepage along a water control structure placed through the dike. The design of the dike should eliminate these dangers as much as possible (USDA SCS 1992).

WATER CONTROL STRUCTURES: Water level and flow control structures are required if some control over the hydraulic regime and water budget of a particular wetland area is desired. The types of structures typically used in wetland design are consistent with water control devices used in general engineering practice.

Inflow is generally controlled by relatively simple structures, such as an open-ended culvert pipe, a vegetated spillway, or a channel. These structures should be sized to handle maximum design storm flows and to achieve the intended wetland function(s). Natural inflow can be supplemented by diversions, spring developments, or pump systems. The inflow structure must be designed to minimize channelization and short-circuiting by diffusing the inflow velocity.

The wetland function being obtained and the ultimate use and design of the wetland system control the outflow from a wetland. The wetland area may be designed for flood conveyance, which requires capacity to store and release storm runoff. Regulation pool elevation might be required to maintain proper water depth for specific habitat needs. The possibility of total drawdown of the wetland might be necessary for wetland management purposes.

For impoundments with dikes 1 ft or less in settled heights, the Soil Conservation Service (SCS) recommends that vegetated spillways may be used in lieu of structures with dewatering obtained by cutting the dikes. For impoundments with dikes more than 1 ft in settled height, the types of structures which may be used include (USDA SCS 1992):

- A straight drop structure, which may be equipped with removable stoplogs constructed of treated timber, metal, sheet piling, rock, or concrete.
- A pipe provided with a swivel elbow and riser.
- A pipe drop inlet structure which may be equipped with a gate, valve, or plug for flow control.
- A pipe provided with a perforated riser.

Wetlands that are hydrologically isolated or that do not have a contributing drainage area will still require control structures to release the water that results from ground water inflow and precipitation.

EXPERIENCE WITH EXISTING STRUCTURES: In practice we have found a variety of structures in place. In general, they can be grouped as follows:

- Drop outlet structures.
- Spillways.
- Culvert pipes.
- Weirs.
- Level spreader inflow pipes.
- Pumping inflow with some type of diffuser.
- Dikes.

All of the above structure types have various designs. This list is not inclusive of all possible structures. The following paragraphs illustrate the diversity of structure types and applications for wetland projects. Detailed information for each example can be obtained from the indicated references.

Drop outlet structures are commonly used in wetland mitigation projects. The SCS in Jackson, WY, provided documentation of an open-type water control structure for use where public access is limited, and an innovative locking type structure for accessible areas (Figure 1). This structure is shown here because of its unique design and capabilities. The wetland function in both areas is year around waterfowl habitat (Personal Communication, 1992, J. Kremer, District State Conservation Engineer, Jackson, WY). The Lyndon Q. Skidmore Wetlands at Harry S. Truman Reservoir, MO, were created by constructing a 3,500-linear-ft levee. Two low-cost water-level control structures using PVC stoplogs were installed. The function of the project is to provide natural foods and sanctuary conditions for migrating waterfowl, shorebirds, and other wildlife (Briuer 1991). The Shop Creek Stormwater Quality Enhancement Project in Aurora, CO, has an outlet structure from the permanent pool pond to the channel and five bowl-shaped, soil-cement drop structures along the channel. Water quality,

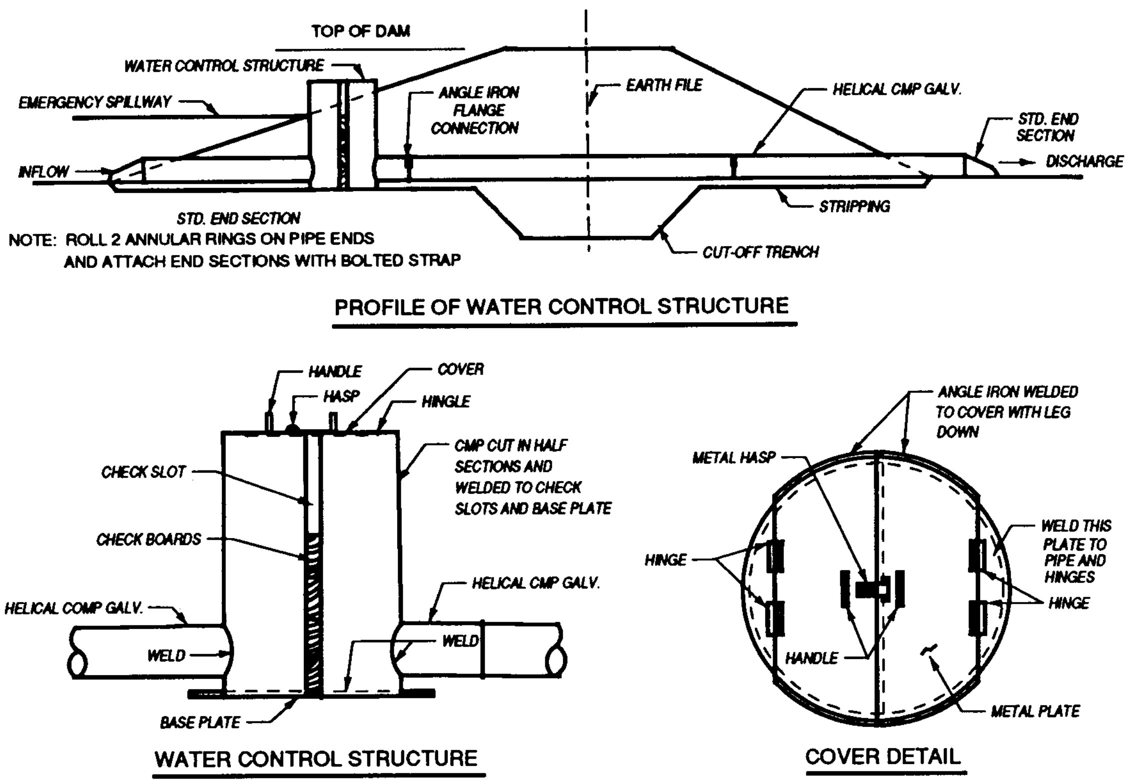

Figure 1 Schematic of a locking type control structure used in accessible areas

sediment control and habitat were design goals of this project (Muller Engineering Company, Inc., et al. 1988).

Spillways have been used in Tennessee Valley Authority's (TVA) constructed wetlands for treating acid drainage. The Fabius Coal Mines acid drainage wetlands system employs spillways for conveying both inflow from the existing pond and outflow into the natural wetlands (Watson and Hobson 1989). In an urban detention pond-wetland system in Orlando, FL, an overflow spillway is used between the detention pond and the wetlands (Martin 1988).

Culvert pipes exist in the Bolsa Chica Wetlands in CA. Three inflow culvert pipes transport water from outer Bolsa Bay into the wetland area. Wetland enhancement is in the future for this muted tidal wetland (Personal Communication, April 1992, L.Z. Hales Research Engineer, USAE Waterways Experiment Station, Vicksburg, MS).

Weirs are used in a variety of projects for controlling wetland outflow. The Des Plains River Wetlands Demonstration Project, a midwestern riparian wetland, utilizes outflow weirs with parshall flumes for flow measurements (Personal Communication, May 1992, D. Manson, Wetlands Research, Inc., Chicago, IL). The design wetland functions include water quality, flood control and habitat (Wetland Research, Inc. 1990). The urban detention pond-wetland system in Orlando also employs a weir built around a drop inlet for discharge from the wetlands (Martin 1988). Everglades National Park in Florida has four gated weirs that regulate the flow into the park (Gunderson 1986).

Level Spreader inflow pipes are used in constructed wetlands for wastewater treatment. TVA has used level spreader inflow pipes in their work in the design of small community wastewater projects (Watson and Hobson 1989).

