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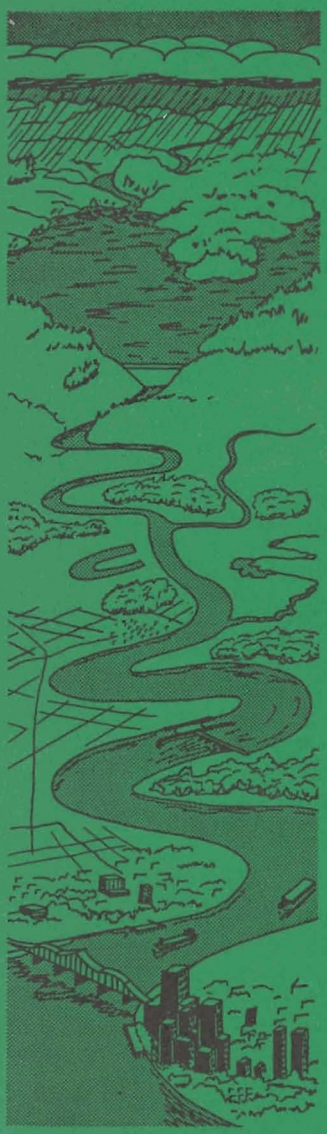

ENVIRONMENTAL AND WATER QUALITY OPERATIONAL STUDIES

TECHNICAL REPORT E-85-3

INCORPORATION OF ENVIRONMENTAL FEATURES IN FLOOD CONTROL CHANNEL PROJECTS

by

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May 1985

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under EWQOS Task VIB

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report E-85-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INCORPORATION OF ENVIRONMENTAL FEATURES IN FLOOD CONTROL CHANNEL PROJECTS		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Nelson R. Nunnally, F. Douglas Shields		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Engineer Waterways Experiment Station Environmental Laboratory PO Box 631, Vicksburg, Mississippi 39180-0631		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS EWQOS Task VIB
11. CONTROLLING OFFICE NAME AND ADDRESS DEPARTMENT OF THE ARMY US Army Corps of Engineers Washington, DC 20314-1000		12. REPORT DATE May 1985 13. NUMBER OF PAGES 277
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aquatic ecology (LC)
Channels (Hydraulic engineering)--Environmental aspects (LC)
Environmental engineering (LC)
Flood control--Environmental aspects (LC)
Water quality (LC)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Channels modified for flood control often experience severe environmental degradation due to erosion and sedimentation, loss of vegetative cover, reduction in amount and value of habitat, and decline in aesthetic value. Many environmental problems result from a failure to recognize the nature of the fluvial system and its interactions with the biological system.

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

Many negative environmental impacts can be avoided by designing flood channels that are in harmony with other fluvial components, minimizing disruptions to existing fluvial and biological systems, and incorporating environmental features into flood channel design. Environmental features are defined as any structures or actions employed in the planning, design, construction, or maintenance of flood control channels that produce environmental benefits. Environmental features may include modifications of standard techniques, such as selective clearing and snagging or single bank construction; modified channel designs, such as low flow channels, pools and riffles, and meandering alignments; structures for erosion and sediment control, water level management, and instream habitat; inclusion of recreational features in project design; and special designs and treatments for aesthetic purposes.

Procedures are presented for the design of environmental features. These procedures are based largely on prior experience with the use of environmental features on modified channels and on fluvial processes and natural stream geometry. Tables are provided to help select the best environmental features based on environmental objectives and stream and watershed conditions.

SUMMARY

The Corps of Engineers (CE) is committed to good stewardship of the environmental resources associated with its Civil Works projects and has published official policies and issued regulations to that effect. These policies and regulations address general environmental concerns, but do not provide the design guidance that is needed.

This report provides guidance for the design and construction of features for improving environmental aspects of flood control channel projects. The procedures presented are based on a review of environmental concepts employed in projects designed and constructed by the CE and other agencies since 1970 and/or literature reviews covering environmental impacts of waterway construction projects, fluvial processes, and hydraulic engineering.

Adverse environmental impacts of flood control channel construction are related to erosion and sedimentation that result in property loss, threaten structures, reduce flood channel and reservoir capacities, and degrade aquatic habitat; loss of riparian vegetation and the shade, habitat, and organic matter it provides; loss of aquatic and wetland habitat and reduced habitat diversity due to reduced channel length, removal of cover, alteration of substrate, and more uniform depths and velocities; loss of terrestrial habitat and reduced diversity caused by channel excavation and disposal of excavated material, extensive clearing, and altered drainage; and replacement of natural channels by aesthetically inferior modified channels that are more uniform in appearance.

Knowledge of the fluvial system and its relationships with biological systems enables project planners to anticipate many of the adverse impacts of proposed channel modifications and to design environmental features that will reduce or compensate for these effects. Environmental features are structures, concepts, or actions employed in planning, designing, constructing, and maintaining flood control channels that improve the net environmental effect. Environmental features include modifications of standard techniques, such as selective clearing and

snagging or single bank construction; modified channel designs, including low flow channels, pools and riffles, and meandering alignments; structures for erosion and sediment control, water level management, and instream habitat; design and maintenance of projects to improve aquatic and terrestrial habitat; inclusion of recreational facilities in project design; and special designs and treatments for aesthetic purposes.

The effectiveness of environmental features used in flood control channel projects is reviewed, and information is presented concerning their advantages and disadvantages, cost, and maintenance considerations. Design considerations are discussed, and, where possible, detailed design procedures are presented. Not all environmental features are appropriate for all streams. Successful use of environmental features depends on watershed conditions and stream characteristics. Guidance for choosing appropriate environmental features based on stream and watershed conditions is presented in the form of matrices.

PREFACE

This report was prepared as part of the Environmental and Water Quality Operational Studies (EWQOS), Task VIB, Design and Construction Techniques for Waterway Projects. The EWQOS Program is sponsored by the Office, Chief of Engineers (OCE), US Army, and is assigned to the US Army Engineer Waterways Experiment Station (WES), under the purview of the Environmental Laboratory (EL). The OCE Technical Monitors for EWQOS are Mr. Earl E. Eiker, Dr. John Bushman, and Mr. James L. Gottesman. Dr. J. L. Mahloch, EL, is Program Manager of EWQOS.

The study was conducted during the period October 1981 to August 1983 by Dr. Nelson Nunnally and Mr. F. Douglas Shields of the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), EL. Dr. Nunnally was on temporary assignment under the terms of an Intergovernmental Personnel Act agreement between the WES and the University of North Carolina at Charlotte. Mr. Randall R. Williams reviewed many of the postauthorization reports and compiled much of the information on environmental features upon which this report is based. Dr. Nunnally, Mr. Shields, and Mr. Williams worked under the direct supervision of Mr. Michael R. Palermo, Chief, WREG, and under the general supervision of Mr. A. J. Green, Chief, EED, and Dr. John Harrison, Chief, EL.

The Commanders and Directors of WES during the study and publication of this report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. The Technical Director was Mr. F. R. Brown.

This report should be cited as follows:

Nunnally, N. R., and Shields, F. D. 1985. "Incorporation of Environmental Features in Flood Control Channel Projects," Technical Report E-85-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENTS

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4.046873	square kilometres
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres
square yards	0.8361274	square metres
tons (2,000 lb, mass)	907.1847	kilograms

INCORPORATION OF ENVIRONMENTAL FEATURES IN FLOOD CONTROL CHANNEL PROJECTS

PART I: INTRODUCTION

Background

1. The Corps of Engineers (CE) is committed to implementing the National Environmental Policy Act (NEPA) and other environmental statutes, regulations, and executive orders. The CE has issued several documents that contain general environmental guidelines and policies pertaining to design and construction of waterway projects, and a review of these is presented by Shields and Palermo (1982). Specific design guidance to implement these guidelines and policies is still needed. The CE is currently conducting a large-scale, multiyear research program, the Environmental and Water Quality Operational Studies (EWQOS), to address high-priority environmental problems. Part of this program (Work Unit VIB) is aimed at providing environmental design and construction guidance for specific types of waterway projects. This guidance will assist CE field offices in implementing Federal and CE environmental policies.

2. Initial environmental guidelines for four main types of projects have been produced under EWQOS Work Unit VIB: streambank protection (Henderson and Shields 1984), levees (Hynson et al. 1985), river training dikes (Burch et al. 1984), and flood control channels (Shields 1982). Background information concerning the environmental problems related to waterway projects is available from Shields and Palermo (1982) and Thackston and Sneed (1982). The four project categories were set up in a somewhat arbitrary fashion to facilitate information collection and review, and there is some overlap. Shields (1982), Shields and Palermo (1982), and Thackston and Sneed (1982) contain limited information on the environmental aspects of flood control channels.

Purpose

3. The purpose of this report is to provide CE personnel involved in the planning, design, construction, and maintenance of flood control channel projects information for improving the net environmental effect of their projects. This document provides background information for the Environmental Engineer Manual on Flood Control Channels.

4. Responsibility for flood control on navigable waterways and their tributaries was assigned to the CE by Congress in the Flood Control Act of 1936 (OCE 1981c) (Office, Chief of Engineers, U. S. Department of the Army). Section 2 of the Flood Control Act of 1944 extended that responsibility by redefining flood control to include "channel and major drainage improvement" (OCE 1981c).

5. General guidance on environmental quality aspects of engineering design for Civil Works projects is provided by Engineer Manual (EM) 1110-2-38 (OCE 1971c). This document stresses the need for innovative design approaches and the importance of "designing with nature in all of its dimensions--ecological, visual, and human-cultural--rather than against or onto it." Increased environmental concern resulted in the inclusion of a greater number and variety of environmental features in CE flood channel projects during the 1970s. Although the CE has incorporated recreational features and aesthetic considerations in the design of some urban flood channel projects, the lack of experience and inadequate guidelines for the design of many features that are needed to maintain and enhance environmental quality have resulted in varying degrees of success. Some features have performed inadequately, failed prematurely, or have been more expensive to build and maintain than had been anticipated. Such experiences are a strong deterrent to innovative design. Despite these problems, many flood control channel projects with new and innovative environmental features have performed well, and the use of such features on other projects should be encouraged. The knowledge gained from these experiences, both successful and unsuccessful, can provide the basis for improved guidelines for the design and construction of features for environmental maintenance and enhancement.

Scope

6. This report summarizes available information on design, maintenance, performance, and cost of environmental features that have been used on CE flood control projects in recent years. It is based on a survey of all CE flood control channel projects with postauthorization reports dated 1970 or later. A limited number of non-CE channel projects designed by the Soil Conservation Service (SCS), State Departments of Transportation (DOTs), and local governments were also surveyed. Only those flood control channels not navigable by commercial vessels were considered.

7. Although emphasis was placed on design, cost, and performance of environmental features, information on stream characteristics and watershed conditions was collected when available. Projects surveyed were distributed throughout the coterminous United States and were physically and ecologically quite diverse. Field visits were made to fourteen projects that incorporated a large number and variety of environmental quality features and represented a cross section of stream and watershed characteristics.

Organization of the Report

8. This report is organized to accommodate user needs to the maximum extent possible. Impacts of flood control channel modifications are reviewed briefly in Part II, and impacts of several example projects are described. In many cases, these impacts have been documented by or for various U. S. Army Engineer Districts or other Federal agencies.

9. Many of the environmental problems associated with flood control channel projects result from failure to consider the total fluvial system when planning the projects. To promote awareness of these problems and encourage innovative solutions, the fluvial system method of analysis that is currently prevalent is discussed in Part III.

10. Environmental features identified by the project surveys and by a literature review are discussed in Part IV. Features are grouped

according to their principal environmental purpose, even though there may be multiple benefits. Individual features or groups of features are evaluated in terms of their environmental effects, hydraulic effects, costs, durability, and maintenance and operational considerations. Any special constraints imposed by size, environmental conditions, or institutional considerations are discussed, and selected application examples are provided. Part IV also contains recommendations for designing environmental features. Adequate procedures already exist for many kinds of environmental features. No attempt is made to reproduce these detailed procedures in this report. Rather, general design procedures are reviewed and readers are referred to specific sources for additional information. In other cases, design guidelines are either nonexistent or inadequate. In these cases, no attempt is made to produce prescriptive guidance. Instead, essential design concepts are reviewed, structural components are discussed, and, wherever possible, design procedures are presented.

11. Part V is intended to help project planners and designers select the most appropriate environmental features for a given project. Tables and matrices are used to organize information in an efficient and systematic manner so that planners can quickly eliminate features that are inappropriate for a particular project due to environmental conditions, hydraulic considerations, cost, or institutional constraints.

12. Reliable data that can be used to evaluate cost and performance of environmental features are quite scarce. Furthermore, little guidance is available to aid engineers in designing hydraulically efficient channels with desirable environmental features. Part VI summarizes findings of the report and recommends a process for continued evaluation of CE flood channel projects to ensure feedback of information necessary to improve project planning and design. Recommendations are made for the continued inprovement of environmental design guidelines and for future research.

13. Supplemental information provided in the appendixes includes: a glossary of water resource terms (Appendix A), an outline of the procedure for designing flood control channel projects (Appendix B), a

checklist of data sources (Appendix C), specifications for constructing a clay blanket bank protection device (Appendix D), a summary of the landscaping maintenance requirements for the Walnut Creek, California, flood control project (Appendix E), and an index of flood control channel projects referenced in the text.

PART II: ENVIRONMENTAL IMPACTS OF CHANNEL MODIFICATIONS FOR FLOOD CONTROL

14. Channel modification has been widely employed to increase stream capacity for flood control and drainage purposes. The major types of modifications employed for flood control are extensive clearing and snagging, channel enlargement, and channel realignment. Flood control projects have provided many positive benefits. Foremost among them are flood control protection for urban areas and reduction of direct and indirect flood losses to agriculture. Flood channel modifications also often have adverse environmental impacts.

15. The environmental movement of the 1960s focused new attention on the importance of maintaining all aspects of environmental quality. The National Environmental Policy Act of 1969 (NEPA) (OCE 1981c) required Federal agencies to formalize procedures for systematically examining environmental impacts of their actions. As agencies involved in channel modification and concerned environmental groups sought to document the nature and magnitude of environmental impacts, large numbers of studies were conducted. Some of these, such as the Report on Channel Modifications prepared by Arthur D. Little, Inc. (1973) for the Council on Environmental Quality (CEQ), were comprehensive in scope and covered all kinds of impacts, a variety of stream sizes, and a wide range of environmental settings. Other studies have been confined to specific types of impacts and geographic areas.

16. These reports, many of which are referenced in the following paragraphs, thoroughly document impacts of flood channel projects, and no attempt is made here to reiterate the detailed findings of these studies. Instead, impacts are summarized briefly and references are provided for those who wish to further pursue these topics. The nature and magnitude of impacts are illustrated by examples selected from flood control channel projects carried out by the CE, SCS, and state and local agencies involved in flood control. For simplicity, environmental impacts are discussed with regard to their effect on channel stability,

hydrologic regimes, water quality, aquatic ecosystems, terrestrial ecosystems, wetlands, and aesthetics.

Channel Stability

17. Channel modifications may cause instability in the improved channel reach and upstream or downstream of the reach. Each segment may experience either aggradation or erosion. These problems are most often attributed to increased bottom width, to slope changes caused by channel shortening or bed excavation, or to the removal of bank vegetation.