Pumps are often used to supply inflow to a wetland area. In the Des Plains River project, inflow pumps, located in the river, pump water through a pipe that terminates in a concrete cylindrical riser pipe that disperses the water and allows for gentle flow into the wetlands (Manson 1992). In two study sites in NC, agricultural waste was pumped into wetlands for natural treatment. The structures included inflow pumps and a diffuser canal to distribute the water laterally before entering the wetland buffer area (Chescheir and Skaggs 1991).

Dikes are used effectively in wetland systems to control flow paths and minimize short-circuiting. TVA uses finger dikes to create a serpentine configuration in the Kingston Steam Plant. Divider dikes are used to separate cells and attain desired length-to-width ratios at constructed wetlands in Benton, KY (Watson and Hobson 1989).

STRUCTURAL FAILURES: Reasons for wetland mitigation failures are varied. Examples of structural failures, that is structures that have been in place and have been the cause of the wetland function not being attained, have been difficult to find. Because successes are usually published, information on unsuccessful designs and problems is more difficult to locate. Often a preference of one type of structure over another can be found. It is not a "failure" of the structure but an engineering preference due to ease of construction, operation, or cost.

The TVA has extensive experience with constructed wetlands to treat both acid drainage from coal mining operations and wastewater for small communities. A water control box with an elbow and a rotating standpipe is the TVA's preferred outlet structure for constructed wetlands. TVA has tried other designs, such as weirs with movable plates but found them to be more difficult to operate and construct compared to the simplicity of the control structure with the swiveling standpipe (Personal Communication, April 1992, J.T. Watson, Water Quality Branch, TVA, Chattanooga, TN).

On the Snake River at Jackson, WY, near the airport north of town, a headgate was constructed without regard to the hydrology of the river. The headgate, presently 3 ft in the dry, had to be replaced to get water into the wetland. The wetlands function is year-round habitat (Myers, Miller, and Tate 1992).

A 2-year study documenting the hydrology of two wetland buffer areas in the Albemarle-Pamlico Peninsula of eastern NC consisted of three main components, the drained agricultural area, the pumping station, and the wetland buffer area. The pumping stations had three pumps each, allowing for a wide range of pumping rates. One site had a diffuser canal to distribute the water laterally before entering the wetland buffer area. The other site did not have a diffuser canal during the first year, resulting in uneven water distribution and reduced effectiveness of the wetland buffer area. A diffuser canal was constructed to correct the problem demonstrating the need to discharge the inflow into the wetland areas using either sheet flow, or some other type of diffuser mechanism, to reduce velocities and to minimize channelization (Chescheir and Skaggs 1991).

Coyote Hills Regional Park located on San Francisco Bay contains enhanced wetlands that have dikes with many large control valves that were installed to allow the water level to be controlled in the various cells. Muskrats have tunneled extensively through the dikes eliminating the capability to vary the water levels. At other locations, beavers have constructed their own water control structures resulting in water levels differing from the original design.

Coastal wetlands surrounding San Francisco Bay have been enhanced by breaching existing levees to allow the tidal flow to enter the previously isolated area. Additional channels were constructed through these areas to allow the flow to reach the remote sections of the wetland.

SUMMARY: Several factors affect the selection and design of hydraulic structures. Considerations include:

- Flow control may be modified by animal or human activities where local populations may attempt to change the level of the water within the project.

- Floating debris may affect the flow conveyance if allowed to collect on or in the structure. The structure may need to pass inflowing sediment or be designed to hold sediment.

- Structural materials should be chosen to be consistent with the project life.

  Steel pipe is subject to corrosion and chemical attack.
  Concrete may be abraded and is also subject to chemical attack.
  PVC is subject to abrasion and ultraviolet light.
  Vegetated structures may be reinforced with geotextiles or gabions.
  Riprap is a traditional material for small flow structures.

  Safety and aesthetics should always be considered in choosing the type of structure.

- Straight drop structures are not appropriate for areas were water sport activities may occur due to the plunging and roller flow conditions at such structures. Strong roller action or hydraulic jumps should be avoided at locations where water sport activities occur.

CONCLUSION: Failures to achieve the desired wetland type and/or function can primarily be attributed to design error rather than structural selection. Wetland restoration, creation, and enhancement are relatively new areas in engineering and design criteria are still in the development stage. Research indicates the design should be as simple as possible.

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Wetland Shoreline Protection and Erosion Control: Design Considerations

PURPOSE: This technical note summarizes information and documented experience concerning wetland protection and erosion control along channels and shorelines. The causes and mechanisms of erosion are described, and general design requirements that should be considered when planning an erosion control project are outlined.

BACKGROUND: Shorelines and structures associated with created and restored wetlands are exposed to the erosive forces of nature. Wetlands invite the use of more natural vegetative solutions for erosion control and a greater emphasis on project aesthetics than in other types of erosion control projects. Sometimes, vegetative techniques alone cannot provide adequate protection of wetlands, and they must be combined with other alternatives. A design goal for a wetland protection project should be to use the minimum amount of structural protection necessary. Innovation is often the key to an appealing and successful project.

DEVELOPING A WETLAND EROSION PROTECTION PROJECT: The process of developing an erosion protection project can be described in several steps (Figure 1). It should be noted that, in many cases, there is significant overlap and iteration between steps. Other important checklists are also included in Figure 1.

DETERMINING THE CAUSES AND MECHANISMS OF EROSION: The causes of wetland erosion, which are discussed below, play an important role in determining the protection alternative that is selected for design and implementation.

- *Wind and boat waves* are often the dominant cause of local instability in tidal wetlands and along fringe wetlands in lakes. Waves erode the bank near the waterline, and can undercut banks, leading to mass failure. The failed material piled at the toe of the bank is washed away by subsequent waves, and the undercutting cycle continues. Boat waves differ from wind waves in their size, frequency, and duration but, otherwise, have similar erosion mechanisms.

- *Boat-induced currents* can cause instability in wetlands, especially where large vessels travel in narrow, confined waterways or where large, commercial vessels travel near bank lines in larger waterways. Boat-induced currents are caused by the propeller jet and by vessel displacement effects. The erosion zones may be on the bottom and sides of the waterway.

- *Channel meander* is caused by current-induced forces. Erosion occurs on the downstream part of bendways and is most severe at intermediate to high stages. As material is removed from the toe of the bank, the bank is undermined and fails. The failed material is removed by the flow, and erosion continues.

- *Channel braiding* occurs on streams with an overload of sediment and/or steep bed slopes where bars and islands can form, producing a wide, shallow channel. The bars and islands may become wetlands. Erosion of banks, islands, and bars in braided channels occurs as a result of flow being diverted against the bank by the bars and islands. Erosion is variable and can occur at any position along the length of the channel.

Steps in developing an erosion protection project:

1. Understand the system and determine the mechanisms and causes of erosion.
2. Consider general design requirements.
3. Develop a list of alternatives to protect against the cause of the erosion problem.
4. Design the protection.
5. Estimate the costs of the project.
6. Construct, inspect, and maintain the project.

Causes of local bank and shoreline instabilities in tidal and riverine environments:

1. Wind and boat waves.
2. Boat-induced currents.
3. Channel meander.
4. Channel braiding.
5. Ice and debris.
6. Water-level fluctuation.
7. Flow constrictions.
8. Other (rainsplash, freeze-thaw, overbank drainage).

Important factors in designing erosion control projects:

1. Geomorphology.
2. Ecological and physical barriers.
3. Aesthetics.
4. Habitat diversity.
5. Hydraulic setting (design event, water-level fluctuations, wind waves, currents, etc.)
6. Top elevation of protection.
7. Toe and flank protection.
8. Geotechnical setting.
9. Surface drainage.
10. Filter layers and fabrics.
11. Safety factor.
12. Locally available materials.
13. Vandalism.
14. Public education.
15. Fate of materials.
16. Effect of alternative on local waves and currents.
17. Access.
18. Animal activity.
19. Water chemistry.
20. Construction and ease of repair.
21. Navigation hazard.

Figure 1. Checklists for planning wetland shoreline protection and erosion control

- *Ice and debris* can reduce flow area and concentrate or deflect flow against otherwise stable bank lines, causing erosion. Ice and debris can gouge bank lines, damage vegetation, and damage improperly designed protective measures.

- *Water-level fluctuation* is a cause of instability in riverine, depressional (reservoirs), and tidal wetlands. Water-level fluctuations allow waves and currents to erode a bank at ever-changing elevations. Causes of water-level fluctuations include naturally varying and controlled stream discharges and lake levels, astronomical tides, seiches, wave setup, climatological effects, and navigation.

  A rapid drop in water level leaves saturated banks in an unstable condition. On steep banks, mass failure may occur. On banks containing layers of different materials, a rapid drop in water level causes saturated banks to drain through the more porous layers. Flow through these porous layers may remove material, leading to bank collapse. This process is called piping or sapping and is also found in environments not having rapid drawdown but having saturated overbanks from ponds or poor drainage.

- *Flow constrictions* at bridge crossings, training structures, and floodplain encroachments can increase flow velocities that may erode otherwise stable banks.

- *Other causes* are rainsplash, freeze-thaw, and overbank drainage. Overbank drainage and rainsplash tend to produce small, local instabilities; nevertheless, these processes should be considered in designing protection methods. Freeze-thaw decreases bank soil strength, which increases the potential for the removal of bank material.

GENERAL DESIGN REQUIREMENTS: To ensure effective erosion protection, a number of design factors should be considered. These factors, listed in Figure 1, are discussed below.

- Geomorphology. Geomorphic evaluations involve determining the beginning point, ending point, and alignment of the protection. The protection may only need to extend along a limited reach of the threatened wetland. In other cases, the protection may have to be extended beyond the limits of the threatened wetland to ensure adequate protection over the design life of the project. For habitat and aesthetic reasons, less emphasis is given to a straight or smooth alignment for wetland protection. However, wetland boundaries may be aligned for reasons of project function and economy. For example, a proposed island wetland restoration design in the Chesapeake Bay had a circular planform that minimized the length of exterior erosion while maximizing the interior wetland area.

- Ecological and physical barriers. Animals should be able to move in and out of the wetland. Steep banks with crevasses (for example, in riprap) may trap small crustaceans and young animals. The protection should not adversely limit the amount of water that flows through the wetland. Improper flows may alter the hydrologic characteristics, water temperatures, dissolved oxygen, and other chemical constituents within the wetlands. If the export of nutrients from the wetland is important, sufficient flows must be achieved to accomplish it.

- Aesthetics. In a wetland environment, preservation of a natural appearance is important from both human and wildlife perspectives. The impact of protection methods on aesthetics depends on the degree to which the protection measures are visually compatible with their surroundings (Henderson 1986).

- Habitat diversity. Development and preservation of habitat and habitat diversity should be high priorities. Diversity of aquatic habitat is the result of diverse depths and velocities. Bank protection methods, such as the indirect methods of dikes and groins, promote diversity of aquatic habitat whereas relatively smooth revetments tend to reduce diversity. Rock structures and other bank protection methods provide stable substrate for macroinvertebrates.

- Hydraulic setting. Quantifying the hydraulic setting is required to determine the causes and mechanisms of bank erosion. Depending on the setting, the effects of hydraulic levels, wind waves, boat waves, currents, and vessels may have varying levels of importance. Guidance for estimating wind waves at a project can be found in the Corps of Engineers' Shore Protection Manual (U.S. Army Corps of Engineers (USACE) 1984). Important variables are the wind speed, wind direction, fetch geometry, and water depth. To determine currents, the channel cross section, inflow rates, and water levels are needed. Flow routing models, such as HEC-2 (U.S. Army Hydrologic Engineering Center 1990), are available to help compute riverine currents.

  Vessel effects are primarily a function of vessel speed, vessel shape and displacement, distance from vessel, and water depth. With regard to vessel shape and displacement, two broad categories are recognized: commercial and recreational vessels. Commercial vessels are relatively slow but have large displacement; recreational vessels are relatively fast but have small displacements. Commercial vessels rarely move fast enough to produce significant waves, but they produce substantial, rapid drawdown when operating in confined channels. Methods for predicting drawdown magnitude and other navigation effects are presented in PIANC (1987). Methods for predicting waves from recreational vessels, which decay with distance from the vessel, are given in Bhowmik and others (1992).

- Top elevation of protection. Wetlands, particularly in a tidal environment, have relatively low top bank elevation, and protection extends over the elevation of the wetland. In the riverine environment, many successful projects have been built with the top elevation of the structural protection well below the top-of-bank or design water surface. Vegetative techniques are often used to protect the upper bank. Factors affecting the required top of structural protection in the riverine environment are stage duration, erodibility of upper bank soil and vegetation, variation of hydraulic forces on the upper bank, bank slope, method of protection, and consequence of failure. Engineer Manual 1110-2-1601 (USACE 1994) presents a method for estimating the variation of hydraulic forces on the bank in the riverine environment.

- Toe and flank protection. One of the most overlooked but critical aspects of bank protection projects is consideration of the toe and ends of the design. In the river, toe scour and the fact that many species of vegetation cannot withstand long-term inundation are the primary reasons that vegetative techniques alone will not provide stable bank protection. Some form of structural protection, often required at the toe of the riverbank, must be able to withstand the changing bed elevation found in alluvial channels. Procedures for estimating toe scour in the riverine environment are given in USACE (1994) and, for the wave environment, in the Shore Protection Manual (USACE 1984).

  Two methods are used to provide scour protection. One is to extend the protection down to the maximum estimated scour depth. This is often the preferred method in dry construction, although it becomes difficult and expensive when excavation is done underwater. Another approach is to place a flexible material that will adjust to the channel scour. This approach lets the stream do the excavation. Riprap is the most common material to use in flexible or “self-launching” aprons. Gabions and cabled concrete block mattresses can also be used to provide a flexible toe structure. Guidance for self-launching riprap and scour depth estimation in the riverine environment is given in

USACE (1994). The Shore Protection Manual (USACE 1984) provides guidance for self-launching riprap in the wave environment.

When considering the ends of the protection, it is desirable to terminate the protection in areas where the erosion forces are reduced. Unfortunately, this is frequently not possible, and the ends of the protection must be designed to not fail when the adjacent unprotected areas experience erosion. When using armor protection such as riprap, increased layer thickness at the ends will allow the protection to adjust to minor adjacent erosion.

- Geotechnical setting. Geotechnical design considerations include slope stability, filters, and subsurface drainage. Slope stability deals primarily with the stable bank angle, which is a function of height, bank material, stratigraphy, stage fluctuation, groundwater conditions, and overbank loading. The purpose of filters and subsurface drainage is to control the movement of water and bank material beneath and through the protection.

- Surface drainage. Surface drainage rarely causes failure of a protection alternative, but may cause maintenance problems, destroy vegetation, and damage the aesthetics of a site. The basic steps in preventing erosion from surface drainage are to protect all bare ground (unless slopes are flat, and wavewash and runoff are moderate), collect overland flow and wavewash in channels, and provide return-flow outlets.

- Filter layers and fabrics. Many protection alternatives require a filter layer at the interface of the protection material and the sediment. The filter layer, which consists of well-graded gravel and stone, prevents sediments from filtering through the protection, which would ultimately undermine or destabilize the protection. The filter layer can also distribute the weight of protection more evenly over the substrate. In many instances, a filter layer may be replaced by an acceptable filter fabric, the pores of which are specified based on the characteristics of the sediments.