18. Changes in slope, channel dimensions, or channel roughness usually alter the existing balance between water discharge and sediment transport. If sediment transport capacity is increased without corresponding increases in sediment supply, bed or bank erosion may occur, although the effects normally decrease through time (Parker and Andres 1976, Yearke 1971).

19. Channels in unconsolidated alluvium may undergo rapid bank erosion when channel slopes are increased and/or when bank vegetation is removed during channel work. One of the most striking examples reported in the literature occurred on Missouri's Blackwater River where the cross-sectional area increased nearly 1200 percent (Jahn and Trefethan 1973). Barclay (1980) reported increases of 500-800 percent on Rush and Wildhorse Creeks in Oklahoma. Loss of property, bridges, and structures due to such instability can be significant. Although land use changes or climatic variability may have been contributing factors in these dramatic cases, there is little doubt that the increases in channel dimensions were triggered by increased channel gradients and bed lowering.

20. When the beds of trunk streams are lowered through excavation or erosion, gradients are radically increased at tributary confluences, and headcuts (knickpoints) often develop and migrate upstream. Classic examples of this problem can be found in the Yazoo Basin in Mississippi. Channel modifications that occurred several decades ago produced headcuts which are still migrating up some tributaries. These Yazoo tributary channels undergo considerable enlargement as the headcuts pass,

increasing 2 to 5 ft* in depth and often doubling in width (Whitten and Patrick 1981). Twenty Mile Creek, a tributary to the Tombigbee River in Mississippi, developed headcuts on the mainstream and its tributaries following modification by the CE in 1966 (U. S. Army Engineer District (USAED), Mobile 1979) (Figure 1).

Figure 1. Headcut erosion on Twenty Mile Creek, Mississippi. Headcuts that caused the enlargement of the channel developed following modification of the channel in 1966.

21. Although aggradation, or channel filling, does not receive as much attention in the literature as does erosion, it is very much a problem. Much of the sediment eroded from channel beds and banks is deposited within a short distance downstream of its source areas. Cederholm (1972) reported that within the first year following channelization, which more than doubled the slope of Big Beef Creek in Washington, rapid streambank and streambed erosion contributed 90 percent of the sediment deposited in the channelized reach. Aggradation of the lower

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 10.

reaches of modified channels often reduces the channel capacity such that flooding problems in these reaches are as bad or worse than those existing prior to channel modification (Parker and Andres 1976; USAED, Mobile 1979).

22. Enlarged channel cross sections in the lower reaches of projects sometimes function as sediment traps. As the channels fill with sediment, flow depths and channel capacities are reduced. The problem is compounded in the lower reaches of streams where local base levels control stream gradients. Griggs and Paris (1982) report that within 10 years after completion of a CE flood channel on the San Lorenzo River at Santa Cruz, California, 400,000 sq yd of sediment had been deposited in the enlarged channel, thereby reducing its capacity from the 100-year flood to the 25- to 30-year flood.

23. Instability decreases project life, increases maintenance costs, and may require large expenditures to replace damaged structures such as bridges, roads, and pipeline crossings. Effects of stream channel degradation and aggradation on highways and bridges are thoroughly reviewed in Brown, McQuivey, and Keefer (1981) and Brice (1981).

Hydrologic Regimes

24. Hydrologic impacts of channel improvements are less well documented than other types of impacts. Manipulation of hydraulic and hydrologic relationships is the major objective of flood control channel projects. Thus, some of the direct hydrologic impacts are intentional. In most successful flood channels, peak discharge capacity is increased by improving channel conveyance. Effects on base flow discharge are largely indirect and depend on whether changes occur in ground water levels, infiltration, evapotranspiration rates, basin land use, and contiguous wetlands.

25. Ground water levels are affected when the stage-discharge relationship is altered, or when streambeds are lowered. Ground water effects are most notable in low gradient streams in porous soils. The U. S. Geological Survey conducted a "before and after" study of ground

water levels on a CE project located on the coastal plain of North Carolina (Simmons and Watkins 1982). Before channel work, water levels in the stream and nearby wells "... responded slowly to rainfall, generally rising less than a foot in one day. Since channelization, both ground water and stream level often rise 2 or more feet in a few hours and also recede at a faster rate." Ground water levels were lowered an average of about 2 ft in wells within 100 ft of the stream, but no effect could be observed 500 ft from the stream.

26. Channels modified for flood control convey water downstream more quickly, and this may increase flooding in downstream reaches, especially if timing is altered so that peak discharge on the main stream coincides with peak discharges from tributaries. These downstream effects are not well documented, even though there is a great deal of speculation about the subject. The Arthur D. Little, Inc. (1973) report concluded that the issue was somewhat overrated. The authors reported that 31 of 42 projects they investigated in detail had negligible downstream effects, and effects on seven others were indefinite.

27. Although substantiative research on hydrologic impacts is lacking, it appears that the nature and extent of effects depend on drainage basin characteristics (topography, geology, shape, etc.), the project design and magnitude, and flows to which the project is subjected. The most critical aspects of project design appear to be depth of excavation, amount of straightening, project length, and percentage of total channel length affected.

Water Quality

28. Direct and indirect water quality changes, including those of a favorable nature, are closely related to erosion problems, loss of shade, and hydrologic impacts. The following discussion is limited to those parameters that are most affected by channel modification and are most often measured--turbidity, temperature, dissolved oxygen, nutrient levels, and contaminants. Two types of studies have been done--before and after studies on modified reaches, and studies that compare modified

reaches with unaltered reaches on the same or nearby similar streams. Other variables that influence water quality were not controlled in either type of study, so findings are not easily evaluated.

Turbidity

29. Almost all studies of channel modifications have concluded that turbidity levels increase significantly, with the highest turbidity levels occurring during construction. Suspended sediment concentrations on the Black River in North Carolina increased by more than tenfold for discharges greater than 30 cfs during channel work using tracked draglines (Simmons and Watkins 1982). Concentrations decreased to as little as half the construction level following construction and bank stabilization. Similar results were observed on Chicod Creek, an SCS project in North Carolina where only limited clearing and snagging was done. Studies comparing previously channelized sections of the Obion and Forked Deer river systems with unchannelized sections of those streams and the Hatchie River in western Tennessee showed that proposed channel enlargement and alignment would probably cause significant increases in sediment and turbidity levels during construction, as well as increased levels resulting from bank erosion of the modified streams (USAED, Memphis 1982).

Temperature

30. Temperature is an important water quality parameter because it influences chemical and biological stream processes. Removal of riparian vegetation along long reaches of streams has been observed to result in higher mean temperatures in and below the modified reaches (Arner et al. 1976, Headrick 1976, Huish and Pardue 1978). Because temperature increases are directly related to loss of shade and to shallow depths, the greatest temperature increases occur in lined channels. Parrish et al. (1978) report that peak daily temperatures in a Hawaiian stream, averaged over a year, were raised as much as 7.8° C during flow through a lined channel 1.5 miles long. Diurnal temperature variations are increased by higher daytime temperatures. Simmons and Watkins (1982) report daytime temperature increases of as much as 4° C on a straightened and enlarged reach of Black River, North Carolina. Similar

ranges were found by Dodge et al. (1976) in Vermont, Headrick (1976) in Wisconsin, King and Carlander (1976) in Iowa, and Lund (1976) in Montana.

Dissolved oxygen

31. Minimum acceptable dissolved oxygen concentrations for support of varied fish populations are generally considered to be in the 4-to 5-mg/ℓ range (Ellis 1937, Environmental Protection Agency (EPA) 1976). Turbulent, high gradient streams rarely exhibit dissolved oxygen levels that approach critical conditions. Oxygen levels in low gradient streams respond in a variable manner to channel modifications. Studies in Mississippi and Iowa found no appreciable differences in dissolved oxygen levels in channelized and unchannelized stream segments (Arner et al. 1976, Bulkley et al. 1976). Coastal swamp streams, which usually have low dissolved oxygen concentrations during the summer months when water temperatures are high and flows are low, often show higher concentrations following channel modification. Simmons and Watkins (1982) found that dissolved oxygen levels in the Black River were often less than 5 mg/ℓ in the summer and autumn prior to channel modification, but seldom fell below that value afterwards. Kuenzler et al. (1977) found that levels were below 4 mg/ℓ for 4 to 5 months in the unchannelized stream they studied, whereas the level in the modified streams seldom fell below 6 mg/ℓ. Increased dissolved oxygen levels in modified streams are attributed to higher flow velocities and turbulence and to the removal of accumulated organic material (Huish and Pardue 1978).

Nutrients and contaminants

32. Often the objective of flood control channel projects in nonurban areas is to reduce high-frequency, low-magnitude flooding of farmlands. Both the CE and SCS are involved in such work. Modern agriculture relies heavily on fertilizers, pesticides, and herbicides, and animal operations generate large volumes of animal wastes that are difficult to dispose of. Nutrients, bacteria, sediment, and other contaminants from farming operations find their way into streams. Although agricultural activities contribute the bulk of pesticides and organic compounds, development of flood-prone urban areas also contributes to

nutrient and contaminant loads (Simpson et al. 1981).

33. Comparative studies of nutrient and contaminant levels of modified and unaltered streams have produced mixed results, with patterns related more to the types of land use and their distribution within the drainage basin than to channel modifications (Omernik 1976, O'Rear 1975, Schlosser and Karr 1980). Thus, no significant differences in nutrient or contaminant levels that could be attributed directly to channel modification were observed in any of the previously mentioned studies. In those cases where reduced flooding encourages urban development or widespread clearing of land and expansion of crop production, concomitant increases in nutrient and contaminant levels can be expected (Arthur D. Little, Inc. 1973).

Aquatic Ecosystems

34. Flood control channel projects may have both direct and indirect impacts on aquatic habitat and associated organisms. Clearly, water quality (especially temperature and dissolved oxygen) and erosion and sedimentation have substantial effects on all forms of aquatic life. The following discussion is confined to impacts upon macroinvertebrate populations and fish.

Macroinvertebrates

35. Benthic macroinvertebrates are the major food source for many species of fish. Abundance and diversity of benthic macroinvertebrates are good indicators of the biologic vigor and water quality of streams. Construction activities which result in the removal of vegetation, replacement of organic substrates with sand or silt, and increased flow velocities seriously deplete macroinvertebrate populations that depend on this organic matter for food supply and cover. Generally, these impacts are not as persistent as some of the physical impacts discussed previously. Short life cycles and recolonization by organisms that drift from unchannelized upstream reaches tend to promote rapid recovery of macroinvertebrate populations, unless the substrate is permanently degraded (Simpson et al. 1981). A number of studies have found no

significant difference in macroinvertebrate diversity on biomass between modified and unaltered streams (Dodge et al. 1976, Griswold et al. 1978, King and Carlander 1976, Wydoski and Helm 1980). Some studies have documented recovery rates that range from 3 months (Kennedy 1955) to a year or less (Gore and Johnson 1980, Meehan 1971, Possardt et al. 1976, Whitaker et al. 1979).

36. Significant substrate alterations can be caused by erosion and sedimentation problems triggered by channel excavation. Erosion of bed and banks may persist for decades and generate massive amounts of sediments that are deposited in downstream reaches. Erosion and deposition of sediment alter substrate by destroying armor layers and depositing finer, less stable bed material. Altered substrate can cause shifts in species composition, diversity, and density or biomass such as those documented by Arner et al. (1976), Griswold et al. (1978), and Hansen (1971).

Fish

37. Impacts on fish populations result from loss of habitat, changes in habitat type, and changes in water quality. Straightening sinuous streams may reduce length by 50 percent or more in some cases, resulting in a corresponding reduction in potential habitat. Even when cutoff bendways are not completely isolated from the flood channel, they gradually fill with sediment and contain fewer species and numbers of fish than the main channel (Bulkley et al. 1976, Fredrickson 1979).

38. Some species are impacted more than others and coldwater fisheries are especially susceptible. White (1973) reviewed 48 studies on channelization of salmon and trout streams and found that catchable fish biomass declined in every case. The declines exceeded 75 percent in 44 of the studies. In warmwater streams, species diversity may not be affected because species lost due to habitat changes are replaced by others, although species lost are more likely to be game fish (Arner et al. 1976, Griswold et al. 1978, Huish and Pardue 1978, Lund 1976). Populations in channelized streams tend to be more uniform in age and size, with juveniles dominating. This is attributed to loss of spawning and nursery habitat and emigration of large fish to more suitable habitats (Arner et al. 1976).

Terrestrial Ecosystems

39. Flood control channel projects that include excavation impact terrestrial ecosystems directly through removal of riparian vegetation, disposal of spoil, and drainage of riparian lands. Indirect impacts occur through induced land use changes. In each case, elimination or alteration of vegetative cover induces habitat changes that affect wildlife.

40. In prairie and desert areas, galleria vegetation along streams provides a type of habitat that is otherwise scarce. Even in humid regions, riparian locations offer special edge habitat that is not found in abundance elsewhere. Flood control projects that specify extensive clearing and snagging or dredging normally require some streambank clearing for equipment access and operations (Figure 2). Loss of woody vegetation eliminates habitat space, alters microhabitats, and increases susceptibility of banks to erosion (Barclay 1980, Fredrickson 1979, Simpson et al. 1981).

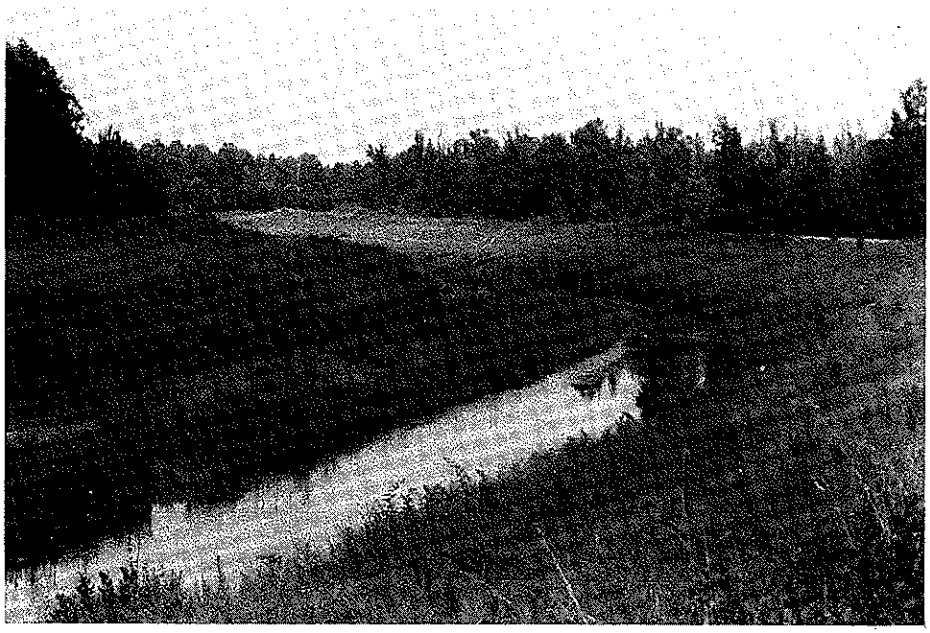


Figure 2. Loss of woody vegetation during channel modification. Trees were removed from both sides of this enlarged channel for equipment access and operation.

41. Streamside disposal of material excavated from channels may cover topsoil, destroy ground cover, and create drainage problems, thereby altering vegetative structure (Arthur D. Little, Inc. 1973, Fredrickson 1979). Revegetated disposal areas can become good wildlife habitat if they are not cleared or leveled, particularly in extremely flat flood-prone areas.

42. Disturbed forest areas normally undergo vegetative succession during which the dominant vegetation changes from annual weeds and grasses to woody shrub forms, usually culminating in woodland or forest. Succession culminates in a stable climax form similar to that which prevailed prior to disturbance unless altered drainage conditions produce shifts to more hydric or xeric forms. Because each successional stage provides habitats that foster specific types of birds and animals, specific impacts vary with the extent of vegetation disturbance and the time elapsed since construction (Barclay 1980, Dale 1975, Fredrickson 1979, Possardt et al. 1976, Simpson et al. 1981). Regular maintenance of bank and riparian zones, such as mowing or spraying with herbicides, can forestall further succession and prevent reestablishment of vegetative diversity.

Wetlands

43. Improved drainage conditions and the lowering of the water table in the riparian zone that often accompanies channel improvements can have major impact on wetlands and wetland vegetation. Waterfowl, amphibians and reptiles, and some mammals are impacted by loss of breeding, feeding, and nesting habitats (Anderson and Glover 1967, Prellwitz 1976).

44. Land use changes stimulated by improved flood protection may affect an area several times the size of the project right-of-way. For example, the Final Supplement to the Final Environmental Impact Statement for West Tennessee Tributaries Project estimates that induced clearing is expected to result in the loss of as much as 11,709 acres of wetland habitat, compared to 1972 acres lost directly to project construction

(USAED, Memphis 1982). The most common changes are conversion of forest land and wetlands to croplands and grazing (Arthur D. Little, Inc. 1973, Best et al. 1978, Simpson et al. 1981).

Aesthetics

45. Ugliness, as well as beauty, is in the eye of the beholder. Little work has been done on quantifying aesthetic impacts of flood control channel projects due to the difficulty in measuring impacts which are perceptual in nature. Leopold (1969a, 1969b) and Melhorn et al. (1975) present numerical rating systems for stream aesthetics, but few, if any, examples exist of application of these systems to evaluate flood control channel projects.

46. Flood control channels may be visual amenities or liabilities depending on whether they blend harmoniously with other landscape components or stand in stark contrast to them. A well-landscaped, winding channel containing clear water is more desirable to most observers than either a straight, uniform ditch or an unaltered channel with severely eroding banks and muddy water. Negative impacts may be compounded when unique landscape features are lost or obscured, or when vegetation that acts as a visual screen is eliminated. Dale (1975) surveyed aesthetic qualities of several channelized streams in Arkansas and concluded that aesthetic acceptibility was influenced strongly by age of project, use of natural vegetation, and maintenance practices.

Summary

47. Not all flood control channel designs have the same types and degrees of impacts. Specific impacts depend on project size, environmental setting, and the extent to which environmental components are disturbed. General impacts can be grouped into seven basic categories: impacts on channel stability, hydrologic regimes, water quality, aquatic habitat, terrestrial habitat, wetlands, and aesthetics.

48. Instability problems are caused by channel enlargement,

straightening, and loss of streamside vegetation. Bed and bank erosion produce large amounts of sediment that is often deposited in downstream reaches where it seriously impairs flood conveyance. Headcuts that develop in response to oversteepening and bed lowering often migrate upstream through tributary channels and cause additional erosion and sedimentation problems.

49. Flood channels are designed for efficiency and, thus, may have higher peak discharges and flow velocities during flood events than unaltered channels. They may also have reduced flow during low flow periods and more uniform flow velocities. Although downstream effects are not well documented, they appear to be negligible in many cases. Hydrologic effects depend largely on watershed characteristics, project design, and experienced flows.

50. Water quality impacts are closely related to erosion, loss of shade, hydrologic impacts, and induced land use changes. Turbidity levels usually increase dramatically during construction but may gradually decline to previous levels once banks are stabilized. Water temperature may be increased significantly on small channels following modification due to shallow flow depths and loss of shade. Dissolved oxygen levels may or may not be affected depending on flow conditions, temperature effects, and other factors. Nutrient and contaminant levels are affected primarily by the land use changes in flood-prone areas that are induced by flood protection.

51. Abundance and diversity of benthic macroinvertebrates may undergo substantial changes on modified channels due to reduced channel length, more uniform flow conditions, reduced organic input, and substrate changes. Fish populations are affected by changes in benthic macroinvertebrates, which are a major food source, and by loss of cover, changes in habitat type, and water quality.

52. Terrestrial ecosystems are impacted directly by removal of riparian vegetation, disposal of excavated or dredged material, and drainage of riparian lands, and indirectly by induced land use changes. Loss of woody vegetation eliminates habitat space and alters microhabitats. Regular maintenance may prevent vegetative succession and

reestablishment of vegetative diversity. Improved drainage and lowering of water tables may reduce breeding, feeding, and nesting areas for waterfowl, amphibians, reptiles, and mammals that need wetland habitat. Land use changes stimulated by improved flood protection may affect an area several times the size of the project right-of-way.

53. Aesthetic impacts associated with channel modification may be positive or negative depending on the condition of the original stream and the manner in which the flood channel is designed. Negative impacts can be significant if unique landscape features are lost or if aesthetic considerations are not given high priority in channel design.

54. More specific information about the impacts of channel modification and their significance to the detailed aspects of project design, construction, and maintenance can be found in reports referenced in this document, including several excellent summary documents (Arthur D. Little, Inc. 1973; Bulkley et al. 1976; Parrish et al. 1978; Simpson et al. 1981).

PART III: THE FLUVIAL SYSTEM

55. An appreciation of the nature and behavior of fluvial systems is essential in planning and designing flood control channel projects that maintain and enhance environmental quality. Streams do not exist as isolated, independent entities. To a large extent, stream characteristics are a reflection of the geology, topography, soils, vegetation, precipitation, and other natural characteristics of the drainage basin. Human activities and natural processes influence the movement of water and sediment over the land surface and within streams. Changes in the watershed can trigger adjustments within streams and related biological and physical systems. Because of these interrelationships, it is virtually impossible to understand stream processes without some knowledge of watershed conditions.

56. Geomorphologists and hydrologists have turned increasingly to systems theory and systems analysis as a means of understanding complex geomorphic, hydraulic, and hydrologic processes. The watershed and stream network is viewed as a unified fluvial system. A systems approach not only provides a convenient and systematic organizational framework, but it also promotes a unified, holistic view of the environment and the role of the fluvial system within it.

Structure of the Fluvial System

57. For simplicity and convenience, the fluvial system can be subdivided into two major subsystems:

a. The drainage basin or watershed system, which is dominated by the processes of overland flow and flow through the soil.

b. The stream system, which is composed of the mainstream and all its permanent and intermittent tributaries in which open channel flow occurs.

Since drainage basin processes control the amount and rates of water, sediment, and dissolved load supplied to the stream system, an adequate understanding of both subsystems is essential for those who plan flood

control projects. The renowned forester and conservationist expressed the problem aptly (Pinchot 1947).

> The forest and its relation to streams and inland navigation; to water powers and flood control; to the soil and its erosion; to coal and oil and other minerals; to fish and game; and many another possible use or waste of natural resources--these questions would not let me be. What had all these to do with forestry? And what had forestry to do with them?
>
> Here were not isolated and separate problems. My work had brought me into touch with all of them. But what was the basic link between them?
>
> Suddenly the idea flashed through my head that there was a unity in this complication--that the relation of one resource to another was not the end of the story. Here were no longer a lot of different, independent, and often antagonistic questions, each on its own separate little island, as we had been in the habit of thinking. In place of them, here was one single question of many parts.

Drainage basin subsystem

58. The processes that produce the fluvial response of the drainage basin subsystem are the type, amount, and temporal-spatial distribution of precipitation; rates of infiltration and evapotranspiration; and soil erosion. These processes are controlled by weather conditions, topography, vegetation, soil characteristics, and human activities. Infiltration is a function of precipitation intensity, antecedent soil moisture, slope, vegetation, and soil type. Runoff rates depend on rates of precipitation and infiltration, and peak discharge and runoff velocities are related to such additional factors as slope length and steepness and the amount of flow resistance offered by vegetative cover. The interactions among precipitation intensity, runoff velocities, vegetative cover, soil properties, and conservation practices control the rate of soil erosion and sediment yield.

59. A complete and accurate model of a drainage basin is virtually impossible to produce because of its complexity. Nevertheless, a number of mathematical models have been developed to predict sediment yield or runoff. Examples include the Universal Soil Loss Equation

(USLE) for predicting soil erosion; the SCS curve number method and regression models for predicting peak discharges; complex unit hydrograph models, such as the Stanford watershed models, for simulating output hydrographs; and stochastic models used to generate synthetic long-term records. Branson (1981) discusses the structure and use of all of these types of models.

60. To evaluate the drainage basin subsystem, a number of parameters and processes must be considered, as summarized in the following tabulation.

Major Watershed Parameters	Major Processes	Major Storages and Outputs
Precipitation	Interception	Soil moisture
Solar radiation	Evapotranspiration	Ground water
Temperature	Infiltration	Water discharge
Vegetation and land use	Throughflow	Sediment discharge
Soils	Overland flow	
Geology	Soil erosion	
Topography		

Major watershed attributes are shown in the left column. In watershed modeling, values or coefficients for these parameters must be measured or estimated. A parameter may have several associated values or coefficients, depending on its use. For example, vegetation may be considered as a roughness factor in equations to predict overland flow velocities, a curve number for calculating infiltration and runoff, or a cover value for predicting soil erosion.

61. Processes that govern output and storage of water and sediment are shown in the middle column. In modeling, the processes are represented by equations, the variables of which are the values of the attributes in column one. Solving the equations with actual or assumed values yields a system response, described by the storage conditions and outputs of the right column.

62. In drainage basins that have not been unduly altered by humans, average parameters are more or less constant over periods of years and equilibrium conditions prevail. Thus, excluding localized disturbances and short-term changes, such as those associated with severe weather events, system response remains relatively constant over time.

Similar rainfall amounts produce similar runoff, erosion, and stream discharges.

63. Equilibrium conditions are upset and system responses are altered in watersheds that have been greatly disturbed by natural processes or human intervention (e.g., forest fires, volcanic eruptions, logging, agriculture, and urbanization). One example of a disturbed system is a forested watershed that has been altered by fire or land use changes. Forest canopy reduces rainfall intensity, and forest soils tend to be very porous. Under forested conditions, infiltration and evapotranspiration rates are high and overland flow is minimal. Consequently, lag time (the time which elapses between the center of mass of rainfall excess and peak runoff) is long; storm runoff and sediment yield are low; soil moisture is high following storms, but may be depleted rapidly during hot, dry conditions; and base flow is high. Removal of forest cover shortens lag time, decreases infiltration and evapotranspiration, increases runoff and sediment yield, and decreases base flow (White and Wells 1979).

64. One advantage of models is that the system must be structured in a logical manner that promotes understanding of the complex interactions among system components and processes. Thus, it becomes possible to estimate the effects that changes in one or more variables may have upon other variables or upon system behavior. Even generalized qualitative models may allow predictions of the type and direction of changes, although the magnitude cannot be specified.

65. A basic understanding of the drainage basin subsystem is essential for the proper planning and design of flood control channel projects. Close coordination between the hydrologic and hydraulic studies during the design stage is important, and the designers must develop an appreciation of the potential effects on flood control channels of events that occur in drainage basins. An exhaustive treatment of drainage basin processes is beyond the scope of this report. In-depth discussions are provided by Dunne and Leopold (1978) and Schumm (1977).

Stream subsystem

66. The stream subsystem is composed of the main channel and all

of its tributaries. The stream subsystem transports both water and sediment, and flow is typically unsteady, nonuniform, and highly turbulent. Under equilibrium conditions, stream systems tend to be morphologically stable, transporting the water and sediment loads imposed from the watershed without enlarging or aggrading the channel. Geomorphologists describe such streams as graded, whereas engineers usually refer to them as being stable or in regime. Under nonequilibrium conditions, an alluvial stream may erode its bed or banks or aggrade its channel, thereby changing its sediment load and altering its width, depth, slope, or pattern. Under these conditions, water inflow from the watershed is the only completely independent variable imposed on the river system. Sediment load is partly independent and partly dependent since it is influenced by erosion and deposition within the channel. All hydraulic and morphologic variables (flow velocity, width, depth, slope, channel pattern, and bedforms) are totally dependent and are free to adjust in response to changing water and sediment inputs. Furthermore, all of the dependent variables are interrelated in such a way that changes in one can trigger adjustments in one or more of the others. The nature and extent of adjustments in a stream system can be predicted accurately only if the interrelationships among the variables that describe the system can be evaluated mathematically. A solution exists to a set of equations only if there are as many equations as there are unknowns. This can be demonstrated for a simplified channel reach.

67. Equations for uniform flow. The simplest channel imaginable would be a rigidly bounded, straight, rectangular channel with constant slope (S) and constant discharge of clear water (Q) which produces constant velocity (V) and uniform flow depth (D). The water input into the channel represents potential energy that is converted to kinetic energy as the water flows downslope. Under open channel flow conditions, the only accelerating force is gravity. Because flow is uniform and steady (no acceleration), the force of gravity is opposed by an equal resisting force exerted on the flow by the stationary bed and banks. Several flow resistance equations have been developed and their derivations are explained in many hydraulic texts. Among the widely

used resistance equations are the Chezy (Equation 1), Darcy-Weisbach (Equation 2), and the Manning (Equation 3).

$$V = c\sqrt{RS} \tag{1}$$

$$V = \sqrt{\frac{8gDS}{f}} \tag{2}$$

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \tag{3}$$

in which the velocity (V) is related to channel roughness factors (c, f, n), channel slope (S), and expressions of flow depth (D, R). If discharge (Q) is changed, the only adjustments allowed, because of the rigid boundary, are depth of flow and flow velocity. Therefore, only two equations are required to solve for the two unknowns--one of the resistance equations (1, 2, or 3) and the continuity equation

$$Q = AV \tag{4}$$

in which A is the cross-sectional area of flow.

68. Alluvial streams. Alluvial streams are much more complex than this simple example. Their boundaries are not fixed, and their channels are neither uniform nor straight. Sediment (Q_s) is input to the channel from the watershed, and the stream may deposit or entrain sediment already within the channel. Thus, a sediment transport equation and equations describing width, slope, channel pattern, and bedforms are needed to predict the behavior of an alluvial channel. The required equations number at least seven, but even seven equations are inadequate to solve for all the variables. The equations are much more complex for alluvial streams than those for the rigid boundary example given above. The flow resistance equation, for example, must contain additional terms to account for the contributions to resistance by sediment particle size and concentration, bank smoothness, bedforms, and channel curvature. Currently, the only required equations that are reasonably well specified are the continuity equation, flow resistance equations, transport equations, and width equations.