- Safety factor. The consequences of failure of the protection project must also be considered. Only limited design information is available for many of the bank protection alternatives that might be used in a wetland. Without well-founded design information, determining a factor of safety is difficult. Usually, a conservative design is selected to compensate for uncertainties, or the design is based on the convenience of construction, materials, or some other feature. If the construction environment is difficult or materials lack quality then, as a factor of safety, the design should account for the prospect of sections of below-average construction or low-quality materials. Safety factors can be reduced if inspection and maintenance are scheduled up front. That is, if the project shows signs of failure after a certain operating time, remedial action could be taken to correct the problem.

  An additional consideration is that, for some projects, even though damage or losses would be acceptable to an agency from a financial standpoint, the appearance of failure in the eyes of other agencies is less acceptable. Often, the agency wants the protection to work without failure so that it will be easier to gain approval for additional projects in the future.

- Locally available materials. The cost of any project can be reduced if inexpensive locally available materials are used. A project design should always consider the advantages of using local materials in some element of the design.

- Vandalism. The effects of vandalism must be anticipated, especially in areas where the public has access. To minimize these impacts, hard-to-damage materials and designs can be used, or periodic maintenance can be planned. Consideration should be given to using a protection scheme that will work in spite of damage to some portions of the project.

- Educating the public. Educating the public to the purpose of the project and making them feel a part of the project may help reduce the frequency of vandalism or inadvertent damage caused by people working or recreating in the area. This can be accomplished through nonconfrontational signs and seminars and by enlisting their help in the construction and planning of the project.

- Fate of materials. Project designers must consider the possible fate of materials used in the bank protection design in the event the project fails or exceeds its design life. Many geotextiles, tires, synthetic materials, metals, and treated woods do not degrade rapidly and may remain as an unappealing result of the project or pose a danger to humans and the environment.

- Effect of alternative on local waves and currents. The impact of bank stabilization on areas adjacent to the protection must be considered in the design. In a naturally eroding stream system, bends migrate downvalley. By stabilizing one portion of this system, the natural downvalley movement is interrupted. The stabilized section causes the point of attack in the next downstream section to be fixed rather than transient. Depending on bank erodibility and other factors, this constant point of attack can alter downstream erosion patterns and rates. Bank protection that significantly reduces channel area or deflects currents can increase downstream or opposite bank erosion.

  Bank protection alternatives may influence the wave field near the protection. Waves refract and diffract near bathymetric variations and structures. For example, refraction will cause wave crests to bend around a mound of material on the bottom. The wave crest may bend so much that it collides with itself on the backside of the mound. The colliding wave crests can damage shorelines or protection works where otherwise the wave may have had little effect. Waves that pass by the end of a structure, such as a breakwater, will diffract into the region behind the breakwater and may cause unexpected damage.

- Access. If the public has access to the site, the protection project must not present a danger to them or their property. Access also affects the selection of the protection method. In some projects, land access for construction may not be feasible. In many of these same projects, water access by large construction equipment is limited by shallow depths. Where larger construction equipment does not have access to the site, more labor-intensive alternatives may be required.

- Animal activity. Animal activity in and adjacent to protection methods can undo otherwise stable systems. Certain coastal crab species burrow passageways into exposed banks. These passageways, especially in conjunction with rapid drawdown from tows in confined waterways, can lead to a piping-type failure of the bank. Conversely, certain types of bank protection structures may create an ecological problem by preventing the use of the bank by such burrowing animals. Another type of animal activity that has repeatedly caused problems is the consumption and destruction of vegetation protection systems by various animal species. Whenever vegetation is used in a project, damage to the plants by animals and techniques to prevent such damage should be anticipated.

- Water chemistry. In tidal wetland environments, the tolerance of protection materials to seawater must be considered. Metals will corrode, and timber will rot. Also, certain species of vegetation are intolerant of high or low levels of salinity.

- Construction and ease of repair. Conditions at the project site (dry, soggy, or submerged) can dictate the type of alternative selected because of the limitations on equipment types that can be used. Costs must be increased to overcome poor construction conditions. Likewise, repairs or modifications will probably be costly as well. Thus, the ease of repair should be considered when designing the project and predicting future maintenance costs.

- Navigation hazard. If the public has access to the site by water, possible hazards to navigation need to be considered. This can be a problem if part of the protection includes partially or fully submerged structures both offshore and on the bank.

SUMMARY: The information presented in this technical note is intended to be used as a checklist of important design considerations. It is highly recommended that project designers refer to the resource documents cited herein and consult with experienced engineers or scientists knowledgeable of wetland erosion protection.

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Geotextile Tube Structures for Wetlands Restoration and Protection

PURPOSE: This technical note provides information for determining appropriate applications for geotextile tube structures in wetland restoration and protection and other coastal engineering applications.

BACKGROUND: In the early 1990s, some U.S. Army Corps of Engineers Districts began using and evaluating custom-made geotextile tubes with fabric tensile strengths ranging between 400 and 1,000 lb/in. (70,000-175,000 N/m). The tubes have been used as containment dikes for dredged material placed in shallow water to intertidal elevations. Wetlands have been restored on the dredged material with the tubes acting as erosion protection. The tubes have also been used as nearshore, low-crested breakwaters to limit erosion. Individual tubes have ranged between 20 and 45 ft (6-14 m) in circumference and between 200 and 2,000 ft (61-610 m) in length. During the planning of these projects, many questions have been asked regarding the best techniques for designing, deploying, filling, and handling the tubes.

After responding to a number of individual requests for assistance in designing and constructing geotextile tube structures and realizing that limited information was available, the U.S. Army Engineer Waterways Experiment Station (WES) held a workshop to document the experiences of people who have used geotextile tubes. The discussions at the workshop focused on specific case studies, experiences with deployment and filling tubes, hydrodynamic and geotechnical engineering design, geotextile fabric characteristics, and risk and contingency planning. The 50 participants in the workshop were from Corps of Engineers headquarters, district, and laboratory offices; the Port of Houston Authority (PHA); academia; engineering consulting firms; material suppliers; and dredging contractors.

The workshop was held in Galveston, TX, and was hosted by the U.S. Army Engineer District, Galveston (SWG). Field trips associated with the workshop were hosted by SWG, PHA, Gahagan and Bryant Associates, Inc. (Houston, TX), and Turner Collie Braden, Inc. (Houston, TX). The workshop was co-sponsored by the U.S. Army Corps of Engineers' Wetlands Research Program, Dredging Research Program, and Dredging Operations Technical Support Program, all of which are managed at WES.

For reference, the geotextile tube structures considered in this technical note are nearshore, low-crested breakwaters and dredged material containment dikes that are not stacked. Figure 1 shows a schematic of a representative tube cross section. Geotextile tubes are made from two pieces of geotextile fabric (polypropylene or polyester) laid over one another and sewed along the edges and ends. Factory-installed filling ports are made by cutting 18-in. (46-cm) holes in the top piece of fabric and then sewing a 3-ft (0.9-m) sleeve of fabric into the hole. A dredge discharge pipe is used to fill the tube by placing the end through the sleeve. The sleeve and pipe are strapped together with rope or other material.

For the geotextile tubes described in this technical note, it is assumed that the fill material is sand. When available, sand is the best fill material because it is easily pumped and, after settling in the tube, further consolidation is minor. Sand also has a higher density than finer materials and thus lends more mass to the tube. Short tubes (approximately 200 ft long) (<60 m) would be placed end to end to create a longer structure.