69. No universal approach to describing and understanding stream behavior is possible without a set of determinate equations. Thus, there is no way to predict precisely what will happen when width, depth, slope, channel roughness, or channel pattern are altered during channel modification or what effect changes in a watershed will have on flood channels. Field and laboratory studies have yielded a considerable body of knowledge about stream behavior.

70. Empirical versus fundamental approaches to understanding stream behavior. Allen (1977) has classified studies of river behavior into two categories--the empirical school and the fundamental school. Geomorphologists who study hydraulic geometry and engineers who ascribe to regime relations are placed in the former group, whereas the mathematical modelers who base their formulas on general physical principles and controlled laboratory experiments are placed in the latter. Each approach has merits and shortcomings. Empirical studies have stressed form and descriptive generalizations at the expense of processes and mechanisms. Model studies, on the other hand, "have led to valuable insights on mechanisms and processes, but at the cost of considerable oversimplification and the relative neglect, to date, of the problems of rivers on the larger temporal and spatial scales" (Allen 1977).

71. Problems with the empirical approach. Results from neither approach can be applied indiscriminantly to predict river response. Thornes (1977) has offered three reasons why stream behavior cannot be accurately predicted from studies of hydraulic geometry. The first, and most critical, is the problem of indeterminacy (paragraph 69). Streams adjust to change in numerous ways. Thus, steepening a stream's gradient might cause no change, or it might increase flow velocity, cause channel erosion, trigger a change in planform or pattern, or some combination of those responses. For example, natural or artificial steepening of slopes on some meandering streams may trigger rapid bank erosion and braiding sufficient to reduce mean flow velocity. The inverse of indeterminacy is equifinality--i.e., a stream can reach a given state by any of several individual causes or combinations of causes.

72. The second problem with empirical studies is that they treat

streams largely as steady-state or equilibrium systems. Most streams have been disturbed to some degree by human activities and are, therefore, transient. Because varying time periods are required for streams to adjust to altered conditions, observed hydraulic geometry may be the product of prior hydrologic and environmental conditions.

73. The third problem involves assumptions about the nature of mathematical relationships that are usually assumed to be continuous and smooth. There is reason to believe that some relationships used to describe fluvial responses may possess discontinuities, often in the form of thresholds (Schumm 1977). Graf (1979a) has suggested catastrophe theory as an alternative to threshold models for describing changes in fluvial systems.

74. Problems with the fundamental approach. The fundamental school is not without problems either. Much of the work is based on flume studies in which certain variables are held constant while others are manipulated experimentally. Other than discharge, any variables held constant in flume studies are free to adjust and interact simultaneously with other dependent variables under natural stream conditions. Because of the physical limitations of flumes and the inability to establish similitude among all factors in scaled down models, certain variables used in flume studies are restricted to a fraction of their true size and range in nature. Finally, flume studies usually do not duplicate the unsteady, random, gradually varied flows that occur in natural streams. For these reasons, conclusions about fluvial processes derived from physical experiments may have limited application to natural fluvial systems and should be applied cautiously.

75. Case studies. In addition to empirical and fundamental studies, case studies may be considered a third approach. Using this approach, behavior is deduced by observing responses of stream systems that have been altered by natural processes or by human intervention. Although the case study approach is empirical, it differs from regime and hydraulic geometry studies that have focused on equilibrium systems. The major problems inherent in the case study approach are the limited domain of available, well documented case studies and the indeterminacy,

discontinuity, and threshold problems that hinder the use of hydraulic geometry and regime relationships.

76. Functional relationships. Although fluvial research has failed to produce a set of determinate equations that fully describe stream behavior, investigators have succeeded in defining some of the functional relationships among some stream variables. If used cautiously, these relationships can suggest the types of adjustments that are most likely to occur when watersheds undergo change or when one or more stream characteristics are modified. The most useful functional relationships are listed below (Lane 1955, Maddock 1972, Santos-Cayudo and Simons 1972, Schumm 1977).

$$Q_s^{+} , Q_w^{++} \sim S^{-} , d_{50}^{+} , D^{+} , W^{+} \tag{5}$$

$$Q_s^{o} , Q_w^{+} \sim S^{-} , d_{50}^{+} , D+ , W+ \tag{6}$$

$$Q_s^{-} , Q_w^{o} \sim S^{-} , d_{50}^{+} , D^{+} , W^{-} \tag{7}$$

$$Q_s^{--} , Q_w^{-} \sim S^{-} , d_{50}^{+} , D^{+} , W^{-} \tag{8}$$

$$Q_s^{-} , Q_w^{+} \sim S^{-} , d_{50}^{+} , D^{+} , W^{\pm} \tag{9}$$

$$Q_s^{+} , Q_w^{+} \sim S^{\pm} , d_{50}^{\pm} , D^{\pm} , W^{+} \tag{10}$$

$$Q_s^{-} , Q_w^{-} \sim S^{\pm} , d_{50}^{\pm} , D^{\pm} , W^{-} \tag{11}$$

$$Q_s^{++} , Q_w^{+} \sim S^{+} , d_{50}^{-} , D^{-} , W^{+} \tag{12}$$

$$Q_s^{+} , Q_w^{o} \sim S^{+} , d_{50}^{-} , D^{-} , W^{+} \tag{13}$$

$$Q_s^{o} , Q_w^{-} \sim S^{+} , d_{50}^{-} , D^{-} , W^{-} \tag{14}$$

$$Q_s^{-} , Q_w^{--} \sim S^{+} , d_{50}^{-} , D^{-} , W^{-} \tag{15}$$

$$Q_s^+ \ , \ Q_w^- \sim S^+ \ , \ d_{50}^- \ , \ D^- \ , \ W^{\pm} \tag{16}$$

$$S \sim W \ , \ d_{50} \ , \ \frac{1}{Q_w} \tag{17}$$

$$Q_w S \sim Q_s \ d_{50} \tag{18}$$

$$\frac{W}{D} \sim Q_w \ , \ Q_{sb} \tag{19}$$

$$\rho \sim \frac{1}{Q_{sb}} \tag{20}$$

$$\rho \sim S_v \tag{21}$$

where

Q_s = sediment discharge
Q_w = discharge of water
$\sim$ = "is proportional to"
S = water surface slope
d_{50} = median particle diameter of bed material
D = flow depth
W = flow width
Q_{sb} = bedload discharge
ρ = channel sinuosity (ratio of channel length to valley length
S_v = valley slope

Superscripts indicate direction and magnitude of change. Constant conditions (no change) are indicated by o's, whereas + and - indicate increase and decrease, respectively. A double superscript indicates a change of considerably greater magnitude than a single superscript. Channel pattern depends on both slope and discharge. It is easier to demonstrate this relationship graphically than by using a formula. Relationships between channel pattern and threshold values of slope and discharge are shown in Figure 3. The following section shows how these fluvial relationships can be used to anticipate stream adjustments to watershed changes and channel modifications.

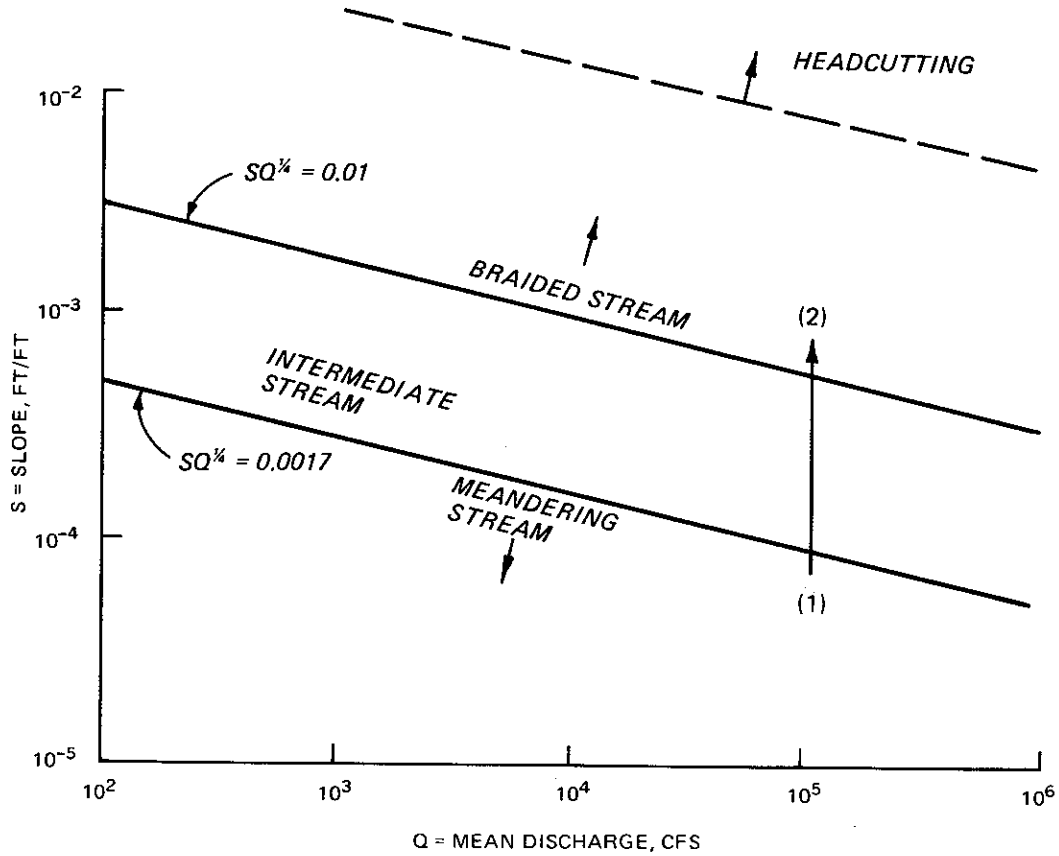


Figure 3. Stream pattern and headcutting as functions of slope and discharge. If slope is increased, meandering streams that are close to threshold values may be pushed across the threshold (1) and become braided (2). A similar threshold may exist for headcutting. (after Simons et al. 1980)

Use of Fluvial Relationships in Planning and Design

77. All individuals involved in planning, design, construction, and maintenance of flood control channel projects should understand the importance of treating the stream, drainage basin, and associated environmental resources as a unified system. Changes in the drainage basin may alter rainfall-runoff and sediment yield relationships. These, in turn, may trigger adjustments in stream systems and associated biological and physical systems. The purpose of this section is to show how the functional fluvial relationships identified in the previous section

can be used to indicate the likely nature of these adjustments.

Drainage basin changes

78. Probably the most extensive and crucial changes affecting streams that occur in watersheds are land cover changes attributable to agriculture, mining, forestry, grazing, and urbanization. Trimble (1974) has documented the effects of agricultural activities on stream systems in the Southern Piedmont. Rapid expansion of intensive row-crop agriculture from the postcolonial period until about 1920 increased runoff and sediment yield. Equation 12 $\left(Q_s^{++}, Q_w^{+} \sim S^{+}, d_{50}^{-}, D^{-}, W^{+}\right)$ best describes the situation, with sediment discharge (Q_s) increasing considerably more than water discharge (Q_w). Equation 12 predicts increased stream slopes, decreased median sediment size, decreased flow depth, and increased flow width (the latter two changes indicate wider, shallower channels). These predictions conform to Trimble's findings. Rapid sedimentation in headwater channels increased overall channel slopes and changed the composition of channel beds from gravel to sand. Tributary streams became shallower and wider and flooded more frequently. Increased frequency of flooding created natural levee deposits and extensive swamp and marsh areas (Figure 4).

79. After the 1920s declining agricultural acreage, improved conservation practices, and reforestation brought about drastic reductions in Q_s and a moderate decrease in Q_w, conditions described by Equation 8 $\left(Q_s^{--}, Q_w^{-} \sim S^{-}, d_{50}^{+}, D^{+}, W^{-}\right)$. According to this equation, the stream changes should have been reversed, and slopes should have decreased, bed particle size should have increased, and streams should have become narrower and deeper. Again, the anticipated results agree with Trimble's findings. As headwater tributaries began to erode accumulated sediments, streams became entrenched and narrower (Figure 4). Sediment eroded from upstream areas was deposited downstream, thereby reducing gradients. Removal of sandy deposits uncovered coarser bed gravels and streams flowed with reduced turbidities.

80. Any watershed change that destroys or reduces vegetative cover significantly is likely to increase sediment discharge proportionately more than water discharge and bring about the same kinds of

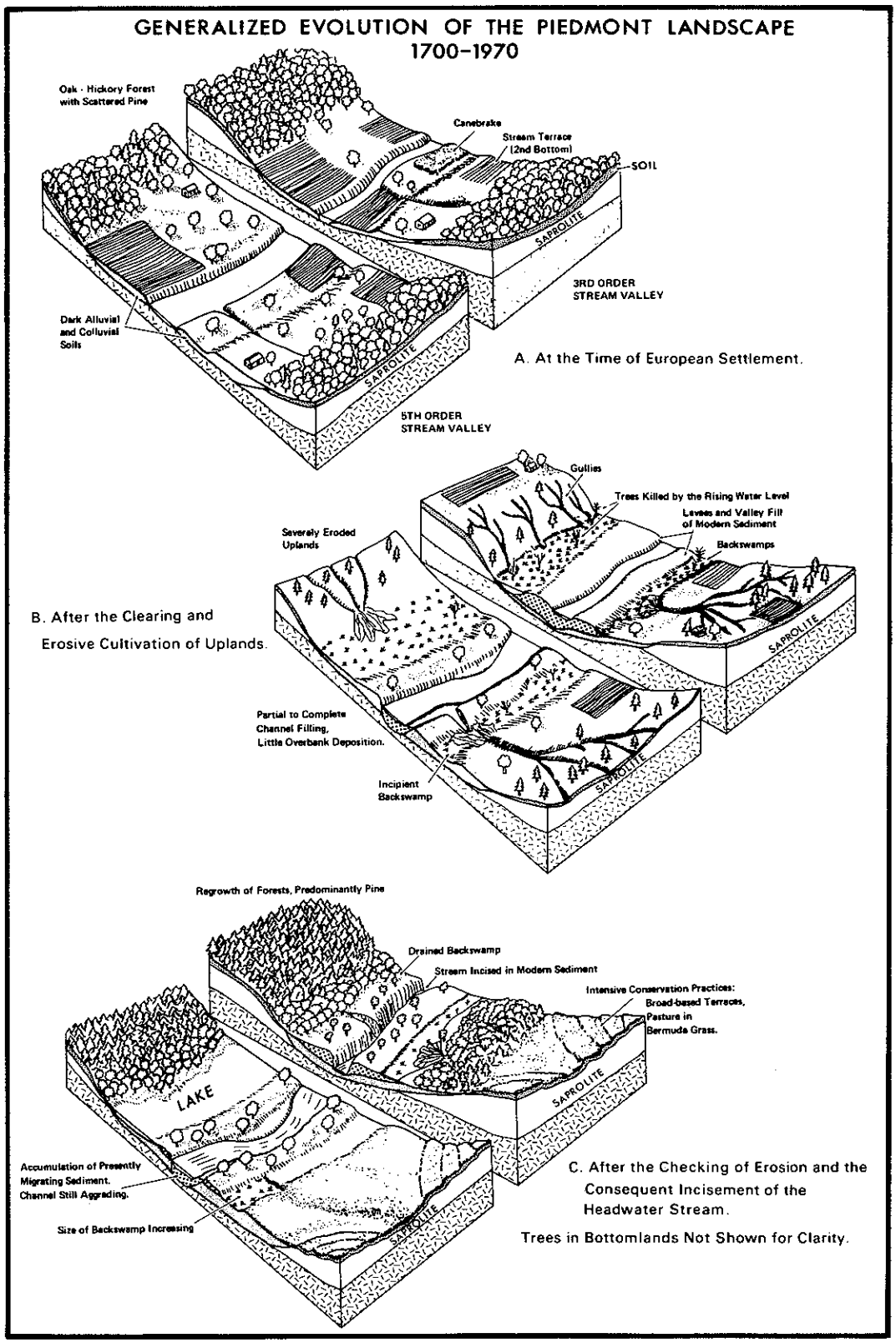


Figure 4. Effects of intensive, row-crop agriculture on the fluvial system as revealed by the generalized evolution of the Piedmont landscape (after Trimble 1974) (courtesy of Soil Conservation Society of America)

changes described above. Logging (Janda et al. 1975, Lull and Reinhart 1963), mining (Collier et al. 1964, 1971; Graf 1979b), grazing (Dunne and Leopold 1978), forest fires (White and Wells 1979), and construction activities (Wolman 1967) are examples of disturbances of this type. Conversely, intensification of vegetative cover through reforestation and improved land management or implementation of conservation practices designed to reduce soil erosion or control sediment have the opposite effect, as indicated by Equations 7 and 8.