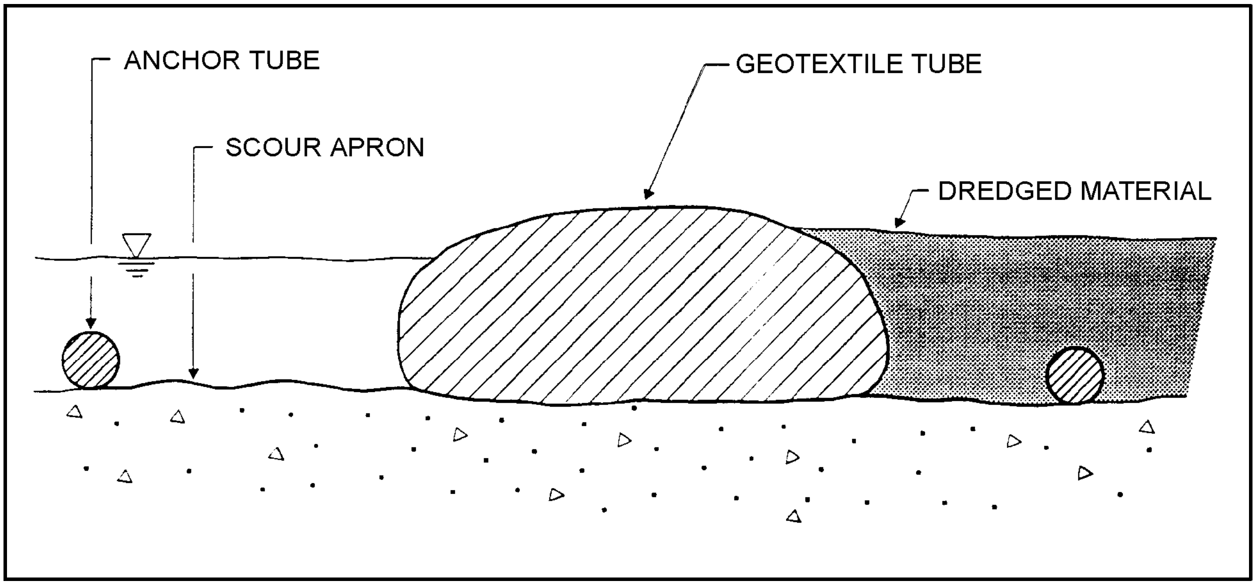

Figure 1. Schematic cross-sectional view of a geotextile tube retaining and protecting dredged material

The discussion below summarizes the information gathered from workshop participants in several areas of concern: limitations of geotextile fabric, criteria for determining appropriate applications for geotextile tubes, and based on these considerations, why the tubes have worked well for wetland restoration and protection.

LIMITATIONS OF GEOTEXTILE TUBES: The concerns raised at the workshop were the same as those raised by Pilarczyk (1995) in his thorough review of "novel" systems for coastal engineering. Participants were concerned about fabric resistance to puncture and abrasion, fabric degradation in the environment, especially under exposure to ultraviolet (UV) light, the difficulty in placing a tube precisely on a given alignment and in achieving a consistent crest height along the length of the tube, and the lack of hydraulic, hydrodynamic, and geotechnical design guidance. Each of these concerns is addressed below.

The resistance to geotextile fabrics to punctures and abrasion is low. Puncturing the materials with a blunt object is not easy. However, it takes no effort to puncture even the highest strength material with a pointed object, such as a knife. Consequently, in areas where the public has access to the tubes, vandalism often results in damage. Debris (for example, a stump with sharp roots) that is forced against the tube by waves or currents can puncture and abrade the material. The workshop participants also suspected that ice could abrade or puncture the fabric. The material can be abraded during shipping and handling, or during deployment. Tubes may be damaged by placing equipment (pipes, flanges, cables, and connectors) on the tubes. Participants also indicated that tubes that are cut or torn will lose sediments within only a few feet to either side of the cut. That is, most of the tube beyond the damaged area will remain intact.

Fabric degradation in UV light is uncertain. Laboratory tests that have exposed the fabrics to intense UV radiation have been conducted. The results suggest that the fabric is resistant, but the results cannot be extrapolated to actual field applications. Some workshop participants suggested that tubes could last several decades (20 to 50 years) in the field; others suggested that, without data, those values cannot be relied upon. It should be noted that exposure to UV light is significantly blocked when the tube is submerged or covered by sediments or marine growth such as algae and barnacles.

The constructed quality of the tubes depends on the skill of the construction contractors and the environmental conditions under which the deployment and filling takes place. The skill and experience of some contractors is increasing within the dredging industry, but no method has yet been widely accepted or documented as the best approach to deploying and filling tubes. Given that the overall average height of the tube depends on the length and circumference of the tube, the permeability of the fabric, the pressure and flow rate inside the tube during filling, sediment characteristics, and other factors, it has been difficult to determine whether it is these factors or the techniques of the contractor that affect the quality of the final tube shape. Ultimately, the experience of the contractor and the available equipment seem to dictate the construction methods chosen.

Some variations of height cannot be avoided. If the contractor stops filling a tube prematurely, because of weather for example, sand in the tube will stabilize and flatten the tube out. Once that happens it is very difficult to pump the tube higher. Also, low spots always occur near the filling ports, with other random undulations elsewhere. It is not surprising to find variations of 0.5 ft (0.15 m) or more along the length of the tube. Based on the results reported at the workshop, the maximum tube height that can be achieved is 5 ft (1.5 m), regardless of the circumference of the tube used. Greater final tube height might be possible, but it has not been the general experience.

Not only does the height of the tube vary, but the elevation of the bed upon which it rests may vary. Hence, if the tube is not placed directly on a given bed elevation, the variations in the bed itself result in variations of the crest elevation. Geotextile tubes are hard to position and hold in place in waves and tidal or wind-driven currents prior to filling. Occasionally, a tube may roll to one side during filling. When this occurs, the tube moves off alignment, it puts the filling ports to the side of the tube instead of on top, and it increases the stress in the fabric.

Existing guidance is limited for designing and predicting the stability of tube structures. Some techniques modified from other structure design techniques were discussed at the workshop. It was suggested that the methods described in the "Shore Protection Manual" (U.S. Army Corps of Engineers 1984) or Minikin (1983) be used for loading on vertically faced structures. Similarly, the methods outlined in Goda (1985) or Walton and others (1989) could be used.

Once the forces are estimated for the tube, one can assume that the cross section of the tube is a rigid, roughly oval object and calculate its tendency to slide or overturn. The recommended friction angles are 18 deg for fabric on fabric and 25 deg for fabric on sand. The WES maintains a discrete-element model that can be used to simulate the deformation of a tube in two-dimensional cross section under loading. A graphical technique to estimate the strength of fabric needed for an application has been developed.* Most workshop participants agreed that, if there is concern about the strength of the fabric, the strongest available fabric should be used. Sprague* also presents a technique for selecting the spacing for filling ports along the crest of the tube. Each of these methods is likely conservative, and all the methods disregard the three-dimensional nature of the tubes.

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* J. C. Sprague. (1995). "P.E.T. geotextile tubes and containers for beneficial use of dredged material," draft contract report prepared for Bradley Industrial Textiles, Inc., Valparaiso, FL, and Hoechst Celanese Corporation, Spunbond Business Group, Spartanburg, SC.

CRITERIA FOR GEOTEXTILE TUBE APPLICATIONS: Based partially on the limitations discussed above, a list of general criteria was compiled for use in determining appropriate applications for geotextile tubes. Pilarczyk (1995) also identifies several of these criteria. The greater the number of criteria satisfied, the more successful the implementation is likely to be.

The listing of criteria given below probably is incomplete, but it can serve as a good guide. The criteria are not listed in order or priority. Priority might be set based on project characteristics.

- Shallow water, low tidal range, and low wave energy. The region in which the tubes are placed should be shallow (0-3 ft, <1 m) and where the tidal range is small (0-3 ft, <1 m). Several Corps of Engineers projects have been stable and have performed successfully in such environments. These criteria limit the size of the waves that will impact the project such that the tubes are inherently stable. Further, tubes placed at low crest elevations as assumed here are usually inundated by surge during large wave events. Larger waves, which might occur with meteorologically induced surges, pass over the tubes with reduced force. The propagation of such waves over the tubes is not problematic, because the area in the lee of the tube is low-elevation marsh.

- Temporary, maintained, and hidden. An appropriate geotextile tube application is one in which the tube is a temporary structure. Obviously, a tube that is used until another approach can be found is just temporary. However, a less obvious temporary application would be a tube that is maintained. For example, a tube used to contain and protect dredged material that is needed only until the next dredging cycle (3-5 years) would be temporary. During the next cycle, the tube may no longer be needed, or it may be maintained or replaced. A hidden tube is one that is covered over, by sediment for example, and serves only as protection when erosion exposes it. This is a useful approach when vandalism or debris is a concern. It also blends the tube into the environment. Once the tube is exposed, however, maintenance is required to repair and rebury it. Material suppliers have indicated that holes in tubes might be patched in situ using marine adhesives. However, if the damage is significant, new tubes can be placed in front of or behind the failed tube. Workshop participants noted that they had little success placing one tube on top of another.

- No threat to life or property. An appropriate geotextile tube application is one where there is no risk of life or property if it fails. Geotextile tubes are effective structures as long as they remain intact. However, since their durability is uncertain, depending on them to protect life or property for long periods of time (without maintenance) is not recommended.

- Flexible height and alignment requirements. Since aligning tubes during placement and achieving consistent crest elevation along the length of tube is difficult, projects where variation in these parameters can be tolerated are best.

- Associated with an existing dredging project. A final criterion is that the tube construction be associated with an existing dredging project. The growing popularity of geotextile tubes is due to several factors, the main one being that they are usually less expensive than other protection or containment alternatives. Geotextile tubes are most cost effective when used in conjunction with a dredging project because the cost of mobilizing a dredge to fill the tubes is minimized. The cost of tube construction is maximized when a dredge has to be mobilized on short notice to fill a small section of tube.

SUCCESS IN WETLAND RESTORATION AND PROTECTION: The first application of geotextile fabrics in wetlands and habitat development was in the early 1970s in Galveston Bay, Texas (Knutson, Allen, and Webb 1990). Large nylon bags (12 by 4 by 3 ft)(3.5 by 1.2 by 0.9 m) were filled hydraulically with sandy dredged material to form a stacked breakwater. The crest of the breakwater was very low, with the marsh built to an intertidal elevation. The bay is broad but shallow, such that wave energy is limited. At the time, it was assumed that the bags would eventually fail, leaving behind established habitat that could maintain itself. In 1995, a visit to the site in Galveston Bay showed that the upper portions of the nylon bags had deteriorated, but the marsh in the lee was prospering.

The successful project in Galveston Bay and the more recent projects that have applied geotextile tubes satisfy several of the criteria established in the preceding section, which would indicate that geotextile tubes are an appropriate alternative structure. The most recent wetlands applications have been monitored for less than 5 years, so long-term performance (10-20 years) is still uncertain. The remainder of this section discusses how these projects fit the criteria listed above.

The Corps of Engineers has constructed wetland restoration projects on dredged material using geotextile tubes as containment dikes and erosion protection in the Chesapeake Bay near Smith Island, Barren Island, the Pokomoke River, and Eastern Neck National Wildlife Refuge (Blama et al. 1995) and along the Gulf Intracoastal Waterway in West Bay north of Galveston Island and near the Aransas National Wildlife Refuge in Texas (McCormick and Davis 1992). These wetland restoration projects were initiated in areas where wetlands once existed. The areas are generally in shallow water with low tidal ranges, and consequently, low wave energies. Because the area in the lee of the structures is intertidal marsh, the tubes are built to low elevation so that they are sufficient to protect the root mat of the marsh from erosion. The naturally low and wide cross-sectional shape of a geotextile tube makes it stable and suitable for this application.

Also, the low wave-energy conditions limit the amount of toe scour that occurs at the tube. As shown in Figure 1, a tube should have a geotextile scour apron to prevent toe erosion. The aprons placed at some Corps of Engineers structures have performed well, suffering little or no damage after several years of service. Some have silted over. However, it is likely that in higher wave energy environments, the apron would not be as effective except perhaps as a temporary measure. Any other type of apron (for example, stone or concrete) would increase the cost of the project and may damage the tube fabric.

The tubes used in the Corps of Engineers projects are not necessarily temporary, maintained, or hidden. At the West Bay site, the Corps of Engineers expects to return to the area in 3 to 5 years (the next dredging cycle) to create additional wetlands, and at that time would correct or modify the project. Therefore, the opportunity for maintenance is present. All of the projects mentioned are in remote areas of bays where the risk of vandalism is very low, since public access is difficult. However, the potential for damage due to debris is always present.

The remoteness of the projects inherently satisfies the criterion that no life or property be at risk in the event of tube failure. The only thing at risk if the geotextile tube is damaged is potential erosion of a portion of the wetland that was restored. However, such erosion may be ecologically desirable. After the wetlands have developed behind the geotextile tubes, it is often desirable to open up the area to the ingress and egress of marine organisms. Removal of a tube is an option. Furthermore, when part of the wetland is eroded, it often remains as shallow, open water or as a mudflat, either of which provides diversity of habitat.

The random height variations along the length of a geotextile tube cause a varying amount of wave transmission into the marsh along the tube. The varying wave energy results in a more random and natural-looking plant growth and propagation in the lee of the tubes.

Finally, all of the Corps of Engineers projects have been associated with existing maintenance dredging where the maintenance material was to be used beneficially. Geotextile tubes provided a means for containing the material and protecting the marsh from erosion in a cost-effective manner. If the projects had been developed separately from maintenance dredging, the costs for the projects would have been relatively excessive.

CONCLUSIONS: Within the Corps of Engineers, geotextile tubes are being considered for alternative structure designs in many applications. They are being considered for sills, low-crested breakwaters, the cores of dunes or rubble mound structures, containment dikes, groins, and compartmentalization structures that limit movement of sand along a beach. Many of these uses challenge designers because of the limitations of geotextile tubes. They are punctured and abraded easily by vandals, debris and ice; their life expectancy after prolonged exposure to UV light is unknown; and they are difficult to construct to precise alignment and crest elevations. Yet, if they are used as temporary structures, hidden components of structures, in shallow water with low wave energy and tidal regimes, in projects where there is no risk to life or property in the event of failure, in projects where inspection and maintenance will be established, or in projects where sand is being dredged, they can be used effectively.

Wetland restoration projects, developed on dredged material placed to intertidal elevations, satisfy many of these criteria. Funds usually available for developing a marsh habitat are limited; therefore, the potential low cost of geotextile tubes makes them an attractive alternative for erosion protection and dredged material containment. Roughly, the cost for placement of geotextile tubes in the Texas projects was $50 to $100 per foot ($150 to $300 per meter). In projects where a dredge was mobilized to fill a short tube, costs approached or exceeded $200 per foot ($650 per meter). The tube containment dikes were generally more expensive than unprotected earthen dikes, but less expensive than an equivalent riprap structure.

Pilarczyk (1995) notes that some worthwhile applications for geotextile tubes exist, but that they should not be generally considered for coastal engineering applications. The criteria identified above, though not all- encompassing, may serve as a reasonable guide because they avoid or minimize the effects of the limitations of geotextiles. The more criteria that are satisfied, the more successful the application is likely to be. Finally, while the construction of geotextile tubes is conceptually easy to understand, one must remember that careful attention must be given to the massive structure and its critical features—the foundation, scour, overtopping, and flanking protection—to develop a successful project.

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Shoreline and Channel Erosion Protection: Overview of Alternatives

PURPOSE: This technical note describes alternatives that can be used separately or in combination to control erosion along wetland shorelines and bank lines. The advantages and disadvantages of each alternative are discussed in this technical note, along with the common reasons for failure.

BACKGROUND: After determining the causes and mechanisms of bank erosion and quantifying the environmental setting of the wetland to be protected against erosion, a list of applicable protection methods can be developed. In general, the minimal amount of protection should be used, and any impact to the wetland should be avoided.