81. The long-term effect of urbanization is an increase in the frequency and magnitude of runoff events. Impervious ground cover and storm sewer systems promote rapid runoff. At the same time, after the initial construction phase, there is relatively little soil erosion to contribute sediments to urban streams. This condition is clearly analogous to that described in Equation 5 or Equation 16. Urban stream systems should respond by degrading, which would tend to reduce slopes, increase depths, increase widths (through oversteepening of banks and subsequent failure), and increase bed material size (which could lead to armoring of the bed). This is the classic response of streams to urbanization as described by Douglas (1974), Hammer (1972), and Wolman (1967). The same effects could be caused by a significant increase in precipitation, and some investigators believe that this may occur cyclically in some watersheds in the southwestern United States. Dunne and Leopold (1978) provide a review of the effects of climatic change on channel change.

82. Although land cover changes are the most frequent cause of altered rainfall-runoff and sediment yield relationships, other factors can also cause changes that might be predicted with Equations 5-16. Irrigation and other consumptive water uses could significantly reduce discharge of water and sediment as indicated in Equations 14 and 15. Reduction of water and sediment discharge in this manner should cause deposition in streams that would increase slope, decrease bed material size, and produce a narrower, shallower stream. In this case, reduced stream width is a function of significantly reduced water discharge. In some circumstances, watershed changes may produce commensurate changes

in water and sediment discharge which, according to Equations 10 and 11, might result in unpredictable combinations of changes in slope, flow depth, and bed material size. Fortunately, changes of this type appear to be of smaller magnitude and of less concern than the types of changes described in paragraphs 78-81. Users should be cautioned that the functional relationships expressed in Equations 5-16 apply only to equilibrium systems where existing stream characteristics can be attributed to prevailing watershed conditions. They are not applicable where existing stream characteristics are the product of prior environmental conditions (climate or vegetation) that no longer exist.

Flood control channel modifications

83. The functional relationships revealed in Equations 17-21 and in Figure 3 allow limited prediction of stream response to flood control channel modifications. These relationships also apply only to equilibrium systems in which all fluvial components have evolved mutually and are products of relatively stable environmental conditions. However, if one is dealing with an obviously nonequilibrium situation, a case study of the stream to be modified which used all available historical channel data, basin land use, and climatic data along with the above relationships would be most helpful in estimating probable responses to modification.

84. Channel straightening. Channels modified for flood control are often straightened. Straightening a channel reduces its sinuosity and increases its slope. According to Equation 18, the product of slope and water discharge is proportional to sediment discharge and median bed particle size. This is logical since the ability to transport sediments depends on stream power, and stream power is proportional to the product $Q_w S$. If water discharge is constant and gradient is increased, then sediment discharge must also be increased by erosion of the bed or banks. Rapid erosion increases bedload, much of which is deposited below the modified reach where gradients are less steep (Figure 5). Erosion is a negative feedback mechanism that works to restore stream stability by lowering channel gradient and increasing bed material size.

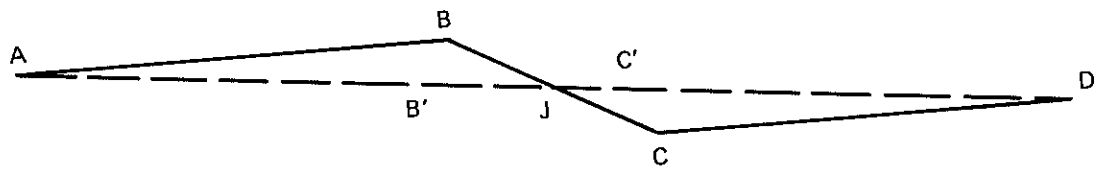
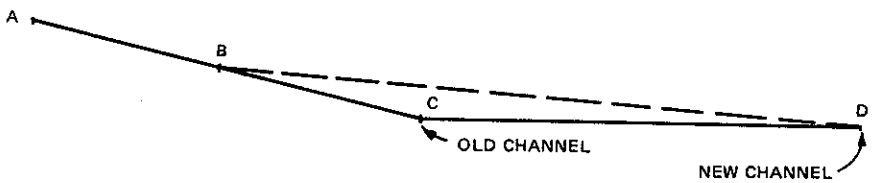


Figure 5. Effect of cutoff in an erodible channel. Slope and velocity above the cutoff (BC) are increased, allowing the stream to carry a greater load. Below the cutoff the slope is unchanged, and the flow cannot transport the increased load. The slope is gradually adjusted, through erosion and deposition, from ABCD to AB'C'D. (after Lane 1947)

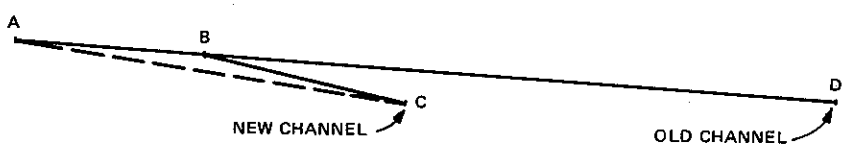
Equation 20 also indicates an increase in bedload transport. Bank erosion in the steepened reaches and aggradation in the lower reaches tend to increase the width/depth ratio as indicated by Equation 19. This sequence is the classic response to cutoffs described by Lane (1947) in alluvial streams flowing through erodible materials. Figure 3 indicates that a meandering stream can be changed to a braided stream if slope is increased enough to move it from point 1 to point 2. The tendency to braid has been observed on streams steepened by natural cutoffs and by channel modifications.

85. Channel straightening may result in shortening or lengthening tributary channels, which causes slope to respond accordingly (Figure 6). By Equation 18, $Q_w^o S^- \sim Q_s^- \, d_{50}^o$, lengthening will decrease slope and deposition should occur in the constructed reach (CD) and reduce channel capacity accordingly. As deposition progresses upstream, a new equilibrium grade (B'D) eventually develops. When tributaries are shortened, one of two conditions may exist. The tributary slope may be left unaltered (AC' in Figure 6b) and a drop structure located at C' to prevent headcutting. Alternatively, a new tributary slope (BC) is provided in a transition reach. Effects of this slope increase are the same as those described in paragraph 84. If slope BC is steep enough, it is possible that a headcut might develop anyway and move up the tributary. Rapid tributary erosion may result in aggradation of the main channel (Equation 13).

86. Channel enlargement. Flood channels are usually deeper and



a. Tributary lengthened. The original slope, AC, is altered to ACD when the main channel is relocated from C to D. The reduced gradient causes aggradation which eventually results in a new equilibrium slope ABD.



b. Tributary shortened. The gradient is altered from AD to ABC. Degradation triggered by the increased slope eventually results in a new equilibrium slope AC.

Figure 6. Effects of channel straightening on tributary slopes

wider than the preexisting natural channels. Deepening the main channel lowers tributary base levels (and increases slope) with the same effects described in paragraph 84. Widening a channel reduces unit stream power, which is proportional to $Q_w S/W$, thereby reducing sediment discharge as indicated by Equation 18. The deposited bedload increases channel gradient, which ultimately increases stream power. The resulting wider, steeper channel which eventually evolves is more efficient at transporting bedload than the newly constructed channel. During the interim period, channel widening often leads to extensive aggradation, the development of mid-channel bars, and braided flow at low discharges.

87. The functional relationships expressed in Equations 5-21 and Figure 3 can be used to anticipate the effects of watershed changes and flood channel modifications. The equations indicate effects that are likely to occur in alluvial channels that are in equilibrium with

prevailing environmental conditions. Actual effects in specific circumstances may differ significantly from expected effects for several reasons.

a. The fluvial system may not be in equilibrium.

b. When more than one interrelated fluvial variable is altered, changes in one of the variables may absorb most of the effect created by the other. For example, if a channel is widened as well as steepened, the reduction in unit discharge might offset the effect of the increase in slope, thereby incurring no adjustment in any other variable.

c. An expected response may not occur because the channel may not be free to adjust. It may not be located in alluvium or other easily altered material.

d. Some processes of channel adjustment may be controlled by threshold mechanisms, and changes may not be sufficient to trigger the process of adjustment. An example is the channel pattern changes indicated in Figure 3.

e. Many of the relationships hold only if all other variables are held constant. This is unrealistic for channels in erodible material, for they are free to adjust any dependent variable.

In summary, functional relationships can assist in explaining anticipated effects of flood channel and watershed changes, but should be used cautiously.

88. A basic understanding of the fluvial system is essential for engineers who plan and design environmentally acceptable flood control channels. In the absence of deterministic relationships, considerable judgment must be exercised in selecting, locating, and designing environmental features to accomplish specific objectives. These judgments are best made by individuals who appreciate the complexity of the fluvial system and its relationships to other environmental components.

PART IV: BASIS FOR PLANNING AND DESIGNING ENVIRONMENTAL FEATURES OF FLOOD CONTROL CHANNELS

Introduction

General design procedure for flood control channels

89. The design of flood control channels is a hierarchical process that begins with the establishment of project objectives, proceeds through the selection and evaluation of alternatives for achieving the objectives, and concludes with a detailed design of the channel and its environmental features. A detailed outline of the planning process for flood control channels is presented in Appendix B. Incorporation of environmental features should begin at the first stage. When project objectives are formulated, environmental concerns should be considered simultaneously with flood damage reductions. Otherwise, alternatives for achieving environmental objectives and opportunities for enhancing environmental resources may be overlooked.

90. Selection of environmental features is discussed in Part V. Although general environmental objectives guide the selection process, watershed and stream conditions that can influence the successful operation and maintenance of environmental features must also be considered. Once selected, alternatives are evaluated according to CE planning procedures (OCE 1982a, 1982b).

91. Detailed project planning begins with the collection and analysis of data which describe project conditions and provide information needed in the design process. Appendix B (item IV A) and Appendix C provide checklists for the types of data needed and data sources. Detailed procedures for conducting site investigations and analysis of data can be found in SCS Technical Release No. 25, "Design of Open Channels," (SCS 1977) and in the SCS "National Engineering Handbook" (SCS 1968). Engineer Technical Letter (ETL) 1110-2-230 (OCE 1978a) provides for the collection and analysis of hydrologic and hydraulic survey investigations. The Environmental Engineering Manual on Streambank

Protection that is being prepared will contain a section on site investigation and laboratory testing for design of bank protection measures. Many of the items of data collection and analysis addressed in that document are common to flood control channels as well.

Evaluation of environmental features

92. Ideally, the selection and design of environmental features ought to be based on well-developed theory and prior experience. Designers need information about cost, maintenance, and the degree of success in meeting environmental objectives if they are to choose environmental features wisely. In order to compile these types of data, design documents for all projects with postauthorization reports dated 1970 or later were examined to identify projects with environmental features. Due to the need for detailed design and cost data, only those projects already built, under construction, or which had reached the feature design stage were evaluated. Detailed evaluations were completed for approximately 75 projects, including several Continuing Authority projects (Section 205 projects), and a few by the SCS, State highway departments, and local governments. Limited data were collected on about 15 additional projects, mostly ones constructed under CE Continuing Authority or built by SCS or local interests. Projects cited in this report are listed in Table 1.

93. The evaluation of environmental features identified by this survey covered their environmental effects, hydraulic effects, costs, durability, and maintenance and operation considerations. In addition, any special environmental, institutional, or other constraints were identified and discussed. However, only a fraction of the data needed for evaluation were available for most projects. Considerable variability in the amount of detail available existed among projects, especially as regards hydraulic and environmental factors considered in determining the type, number, and locations of environmental features. Requirements for maintenance of local flood protection projects are given in Section 208.10, Title 33, CFR. District Engineers are required to keep informed as to the extent of compliance with the local operation and maintenance requirements through analysis of semiannual reports submitted by the

local operating agency and through regular periodic inspections performed in accordance with ER 1130-2-339 (OCE 1973) and ER 1130-2-303 (OCE 1967). Required inspections are directed toward evaluating the adequacy of maintenance procedures as they affect the condition and carrying capacity of the flood channel and the condition of any structural components. Neither these visits nor the semiannual reports provide much direct information concerning the environmental adequacy of the overall design of individual environmental features. Accurate and detailed cost data for environmental features are available only for those projects already built or for which bids have been received. No systematic attempt is made by Districts to solicit information about maintenance of environmental features. To partially compensate for the lack of data, 14 flood control channel projects were visited. These were selected because of the variety of environmental features they contained and the diversity of their settings. The site visits and conversations with CE personnel and local sponsors provided the basis for the evaluations presented.

94. Although many features have multiple environmental benefits, most are designed for a specific purpose. In the following discussion, features are classified according to their principal intended purpose: channel designs and construction techniques for environmental improvement; environmental features for channel stabilization and erosion control; environmental features to improve instream habitat and water quality; features for streamside aquatic and wetlands habitat; features for terrestrial habitat restoration and maintenance; aesthetic considerations and features; and recreation features. In each case, feature performance, cost, and maintenance are evaluated and design guidance is provided to the extent possible. Due to the limited experience with most environmental features, the discussions of design tend to be procedural in nature and rely heavily on theories of fluvial processes and input from game and fishery biologists, foresters, geomorphologists, and others to supplement the limited engineering experience with environmental features in flood channels. The guidelines are subject to continual refinement as more experience is gained.