NO-ACTION ALTERNATIVE: This alternative is selected when the environmental setting is mild enough to not require protection. It is possible, at times, to let an erosion problem continue if it appears that it will stabilize with time or that the wetland will not suffer unrecoverable losses. Experience and familiarity with the location is important in the somewhat subjective decision whether to take no action or apply protection.

ACTION ALTERNATIVES: A number of alternatives, alone or in combination, are available for consideration. Summary descriptions of these alternatives (listed in the tabulation below) are provided in this technical note.

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VEGETATION AND NATURAL MATERIALS:

Advantages:

1. Vegetation and natural materials used for protection complement, or become an element of the wetland.
2. Additional habitat can be created. Since the protection is often at the interface between open water and heavily vegetated water or land, it lies within the very productive portion of the wetland. Vegetated banks provide more appealing vistas for humans and more attractive habitat for wildlife, which may otherwise be deterred by unnatural settings.
3. Vegetation is self perpetuating.
4. Vegetation will continue to strengthen and stabilize the bank, assuming that no destabilizing forces overcome the vegetation.
5. Successional or invasional species colonizing a site can add natural variety to the original protection scheme.
6. Vegetation minimizes the potential obstructions to the ingress and egress of organisms to the wetland, as well as the movement of water into and out of the wetland.

Disadvantages:

1. This alternative takes 1-3 years to fully develop.
2. Often requires stabilization measures to protect the vegetation during development.
3. Can be applied only in mild erosional climates.
4. Requires monitoring and maintenance.
5. Minimal guidance is available for designing erosion protection based on wave and current conditions.

Common reasons for failure:

1. No protection during development stage.
2. Improper plant selection, handling, planting technique, or positioning.
3. Poor-quality substrate.
4. No monitoring and maintenance.

General considerations: Vegetation used for bank protection must often be protected itself (or its foundation enhanced) until it has had time to develop root systems and a thick stand. Vegetation is sensitive to the conditions of its environment, such as water depth, water clarity, water quality, sediment type, and nutrients. A good indication of whether vegetation will survive at a given location is to look for similar conditions in the region where vegetation has survived.

Vegetation has a limited range over which it is able to maintain sediment stability. That is, vegetation can only withstand a certain level of wave and current magnitude, before it is undermined or otherwise destroyed. However, even in cases where something other than vegetation is proposed for erosion control, one should always consider the possibility of adding vegetation to the design. For example, if rock revetment is necessary, it may be possible to plant vegetation between the rocks.

FIBER MATTRESS: Fiber mattresses consist of intertwined natural or synthetic fibers. The mattresses are porous, allowing water to permeate while retaining some sediments. Fiber mattresses are strong but depend on the quality of the materials for durability. The success of a mattress depends on its strength, durability, and the system used to anchor it.

Advantages:
1. Biodegradable fiber mattresses can be used as temporary protection during the establishment of vegetation.
2. Vegetation can be sprigged in the mattress.
3. Mattresses are relatively inexpensive. (However, depending on the application, the labor costs required to anchor the mattresses can be high.)
4. Properly selected and installed mattresses are less noticeable and enhance aesthetic values.

Disadvantages:
1. Sometimes difficult to anchor sufficiently because the broad surface may experience large uplift forces.
2. If the anchoring system is damaged, the mattresses that are free to move may damage wetland vegetation and create an unsightly appearance.
3. No design guidance is available for proper selection of mattresses for given currents or wave conditions.
4. No guidance is available for sufficient anchoring techniques for given currents or wave conditions.

Common reasons for failure:
1. Materials used in the mattress degrade too rapidly. For example, some glues used to hold the mesh together may soften in a wet environment.
2. Anchoring systems are pulled out by wave- or current-induced uplift and drag forces on the mattresses.
3. Anchoring systems are undermined by currents or waves.

CELLULAR CONCRETE MATTRESSES (CCM) BLOCK REVETMENTS: Erosion protection from wave attack or streamflow can be provided by man-made concrete blocks (often labeled CCM, for cellular concrete mattress). These interlocking or cable-tied blocks form a revetment similar to a gabion mattress. Cable-tied blocks are usually placed mechanically by crane and spreader bar, whereas interlocking blocks can be mechanically or hand placed.

Advantages:
1. CCM open area of 20 to 25 percent allows colonization by vegetation.
2. Cost-effective in urban streams.
3. Flexible and durable. Can conform to minor bank settlement.
4. Requires less tonnage than riprap. Thickness one third to one fifth that of riprap for channel flow applications.
5. Easily maintained. Can be mowed if vegetation must be controlled.
6. Voids and hardened substrate provide habitat for various biota.

Disadvantages:
1. Cable-tied and geotextile-bonded systems are usually proprietary.
2. Can be expensive in rural areas.
3. Susceptible to vandals removing blocks (noncabled application).
4. Presently, design guidance is lacking for some CCMs.
5. Unnatural appearance unless vegetation is allowed to hide protection.

Common reasons for failure:
1. Toe scour undermines revetment.
2. Excessive settlement that leads to irregular block surface, which can expose blocks to large hydraulic forces.

3. Inadequate treatment and attention to edges, ends, and transitions to other surfaces.

Attention to detail is critical with CCM blocks. Special care should be given to selecting experienced contractors who practice good quality control.

RIPRAP REVETMENT: Riprap revetments are placed on a sloping bank and depend on the stability of the underlying soil for support. Fill material beneath a revetment must be adequately compacted prior to installing the riprap. Riprap revetment, like other revetments, consists of two or more layers (filter and armor).

Advantages:

4. Riprap is self-adjusting to small amounts of substrate consolidation or movement.
5. Riprap may experience minor damage and still continue to function adequately without further damage.
6. The rough surface of riprap dissipates local currents and minimizes wave runup more so than a smooth revetment such as a concrete block revetment.
7. Material is readily available in many locations and can be less expensive than other structural alternatives.
8. Aquatic organisms can use the riprap as suitable habitat.
9. Riprap can be repaired easily by placing additional stone when needed (if access to the location is reasonable).

Disadvantages:

1. If material is not locally and readily available and easily transported to the site, costs can be prohibitive.
2. Riprap may present a barrier to organisms entering and leaving the wetland.
3. Riprap may not be aesthetically pleasing to some people.
4. Riprap may pose a hazard to people who must access the revetment.

Common reasons for failure:

1. Flanking, overtopping, and undermining of the revetment.
2. Settlement of sections of the revetment due to poorly consolidated substrate material.
3. Improperly designed or installed filter layer or fabric.
4. Undersized stone riprap displaced by large waves or currents.

DYNAMIC REVETMENT: A dynamic revetment consists of a larger volume of smaller stones as compared to a standard riprap revetment (described above). Because of the smaller stone size, the cross-sectional form of a dynamic revetment will be adjusted by the forces acting on it, creating an equilibrium form for the given forcing. The larger volume of stone is required to ensure that the bank is fully protected even after the cross-sectional shape of the revetment is altered.

Advantages:

1. Smaller equipment is required to place the smaller stones.
2. Placement of stone requires less care than a standard riprap revetment.
3. Smaller stone may cost less than the larger stones required for a standard riprap revetment.
4. The final cross-sectional shape is more natural looking than a typical revetment. The composition and form is similar to that of a pebble or shingle beach.
5. The smaller stone size presents less of an obstruction to smaller organisms that need to enter or leave the wetland.
6. The smaller stone size presents less of a hazard to foot traffic.

Disadvantages:

1. Smaller stones are not always less expensive than conventional riprap sizes. Without lower costs, the greater uncertainty in the performance of dynamic revetments (over conventional riprap revetments) may not be warranted.
2. Foot traffic and other activities may damage the equilibrium cross section obtained by the revetment. The cross section of a conventional riprap revetment is not likely to be damaged by foot traffic.
3. Less guidance and verification of guidance is available for dynamic revetments as opposed to conventional riprap revetments.