Channel Designs and Construction Techniques

95. Flood control channel design guidance traditionally has stressed that the best design "for a given reach is the one that has adequate hydraulic capacity for minimum cost of construction and maintenance....In rural areas a trapezoidal cross section may be least costly, whereas in urban areas a rectangular cross section is often the least costly" (OCE 1970). Until recently, modified trapezoidal cross sections and V-bottom channels (Figure 7) have been used primarily to minimize sedimentation and to reduce maintenance rather than for environmental reasons. Increasing environmental concern has prompted designers to consider environmental benefits of selective clearing and snagging, modified cross sections, floodways and bypass channels, pools and riffles, meandering alignments, and single bank modification.*

Selective clearing and snagging

96. Clearing and snagging is the removal of woody vegetation and debris from stream channels and banks to increase hydraulic capacity and prevent hazards to navigation or bridges. For flood control on small streams, conventional practice has been to remove all obstructions from the channel and to clear all significant vegetation within a specified width on both sizes of the channel. Concern over the undesirable effects of clearing and snagging and improved understanding of the ecological and aesthetic importance of organic debris and riparian vegetation have prompted modification of traditional clearing and snagging practices (Gregory and Stokoe 1980; McCall and Knox 1978; McConnell et al. 1980; USAED, Vicksburg undated; USAED, Wilmington 1980; Willeke 1982). Adverse environmental effects may be greatly reduced with little loss in flood control by limiting the type and amount of snags and vegetation removed and by using construction methods that create only minimal disturbance (Figure 8). Revegetation of disturbed areas and control of future maintenance procedures ensure the long-term effectiveness of the modified

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* Many of the terms for environmental features used in this and following sections have definitions unique to this report. Definitions of these and other terms are provided in the glossary (Appendix A).

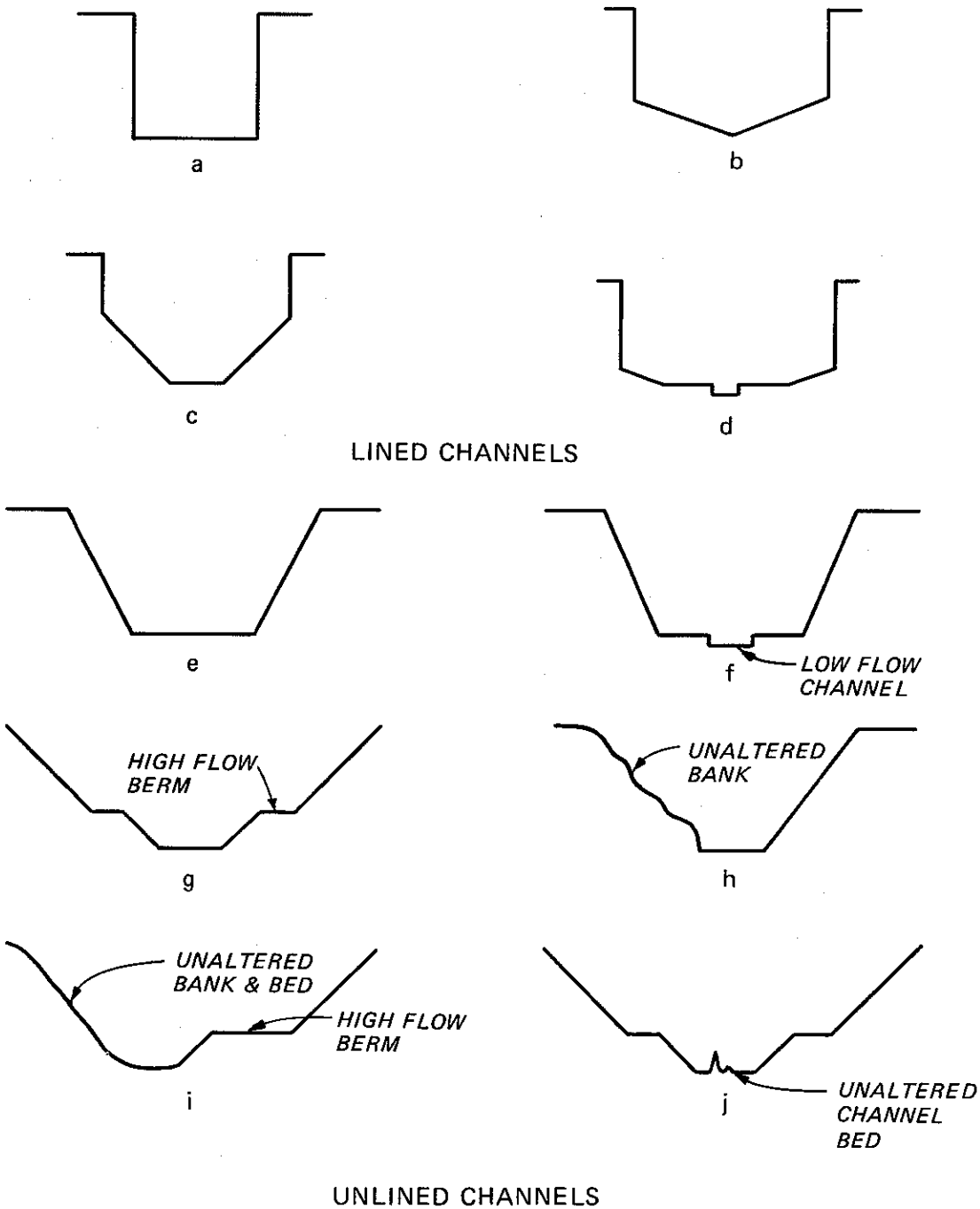

Figure 7. Typical flood channel cross sections. Lined channels typically have vertical walls to minimize costs and may be rectangular (a) or may have some modification to concentrate low flows (b, c, d). The most frequently used cross-sectional geometries include trapezoidal (e), trapezoidal with a low flow channel (f), trapezoidal with a normal flow channel and high flow berms (g), and variations in which one bank and/or the channel bed are not disturbed (h, i, j).

Figure 8. Results of selective clearing and snagging on Chicod Creek, North Carolina. Stringent guidelines required that only those trees and snags that directly obstructed flows be removed.

approach. Key aspects of modified clearing and snagging involve selective removal of vegetation based on size, condition, species, or location; removal of only those snags that are major flow obstructions; use of hand labor and small equipment when feasible and rigid access controls when heavy equipment must be used; protection of existing vegetation of disturbed areas; and greater reliance on multidisciplinary teams in all phases of project planning and management.

97. The so-called "channel-forming" or "dominant" discharge, usually having a return period of 1 to 2 years (Dunne and Leopold 1978, Henderson 1966), is about the upper limit of flow capacity that may be obtained by clearing and snagging. Because of the limited improvement in flow hydraulics, clearing and snagging is most often used to provide relief from high frequency nuisance flooding and for drainage improvement in agricultural areas. Occasionally, however, recreational benefits to canoeists, hunters, and fishermen provide the major justification.

98. Environmental effects. The magnitude and significance of

clearing and snagging impacts vary greatly from site to site. No scientific studies of the effects of clearing and snagging on specific streams (before and after) were found in the literature. There are, however, publications that assess the impacts of loss of streamside vegetation on stream morphology (Keller and Swanson 1979; Maddock 1972; Nunnally 1978; Zimmerman, Goodlett, and Comer 1967), water quality (Arthur D. Little, Inc. 1973; Corbett, Lynch, and Sopper 1978; Karr and Schlosser 1977; Simpson et al. 1981), and stream biota (Bilby and Likens 1980, Brinson et al. 1981, Funk and Robinson 1974, Hickman 1975, Marzolf 1978, McIntire and Colby 1978, Motroni 1980, Vannote et al. 1980).

99. Hydraulic effects. With selective clearing and snagging, specific obstructions are designated for removal while environmentally valuable logs, snags, and vegetation which have little or no effect on flow capacity are left in place. Hydraulic effects of clearing and snagging may be estimated by manipulating the resistance factor in a uniform flow equation. Selection of values for resistance factors or coefficients is a skill developed through experience. When channel roughness varies laterally along the wetted perimeter, equivalent or composite resistance may be computed from estimated values for each subsection. Most practitioners use tables of typical composite resistance factor values and photographs of example reaches presented by Barnes (1967), Ramser (1929), and Scobey (1939). Some of these data are reproduced by Chow (1959) and Fasken (1963). A small portion of these tables and photographs deals with changes in the resistance factor due to changes in the type and amount of vegetation or obstructions in the channel.

100. Reported changes in Manning's "n" values following removal of vegetation and snags and after regrowth of vegetation are summarized in Table 2. Effects of removing logjams and midchannel bars vary, depending on the degree of obstruction. Willeke (1982) measured a water surface drop of 2 ft over a logjam that blocked about three-fourths of the width of a moderate-sized river. Backwater computations for a reach of the Cumberland River revealed that partial removal of a midchannel bar would reduce height for the 2-year event by only 0.35 ft. While these reported values give some indication of the effects on flow resistance

of removing snags and vegetation, they provide little guidance for the design engineer. Procedures for estimating roughness values are given in paragraphs 106-109.

101. Costs. Construction costs for selective clearing and snagging using manual labor, small boats or barges, and small tractors or log skidders tend to be lower than conventional work with bulldozers and draglines. However, site-specific considerations such as the cost of labor and ease of access heavily influence costs. McConnell et al. (1980) reported costs of $11,000 per mile and $22,000 per mile (1979 dollars)* for selective clearing and snagging and conventional channel maintenance work, respectively, on the Wolf River, Tennessee. Reaches worked with conventional heavy equipment had more severe sediment blockages, however. Willeke (1982) reported a cost of $10,000 per mile (1981 dollars) for selective work done by George Palmiter on Swamp Creek, Ohio. The St. Paul District (USAED, St. Paul 1975) reported costs of $5,000 per mile (1975 dollars) for the selective clearing and snagging on the Souris River.

102. Maintenance. Clearing and snagging projects require more frequent inspection and maintenance than other flood control channel designs, especially in areas having long growing seasons. Regrowth of vegetation on cleared channel sides and top banks can significantly increase the resistance factor within one or two growing seasons. Understory vegetation usually grows much more rapidly after removal of the shade canopy. Even when trunks are chemically treated, sprout regeneration is still a problem. Poor access and stumps restrict and hinder

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* No attempt has been made in this report to adjust costs to a common price level. A number of published cost indexes are available for this purpose. The best known and most widely used are probably those published by Engineering News-Record (ENR). The ENR building cost index is a weighted aggregate index of the prices of constant quantities of structural steel, portland cement, and lumber, and an average of carpenter, bricklayer, and structural ironworker wages. Because of the highly diverse nature of materials and labor required for the construction of environmental features of flood control channels, use of such an aggregate index would yield a distorted view of costs. Copies of the current ENR price indexes can be obtained from Engineering News-Record, P. O. Box 950, New York, N. Y. 10020.

mechanical maintenance, thereby requiring more expensive hand labor. Detailed maintenance guidelines and rigid enforcement are required to ensure satisfactory performance of clearing and snagging projects. Generally, clearing and snagging is not a desirable alternative on unstable streams with wooded banks unless combined with extensive bank protection.

103. The guidelines for selective clearing and snagging presented below are based on experience reported by SCS on Chicod Creek, North Carolina, and the Wolf River, Tennessee (McConnell et al. 1980) and the work of George Palmiter (Willeke 1982). Selective clearing and snagging has been used on some CE projects, and the experience gained from these applications is incorporated into the guidelines.

104. Selection of trees and snags for removal. A team composed of a biologist, a hydraulic engineer, a geotechnical engineer, and a forester should either walk the channel and flag trees and snags for retention or removal, or prepare sketches, maps, or marked-up photographs. Alternatively, detailed descriptions of material to be left or removed may be included in the specifications. In either case, any combination of the following procedures may be used:

a. Remove all vegetation on the banks greater (or less) than a given diameter and height. Alternatively, individual trees may be selected for retention to achieve a predetermined density. Hardwood and mast-producing trees are usually preferred over willows and cottonwoods. Pickles (1931) observed that 6- to 8-inch tree trunks offered less flow resistance than dense undergrowth. Further reduction in flow resistance may be obtained by pruning limbs that protrude below normal flood height. A row or rows of trees roughly aligned with the current offer much less resistance to flow than perpendicular blocks of vegetation (Li and Shen 1973) yet retain much of the shade and visual harmony of an uncleared bank.

b. Leave stumps on the bank in place except when badly undercut. Specify maximum stump heights and treat stumps to reduce sprout regeneration unless prohibited by local environmental regulations.

c. Remove fallen trees and trees relying on adjacent vegetation for support.

d. Remove trees likely to fall into the channel within a year. Experience and professional judgment are required to decide which trees constitute an immediate hazard. Several authors have suggested removal of all trees leaning at an angle of 30 degrees or greater from vertical (McConnell et al. 1980; USAED, Wilmington 1980). However, since many healthy trees lean over channels toward sunlight and remain in place for many years, this criterion is probably overly conservative. Others suggest removal of all dead and dying trees. However, dead trees that are valuable as den and nesting sites should not be removed if located far enough from the channel that they will not fall in. They will be affected by floods, however. Determination of the hazard potential of a given leaning or dead tree should consider the overall condition of the tree, amount of undercutting, current attack, wind loading, and tree species. When stands of tall, mature trees are thinned, remaining isolated trees are sometimes more susceptible to windthrow. In some cases, leaning trees may be topped.

e. Remove only those snags that are major flow obstructions or which are likely to trap debris during flood discharges. Leave embedded logs that are aligned with the flow and minor debris. Remove debris from mouths of tributaries, distributaries, and from side channels.

f. Excavate major sediment deposits that have formed upstream or downstream of jams if it appears that jam removal will not be sufficient to flush them out.

105. Disposal and utilization of debris. Debris from conventional snagging and clearing projects is usually piled, allowed to dry, and burned. Burning in compliance with appropriate air pollution regulations remains a useful alternative in some cases; however, the following alternatives have also been identified:

a. Erosion control. Snags may be positioned parallel to eroding banks and anchored in place to create a brush pile revetment (Willeke 1982). Design details are provided by Edminster, Atkinson, and McIntyre (1949). Sedimentation induced by properly sited brush piles rapidly locks them in place. Eventually, cuttings of flood-tolerant woody species may be planted in the sediment-filled brush pile to provide long-term stability.

b. Channel training. Whole trees may be placed perpendicular to eroding banks to deflect the current (Gregory and Stokoe 1980, Willeke 1982). Design details for tree jetties or deflectors are presented by OCE (1978b) and

Edminster, Atkinson, and McIntyre (1949). Whole tree deflectors are particularly vulnerable to ice damage (OCE 1981b; Edminster, Atkinson, and McIntyre 1949). Whole tree deflectors 2-3 ft in diameter installed on a Vermont river gave adequate protection for 4-5 years, but rotted and lost their effectiveness within 9 years (Edminster, Atkinson, and McIntyre 1949). Bank slides along the Cumberland River are sometimes repaired by interlocking snags resulting from the slide along the bank toe and covering them with soil from the slide.

c. Side channel closure. Edminster, Atkinson, and McIntyre (1949) give design details for tree barricades and log-pile check dams used in conjunction with tree and sod plantings to halt development of overflow secondary channels.

d. Piling on floodplain. Cleared and snagged material that is piled on the floodplain should be tied down, anchored, or lodged to prevent reentry to the channel. The effect of piles on flow resistance should also be considered. Interference with land use such as recreation, cultivation, or access should be avoided.

e. Wildlife habitat. Brush piles provide valuable wildlife habitat in cleared areas. Partial burial of debris piles anchors them and provides habitat.

f. Firewood. After drying, woody debris may be made available for firewood if the piles are accessible.

106. Estimating resistance factors for selectively cleared and snagged channels. Improvements in channel conveyance derived from selective clearing and snagging result from reductions in flow resistance (n). Chow (1959) suggests estimating separately the effect of each factor that influences n . Of the eight factors he identifies, three are influenced by clearing and snagging--vegetation, channel irregularity (removal of bars), and obstructions to flow (log and debris jams, snags). Fasken (1963) advocates a similar approach in which a basic value for n is selected for a straight, uniform channel of the required dimensions in the natural materials involved. This value is subsequently modified for each additional factor that influences roughness.

107. Petryk and Bosmajian (1975) present a formula for composite resistance that includes vegetation density. Variation of composite resistance and vegetation density with depth is presented for four natural channels. Use of the formula requires direct or indirect determination

of the vegetation density and its variation with depth. Sokolov (1981) proposes a rather complex formula for the vegetational component of the resistance factor for floodplains. Sokolov's procedure considers the morphology, density, and amount of inundation for trees, shrubs, and grass. Li and Shen (1973) gave theoretical and experimental proof that flow retardance for staggered patterns of tree trunks or rows of trunks perpendicular to flow is much higher than for rows parallel to flow. Their methods could be used to estimate flow retardance due to various tree patterns.

108. One of the best approaches for estimating hydraulic effects of clearing and snagging for a given stream is to estimate changes in the resistance factor using the aforementioned aids, and then "calibrate" or "fine-tune" the estimate by performing the work on representative reaches and measuring the results.* When using this approach, test reaches should be carefully compared with the remaining project area to ensure correction for uncontrolled variables when extrapolations are made. Care should also be given to extrapolations of measurements at moderate or low flow to design flow conditions.

109. Obstructions such as logjams large enough to have a damming effect or midchannel bars may be incorporated in backwater profile computations as geometric elements in the channel boundaries rather than being treated as roughness components (Willeke 1982). Since a good deal of water may pass through or around a logjam, the height of the "dam" should be set equal to the estimated or observed water surface differential across the jam, and not to the height of the jam.

110. Construction methods. Selective clearing and snagging methods tend to replace energy-intensive heavy equipment with manual labor and the energy of the flowing water. The use of hand tools, such as chain saws and small boats or portable barges equipped with cranes and/or winches, is preferred. Small crawler tractors, log skidders, or draglines that require minimal space for access and maneuvering may be

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* Personal Communication, 1982, D. B. Simons, Associate Dean of Research and Professor of Civil Engineering, Colorado State University, Fort Collins, Colo.

considered next. If these approaches are inadequate, the use of heavy equipment from selected points may be considered. Sometimes snags may be lifted or winched from the channel by equipment working outside a buffer strip. Trimming major branches and winching snags out butt first reduces damage to banks and undergrowth. Winch cables may be fastened to snags by laborers in small boats. Clearing and snagging of the Souris River near Minot, North Dakota, was done in midwinter when the stream was frozen. Snags and logs were pulled through the ice or cut at ice level.

111. Trimmed snags may be floated to preselected takeout points or to eroding banks for use in revetment construction. Palmiter suggests cutting debris into short lengths (a small fraction of channel width) and allowing it to float freely downstream or to be deposited overbank by floods (Willeke 1982). This approach should be used carefully upstream of bridges and other channel constrictions.

112. Sediment deposits resulting from snags or jams may be scoured away gradually after jam removal. The process may be accelerated by removing armoring rock or debris from the head of the bar or by digging a small pilot channel across the bar. A small brush deflector or rock jetty may be placed opposite and just upstream of the bar to concentrate and direct the current (Willeke 1982).

113. Access controls. When heavy equipment must be used, clearing and disturbance may be minimized by careful selection of access routes and staging areas. Ground reconnaissance and study of recent aerial photos is helpful in preparing access plans. In general, access routes should take advantage of existing roads, trails, and cleared land. When clearing is required, an effort should be made to avoid disturbing ecologically and aesthetically valuable species. Width of access roads should be minimized and, when possible, an uncleared strip should be left between the road and the channel. Narrow channels may be accessed by clearing a narrow band on one side with wider openings at irregular intervals for debris disposal. Single-bank clearing should generally be restricted to the north side of the channel to maintain maximum shade on the channel.

114. Revegetation. Denuded areas may be seeded or planted with species suitable for erosion control or for wildlife food and cover. In some cases, natural succession is superior to planting. Long-term effects of a clearing and snagging project will be more positive if vegetation management zones ("greenbelts" or "buffer strips") are established on both sides of the channel and around contiguous and adjacent waterbodies by easement or fee acquisition. Criteria for determining buffer strip width to maintain water temperatures and sediment levels and to catch debris are available in literature dealing with forest clearcutting (Broderson 1973). Fencing is sometimes needed to exclude livestock from these zones. In addition to ecological and aesthetic benefits of riparian vegetation, bank stability may be enhanced, and shade over the channel will hinder establishment of aquatic and terrestrial vegetation that increases flow resistance.

115. Bank protection and stabilization. Judicious use of bank protection measures may extend the useful life of clearing and snagging projects and reduce maintenance costs since undercut banks are a primary source of snags. Some of the bank protection measures most commonly used on selective clearing and snagging projects have already been discussed. More durable measures that provide greater protection may be required on unstable streams with rapidly eroding banks or at especially vulnerable locations such as tight meander bends. Detailed environmental considerations for streambank protection may be found in Henderson and Shields (1982, 1984).

116. Protection of existing vegetation. Techniques for protecting trees from construction activities are available from Amimoto (1978). Trees should be protected with shims or padding when used for winch bracing cables. Damaged trees should be repaired or removed. Pruning should be done with saws or shears, not axes, and use of climbing spurs should be avoided.

117. Miscellaneous considerations. The completed project will appear more "natural" and less "engineered" if an irregular, random character is preserved. Disturbed areas should be restored to natural contours, and preserved trees should be spaced at irregular intervals.

Natural sloughs, drains, and flood-plain depressions should be left in their original condition. Disturbance of dens, burrows, and nesting sites should be avoided when possible. Loss of den trees may sometimes be mitigated by installing nesting boxes or platforms.

118. Project planning and management. The total effect of clearing and snagging projects will be enhanced if a multidisciplinary approach is adopted during the planning stage and continued through maintenance. A hydraulic engineer, a forester, and a fish and wildlife biologist make a good team. A landscape architect may also be included for stream reaches that are visually prominent. Project planning and design may be based on a statement of intent or purpose that recognizes both flood control and environmental goals. Once a contractor is selected, the interdisciplinary team should tour the site with responsible employees of the contractor and discuss the philosophy and prescribed methods for the work.

119. Some adverse impacts may be avoided by scheduling work to avoid prime fish spawning and recreational seasons. Scheduling work so that clearing is promptly followed by debris disposal (temporal or spatial limits may be specified) prevents additional jamming problems downstream.

120. Specifications for selective clearing and snagging work need to be simple to understand, yet highly detailed. As noted above, the material to be removed, equipment and methods to be used, access routes, and methods for debris disposal should be specified, and these specifications may vary from reach to reach depending on the nature of the surrounding environment and the severity of channel obstruction. The geographical limits of work should be clearly specified, including reach delineation, clearing zones, debris disposal areas, access routes, and "no-work" zones. Specifications should be written to require the contractor to maintain accurate records of the work accomplished.

121. Project management may be extended to include provisions for requiring maintenance methods similar to construction. Periodic inspection is especially needed for selective clearing and snagging projects, since so much material is retained in the channel and on the banks.

Low flow channels

122. A low flow channel is a subchannel constructed inside a larger flood control channel to concentrate flow during low to moderate flow conditions. Not all low flow channels produce significant environmental benefits. The V-bottom cross section mentioned earlier produces flow with little aesthetic, water quality, or fish habitat value. On the other hand, a meandering low flow channel carrying a permanent stream may enhance fish habitat, water quality, and aesthetics.

123. Despite its inferior environmental aspects, the most commonly used low flow design in concrete lined channels is the V-bottom (Figure 7). Most have uniform grades, but some have incorporated pool and riffle designs for fish habitat (paragraphs 158-161). A few lined channels have employed more innovative designs. Iao stream, Hawaii (USAED, Honolulu 1975) has a 10-ft-wide, 1-ft-deep V-notch channel constructed of boulder concrete. Individual boulders project 6 in. above the invert to provide shade and places for aquatic species to rest and hide.

124. An increasing percentage of flood control projects which employ trapezodial cross sections incorporate low flow channels. Figure 9 shows two examples from urban environments. Apache Creek in San Antonio, Texas (USAED, Fort Worth 1973) has a concrete low flow channel inside a partially lined flood control channel. The low flow channel in Indian Bend Wash (USAED, Los Angeles 1973) is a meandering grassed channel in a broad, grassed floodway. Apache Creek is a perennial stream, whereas Indian Bend Wash, located in Scottsdale, Arizona, is dry between runoff events, except for some irrigation seepage into the low flow channel. Meandering low flow channels emulate the thalweg pattern of natural streams and are more aesthetically pleasing, and perhaps more stable, than alignments that follow the center line of the flood control channel.

125. Maintenance. The main problems with low flow channels are erosion and deposition. Flood control channels excavated in easily eroded material must be protected adequately from scour by using linings or turfing to prevent erosion and subsequent deposition in the low flow channel. Low flow channels generally have not performed well on streams transporting heavy sediment loads. The flood control project on Tenmile

Figure 9. Low flow channels. (a) The concrete-lined low flow channel in Apache Creek, San Antonio, Texas, provides a striking contrast to (b) the grass-lined low flow channel in Indian Bend Wash, Scottsdale, Arizona.

Creek near Marianna, Pennsylvania (USAED, Pittsburgh 1976) terminates upstream at a water supply dam that functions efficiently as a sediment trap. A meandering low flow channel 10 ft wide by 1 ft deep was constructed in the shale bottom of the project channel in 1979. Between the dam and the first tributary, the low flow channel has remained completely sediment free. Below the tributary confluence, sediment accumulation has filled the low flow channel and covered a gabion riffle area. A similar effect was observed on Sandy Lick Creek at DuBois, Pennsylvania (USAED, Pittsburgh 1977), where a low flow channel was quickly filled with sediment to produce broad, shallow low flow conditions (Figure 10). Low flow channels require no unique maintenance measures other than the regular removal of sediment accumulations that might otherwise reduce flow capacity or entirely block the low flow channel.

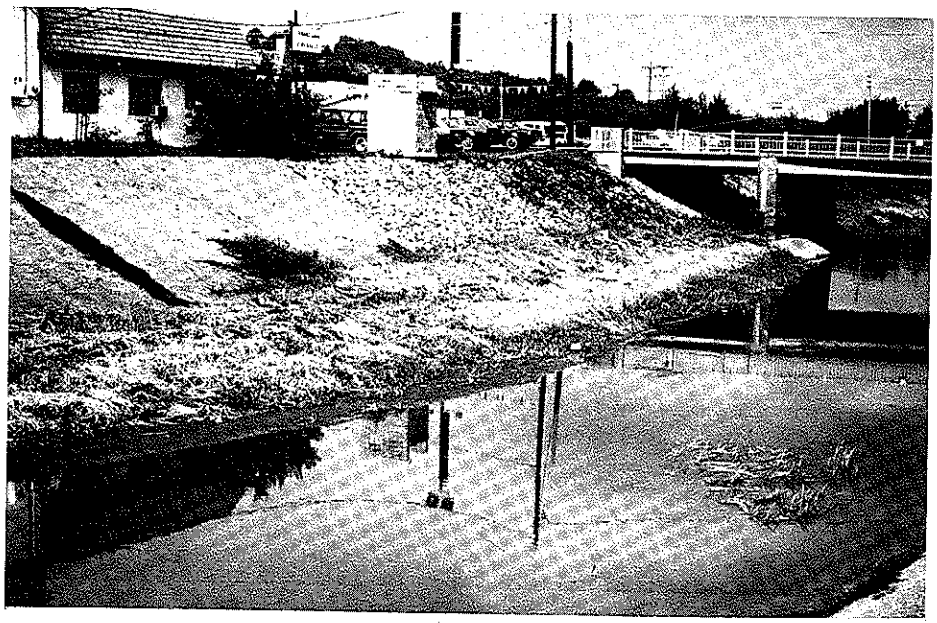


Figure 10. Sandy Lick Creek, DuBois, Pennsylvania. Heavy sediment load has totally obscured the low flow channel, producing thin sheetflow across the channel bottom during low flow conditions.

126. Cost. Most low flow channels are designed by simply adding them to the cross section required for flood conveyance. Hydraulic effects of the low flow subchannels during design events are considered to be negligible. Costs of low flow channels are seldom itemized

separately, but in unlined channels cost is simply a function of the additional excavation required. In lined channels, the costs of the additional lining must be added to the extra excavation cost. The 10-by 1-ft low flow channel on Tenmile Creek had to be excavated mostly in bedrock and added $9.00 per linear foot (1977 dollars) to the project cost. The lined V-bottom low flow channel used on the Saw Mill River at Chappaqua, New York (USAED, New York 1974), which was 30 ft wide and 1 ft deep at the center, cost about $0.83 per linear ft (1970 dollars) more than a rectangular channel. The use of boulder concrete rather than regular concrete lining on Iao stream in Hawaii did not increase costs because of the amount of concrete displaced by the less expensive boulders. These figures indicate that costs for low flow channels vary from one project to another depending on type of excavated material, geometry of the low flow channel, economic conditions, economies of scale, local prices, and other factors.

127. Design considerations. Although V-bottoms are sometimes used in lined channels to prevent sediment accumulations, low flow channels should generally be avoided on streams with high sediment transport unless provision is made to trap and remove sediment or a sediment routing study can be made of the proposed design. Such streams can usually be identified by their appearance. They are likely to have beds of sand or sand mixed with gravel and have numerous transient bar deposits. Alluvial streams with low sediment transport are more likely to flow over beds that are armored with gravel and have more stable bar deposits. Once it has been determined that a low flow channel is desirable to meet water quality, biologic, or aesthetic objectives, the basic design decisions involve the size, shape, placement, and stability of the low flow channel.

128. The purpose of a low flow channel is to concentrate flows during low flow periods to meet biologic, water quality, recreational, or other needs. Dimensions of the low flow channel ought to be based on the instream flow conditions required to meet these needs. If recreational boating needs are important, this might determine minimum depth and width. According to Hyra (1978), a channel at least 1 ft deep and

6 ft wide is required for nonmotorized boating (except sailboats). SCS recommends minimum depths of 2 ft and 3 ft for nonmotorized and motorized boats, respectively. The suggested minimum width is three times boat length for rowboats and 17 ft for canoes (SCS 1977). When fishery needs dominate, critical instream needs (usually flow velocities and depths) should be established for the month or months during which low flow conditions are expected. Fishery biologists familiar with local streams should be able to provide such information, which can then be used as a basis for determining low flow channel dimensions. The value of low flow channels built for fishery needs can be enhanced considerably by incorporating pools, riffles, and habitat structures so that a variety of flow conditions are maintained during low flow. Pool-riffle design is discussed in paragraphs 158-161; habitat structure design is covered in paragraphs 240-249.

129. Placement of low flow channels has been arbitrary in most CE projects and has included alignments that follow the center line of the flood channel, meander within the flood channel, or are adjacent to a shady bank. Meandering low flow channels may be designed according to the procedure discussed in paragraphs 165-169 by using the discharge or dimensions of the low flow channel.