Common reasons for failure:

1. The stone size is too small to remain stable under the given wave conditions.
2. Insufficient volume of stone is placed on the bank.
3. The stones are not constrained from moving laterally along the shoreline.
4. The revetment is undermined by poor filter layer or fabric, or overwash.

GABIONS: Gabions are rectangular baskets or mattresses made of galvanized (and sometimes polyvinyl chloride-coated) steel wire in a hexagonal mesh. The gabion is subdivided into approximately equal-sized cells. At the job site, the baskets are unfolded and assembled by lacing the edges together with steel wire. The individual baskets are then wired together and filled with stone. The lids are finally closed and laced to the baskets, forming a large, heavy mass.

Advantages:

1. The smaller stone used in a gabion can offer equivalent protection as the much larger stone needed in a riprap revetment. (Assumes no destruction of the wire baskets.)
2. Can support some vegetation.
3. Can be cost effective when using locally available stone filler.
4. Requires less tonnage than riprap. Gabion thickness is roughly one third that of riprap revetment.
5. Flexible and durable if properly maintained.
6. Can be stacked to obtain near-vertical side slopes where available right-of-way is limited.
7. Gabion baskets can be built without heavy equipment.
8. Gabions are flexible and can adjust to minor settlement of their substrate.
9. Gabions can be repaired easily by mending or replacing damaged baskets and refilling them as needed.

Disadvantages:

1. Wire mesh is subject to damage from strong waves, floating debris, corrosion, wear from high-velocity sediments, and vandalism.
2. Labor-intensive installation required.
3. Gabions require monitoring and maintenance to identify wear before failure occurs.

Common reasons for failure:

1. Baskets are not filled adequately. This allows them to move, and results in abrasion and fatigue failures of the wire.
2. Baskets are damaged by floating debris, wear, or corrosion.

PARTIAL BANK PROTECTION: On small to intermediate streams, most banks can be protected by a combination of structural protection on the lower bank and vegetation on the upper bank. As a general rule, the larger the stream, the greater the portion of the bank that must be protected with structures. Partial bank protection reduces the quantity of structural protection, which is often costly, and promotes vegetation in the riparian zone.

WINDROW AND TRENCH-FILL REVETMENTS AND TOE PROTECTION: Windrow and trench-fill revetments are armor methods used in the riverine environment in which the stream erosion places the riprap revetment. Riprap is the most common method for providing toe protection in the riverine environment. The riprap is either placed down to the elevation of the maximum scour or, similar to windrow and trench-fill revetments, is placed in a section of riprap called a weighted toe to launch down as toe scour occurs. The weighted toe method is particularly useful in protection that is constructed underwater. The volume of stone in the weighted toe is more important than the shape of the before-launch section.

Advantage: Eliminates underwater excavation.

Disadvantages:
1. Requires greater stone volume due to uncertainty in the launch process.
2. Requires noncohesive bank to properly function.

MILD OFFSHORE SLOPES: In wave-dominated climates, a mild bottom slope (especially, when vegetated) is less likely to develop a serious erosion problem. A mild offshore slope helps to dissipate wave energy before it reaches the edge of the wetland. If the slope is vegetated, additional energy losses occur.

SAND: In some wave-dominated projects where wave heights are small, if a sufficient amount of sand can be placed offshore of the wetland, this can cause waves to break and dissipate their energy before reaching the wetland. This is similar to the idea of developing very mild offshore slopes, as mentioned above. If the sand is contained within the project area (bounded laterally by land or structures), then it may shift around within the region due to wave action and eventually form an efficient energy dissipation zone. A “back wall” is needed.

SILLS: A sill is an offshore structure with its crest usually submerged. Sills are designed to retain sand and sediments and to prevent migration offshore. Design of a low-permeability structure is therefore important. A sill is often used in conjunction with other shoreward structures.

BERMS: These submerged linear mounds of sediment can be placed offshore from the project site. Berms reduce wave energy incident to the site by causing waves to break as they pass over the structure. Berms should be used in conjunction with other alternatives for bank protection.

Advantages:
1. Add interesting features and variations to local bathymetry.
2. Afford (at least temporarily) some protection against wave energy.
3. Add sediment to the local sediment transport system.
4. Provide a useful means of using otherwise excess sediment from a restoration or creation project.

Disadvantages: The disadvantages occur when the advantages do not apply. That is, berms are a disadvantage when they do not add useful variations to the local bathymetry but merely cover up existing bathymetry; when they add too much sediment to the sediment transport system; and when they require significant effort to construct but do not survive long enough to provide much protection against incident waves.

BREAKWATERS: Breakwaters are generally shore-parallel structures that reduce the amount of wave energy that reaches a protected area by dissipating, reflecting, or refracting incoming waves. The reduction of wave action promotes sediment deposition shoreward of the structure. Littoral material is deposited, and sediment is retained in the sheltered area behind the breakwater. Breakwaters may be totally detached from shore or connected at one or both ends.

Advantages:
1. Breakwaters can provide protection in medium- to high-wave energy environments.
2. Extensive experience is available for design and construction of rubble mound breakwaters in terms of stability and expected wave transmission.
3. Rubble mound breakwaters that suffer minor damage can still be functional.
4. Breakwaters provide protection with minimum disturbance to the existing shoreline.
5. Segmented, detached breakwaters allow uninterrupted movement of littoral material and aquatic organisms.
6. Aquatic organisms use some breakwaters as habitat.
7. Displaced stone in a rubble mound breakwater can be easily repaired or modified.

Disadvantages:
1. Construction costs can be high due to equipment access requirements for offshore breakwaters.
2. Limited design guidance is available to predict the response of vegetated shorelines behind detached breakwaters.
3. Continuous shore-connected breakwaters may present a barrier to organisms entering and leaving the wetland.
4. Breakwaters may not be aesthetically pleasing to some people.

Common reasons for failure:
1. Undersized stone displaced by large waves.
2. Excessive wave energy allowed to reach shoreline due to improper crest elevation or gap widths.
3. Improperly designed filter layers that allow substrate material to be removed from structure.
4. Flanking and scour at the toe of the structure.
5. Excessive settlement due to poor foundation conditions.

GEOTEXTILE TUBES: Geotextile tubes usually consist of two sheets of geotextile (woven or non-woven) sewn together with inlets and outlets sewn at intervals when necessary. The tubes are hydraulically or mechanically filled onsite with a variety of dredged material types to form the desired tube dimensions.

Geotextile tubes are used as an alternate material for constructing some of the structures listed above. The tubes have been used in a broad range of applications, including berms, dikes, sills, breakwaters, and groins. Additional information on the use of geotextile tube structures is provided in WRP Technical Note HS-RS-3.2.

Advantages:
1. Wide variety of uses.
2. Simplicity in placement and construction.
3. Structures can be easily removed if needed only temporarily.

Disadvantages:
1. Limited design guidance on stability in moderate wave environment.
2. Construction costs can be high if construction requires specialized equipment.
3. Can be damaged by large debris, boat propellers, vandalism, and ice.

Common reasons for failure:

1. Poor stability in wave climates on sloping plane.
2. Improper geotextile selection.
3. Final crest elevation too low due to improper filling of tube, excessive consolidation of material within tube, or excessive structural settlement due to poor foundation conditions.
4. Damage from floating debris or vandalism.
5. Toe scour results in shifting of tube.

CONCLUSIONS: Many alternatives are available for erosion protection in the mild- to moderate-energy environments in which wetlands are found. Often, a combination of alternatives can be used to provide the most satisfactory result. In selecting an alternative or alternatives, consideration should be given to the advantages, disadvantages, and common causes of failure, as well as minimizing adverse environmental impacts. For example, the alternative and its design should, as much as possible, not hinder the ingress or egress of organisms to the site.

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