130. Low flow channels excavated in erodible materials may be subject to erosion during intermediate and high discharge events, and meandering low flow channels may migrate within the flood control channel and cause undesirable bank erosion. The most common solution to this problem is to line the low flow channel and the flood control channel invert with concrete or rock sized to withstand the shear stresses caused by high discharges. There is considerable evidence that suspended sediment is deposited against the streambanks (Einstein 1972, Lane 1955, Mahmood and Shen 1971, Parker 1978, Simons 1971). Thus, problems of sediment deposition and toe slope erosion can be avoided to some extent by locating unlined meandering low flow channels in the central portion of the flood control channel (e.g., the middle two-thirds) rather than allowing them to meander from bank to bank. Other options include protecting the toe slope of the flood channel and allowing the

low flow channel to migrate freely or burying sills or training dikes in the invert at specified intervals to control meandering (Figure 11). Procedures recommended for the design of stable channels in erodible materials are not applicable to low flow channels because of their unique geometry and flow conditions. Nevertheless, cross sections and rating curves of many stable natural streams suggest that irregular cross sections with berms and subchannels may be the rule rather than the exception (Nunnally and Keller 1979).

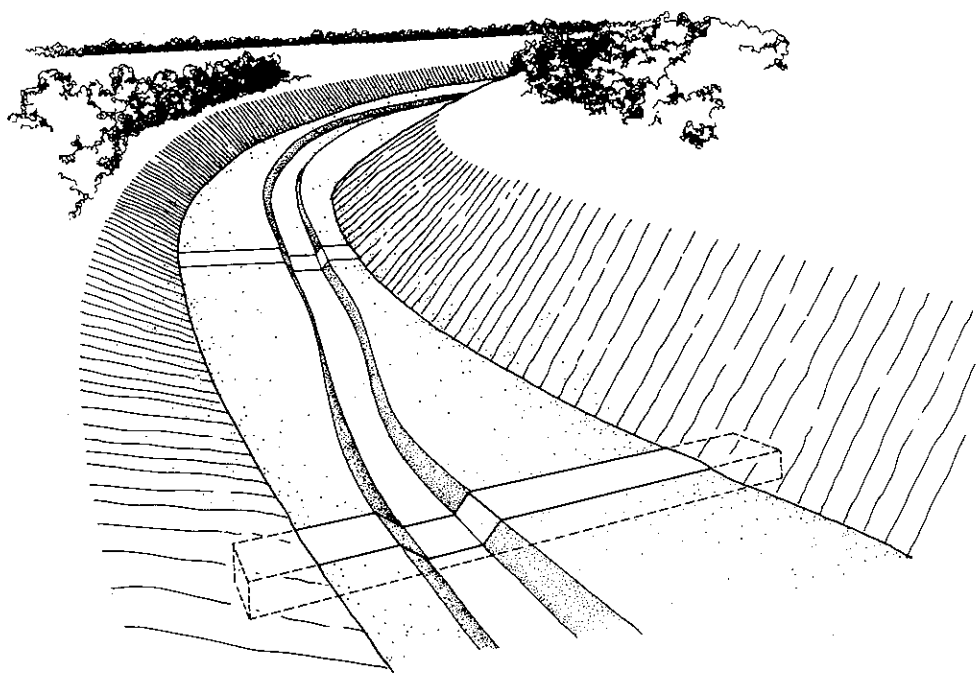


Figure 11. Use of notched sills to control meandering of low flow channels. Notched sills flush with the flood control channel invert can be used to stabilize the low flow channel and prevent undercutting of flood channel banks.

High flow channels

131. High flow channels are flood control channels with modified cross sections that include a subchannel and high flow berms on one or both sides of the subchannel (Figure 7g, h, i, j). The high flow berms form the invert of a high flow channel designed to be inundated only by flood flows that exceed a specified return interval discharge, normally equal to or larger than the mean annual flood based on the annual series.

When the existing channel is used as the normal flow subchannel, excavation often takes place from one side only, and the existing channel is disturbed as little as possible.

132. Subchannels in high flow channels differ from low flow channels. Low flow channels are designed to concentrate low flows that occur in many areas during summer and fall seasons and to provide deeper flow conditions than would otherwise exist during normal flow periods. Subchannels in high flow channels are larger than low flow channels because they are expected to contain the entire flow during nonflood conditions. Typical cross sections of flood control channels with high flow berms are shown in Figure 7.

133. Costs. Data are generally not available to allow comparisons of costs of high flow channels with other designs. High flow channels may be more expensive than unmodified designs, especially when existing channels are used as subchannels, because the channel may require wider rights-of-way and greater relocation expense. However, this expense may be partially offset by reduced excavation costs. Unlike low flow channels, the subchannel of high flow channels is included in the computation of the required cross-sectional area. Maintenance costs are likely to be higher than for unmodified cross sections, especially if single-bank construction is used.

134. Environmental benefits. High flow channels have several environmental benefits over conventional trapezoidal cross sections. If properly designed, high flow berms are not inundated very often and may be used for parks, trails, recreation, or other purposes that are compatible with their functions as flood channels and that do not interfere with their ability to convey the design discharge. Instream habitat and low flow conditions are altered very little if the existing channel is used as the subchannel. Turbidity levels during construction and shade loss impacts depend on whether one bank or both are disturbed but should be less than for conventional designs. High flow channels may be aesthetically pleasing when natural or meandering subchannels are used and high flow berms are well maintained. Selective landscaping of berms may add to aesthetic values.

135. Maintenance. The Little Blue River near Independence, Missouri (USAED, Kansas City 1972), provides an instructive case study of the most common problem with high flow channels. If the subchannel is not large enough, the high flow berms are inundated too frequently, creating wet conditions that may interfere with vegetative growth, recreational uses, and maintenance. In addition, the Little Blue is a turbid stream, and the frequent flooding of the berms has led to considerable sediment deposition that further reduces the usefulness of berm areas, compounds maintenance problems, and impairs project aesthetics (Figure 12). Trade-offs do exist, however. Higher berms would have required a wider high flow channel and more right-of-way. In the reaches where single-bank construction was used, erosion problems have been worse on the natural banks, and undercut trees will require removal when they fall into the stream. Despite its maintenance problems, this channel project represents a major improvement over usual design.

136. Design considerations. The best approach to the design of high flow channels is to use the existing natural channel as the

Figure 12. Sediment deposition on high flow berms, Little Blue River, Independence, Missouri

subchannel and to excavate the required high flow channel adjacent to it. Where that is not feasible, the subchannel can be designed in a manner similar to low flow channels with two exceptions. First, the capacity of the subchannel is sufficiently large that it should be included in the computation of flood channel conveyance. Second, since the subchannel is designed to convey all flows up to and including a given design discharge (such as mean annual flood), its size can be based on natural channel hydraulic geometry if the natural stream is stable and its watershed is relatively undisturbed.

137. Some choice can be exercised in the selection of the design discharge for the normal flow subchannel. If the high flow berm is to be used for recreation or agriculture, it is not desirable to have the subchannel overflow very often. If the natural channel bankfull discharge, which normally has approximately a 1.5-year recurrence interval (annual series), is selected as the design discharge, the berms will be inundated an average of 1.1 times per year (Dunne and Leopold 1978). If the 1.0-year return interval discharge (annual series) is selected, the berms will flood more than twice a year on the average. Too frequent flooding of the berms also causes maintenance problems, as discussed in paragraph 135.

138. The relationship between channel width (W) and depth (D) and bankfull discharge ($Q_{1.5}$, 1.5-year recurrence) can be established by measuring W , D , and $Q_{1.5}$ at various locations along the stream and fitting equations of the form

$$W = aQ^b \tag{22}$$

$$D = cQ^f \tag{23}$$

where coefficients a and c and exponents b and f are determined from the curve fitting. These equations can then be used as a basis for sizing the subchannel. Hydraulic geometry relations such as those expressed in Equations 22 and 23 where W , D , and Q , which are measured at various locations along the stream, are called downstream relationships. Where it is not feasible to derive explicit relationships

for a given stream, regional equations can be used if they are available. Leopold, Wolman, and Miller (1964) give some regional equations for the Green River Basin, ephemeral streams in the western United States, Midwestern streams, and Appalachian streams. These equations are reproduced in Chang et al. (1982). Care must be exercised in using regional values, however, since regional equations mask stream-specific variables such as slope, sediment size, flow variability, and channel pattern, all of which influence channel geometry.

139. Hydraulic geometry is not likely to be highly correlated with discharge in recently disturbed fluvial systems. However, if the effect of the disturbance on the flood frequency distribution can be estimated, Equations 22 and 23 can be used to determine the width and depth of channel required to accommodate the estimated $Q_{1.5}$. Urbanization of watersheds is the most common disturbance to fluvial systems encountered in flood control channel projects. Impacts of urbanization on channel geometry have been studied extensively (Douglas 1974; Guy et al. 1963; Hammer 1972; Holman and Geiger 1959; Leopold 1968, 1973) and are summarized by Nunnally and Keller (1979). The net result of urbanization is an increase in channel cross-sectional area due to bank erosion, with width increasing more than depth (Figure 13). Although some investigators have derived formulas for estimating the effect of urbanization on stream cross-sectional areas for certain localities, no general formulas exist that can be used as a basis for channel design.

140. High flow channel inverts should be sloped gently toward the subchannel. Otherwise, poor drainage might create persistent wet conditions that interfere with vegetative growth, maintenance, and multiple use. Infrequent inundation allows the use of vegetative channel linings for erosion control and aesthetics. Irrigation may be required in dry or semiarid climates.

141. The procedure for designing high flow channels can be summarized as follows:

a. Determine the flood channel slope. The overall slope is fixed when the alignment is selected (from channel length and elevations at the upper and lower levels). Generally, the alignment of the unmodified stream is

Figure 13. Channel enlargement in an urban stream. Increased frequency and magnitude of flooding following urbanization often leads to rapid bank erosion and channel enlargement.

the most desirable from an environmental perspective, but economic or cultural constraints may dictate realignment of some channels.

b. Select the subchannel slope if the unmodified channel is not to be used for the subchannel. Meandering alignments can be used to reduce subchannel slopes in straightened flood channels. A slope approximating the unmodified channel slope is best.

c. Size and shape the subchannel. The first step in sizing the subchannel is the selection of a design discharge for the subchannel, based on the allowable or desirable frequency of flooding of the high flow berms (paragraph 137). Given the design discharge, determine the average subchannel width and depth based on natural channel conditions or by using a formula such as the Manning formula. The latter procedure is recommended if the channel roughness coefficient departs substantially (more than 10 percent) from that of the unmodified channel, or if there is reason to believe that the existing channel geometry is not adjusted to prevailing hydrologic conditions. Otherwise, the procedure described in paragraph 138 should be used. Ideally, subchannel geometry should reproduce unmodified channel geometry as closely as possible for environmental reasons. Thus,

pool-and-riffle grades and asymmetric cross sections in meanders are desirable. Procedures for designing these features are presented in paragraphs 158-161 and 167. Once channel dimensions and roughness have been fixed, check the conveyance of design flow.

d. Size the high flow channel. The additional flow channel capacity required can be determined by subtracting sub-channel conveyance from required channel capacity. Determine the additional cross-sectional area needed and shape the high flow channel. Considerable discretion may be exercised in shaping the high flow channel. The shape of the cross section may be influenced by such factors as anticipated use of high flow berms, cost, or additional environmental considerations.

Floodways and bypass channels

142. Floodways and bypass channels are realigned channels constructed to convey floodwaters over shorter and usually straighter routes than those followed by the natural stream. A floodway is a separate channel into which flood flows are directed. When gated structures or "fuse plug" levees located at the entrance to the floodway are used to release flows, the floodway is often referred to as a flood diversion channel. Conversely, floodways may contain structures that divert or pass low flows to the natural channel. Most floodways are entirely excavated, but old river courses and other low-lying areas may be used on large rivers such as the Mississippi.

143. Bypass channels are excavated flood control channel segments which bypass sections of a natural stream, such as meanders, or features of special interest, such as lakes or wetlands. A bypass channel may be designed to convey all flows or flood discharges only. In the latter case, low and moderate flows usually are diverted through the existing channel. The distinction between bypass channels and floodways is more functional than morphological, and the two terms may be used interchangeably in some cases. However, bypass channels usually are shorter than floodways and often carry low flows as well as floods.

144. Floodways and bypass channels are attractive flood control alternatives for several reasons. On highly sinuous streams, bypass channels that cut off tortuous meanders may require right-of-way that is only a fraction of the natural stream length. Furthermore, there is the

option of maintaining the natural stream as a low flow channel, thereby preserving its associated environmental values. Floodways that carry flow only during flood events often may support multiple uses which are compatible with flood control. Recreation and agriculture are especially well-suited for floodways. Any structures placed within the flood zone should be flood proof, well anchored or removable on short notice, and should not obstruct flow.

145. Aesthetic and environmental benefits of floodways and bypass channels depend on whether they employ modified or unmodified construction and whether features for environmental improvement are incorporated into their design. Although it is not essential to leave the natural stream as a low flow channel, it is environmentally desirable in most cases. Flows below flood stage can be directed through the natural channel by means of flow diversion structures in the floodway and culverts that control the rate of discharge into the natural channel (Figure 14).

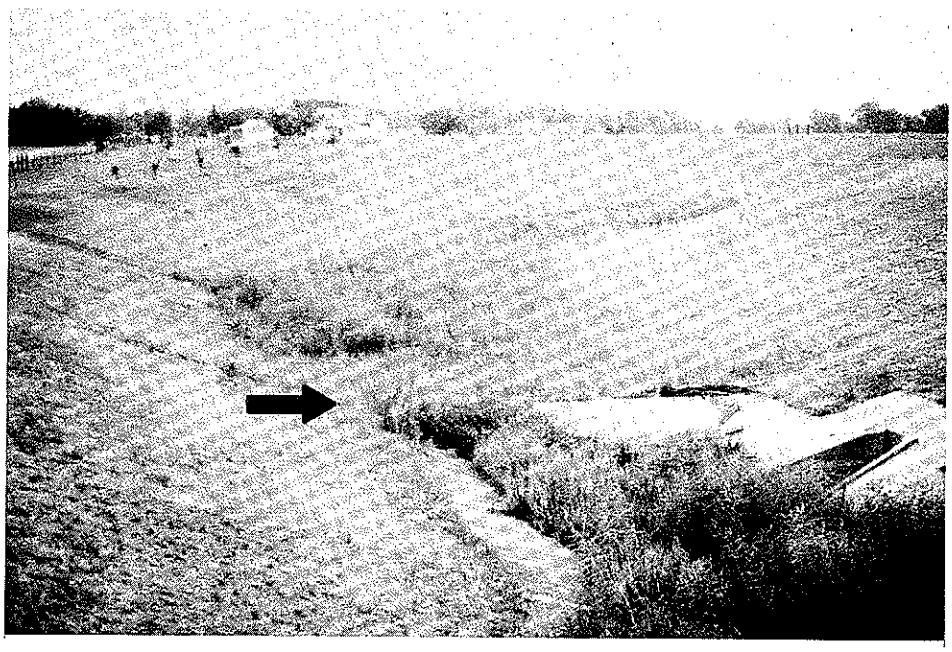


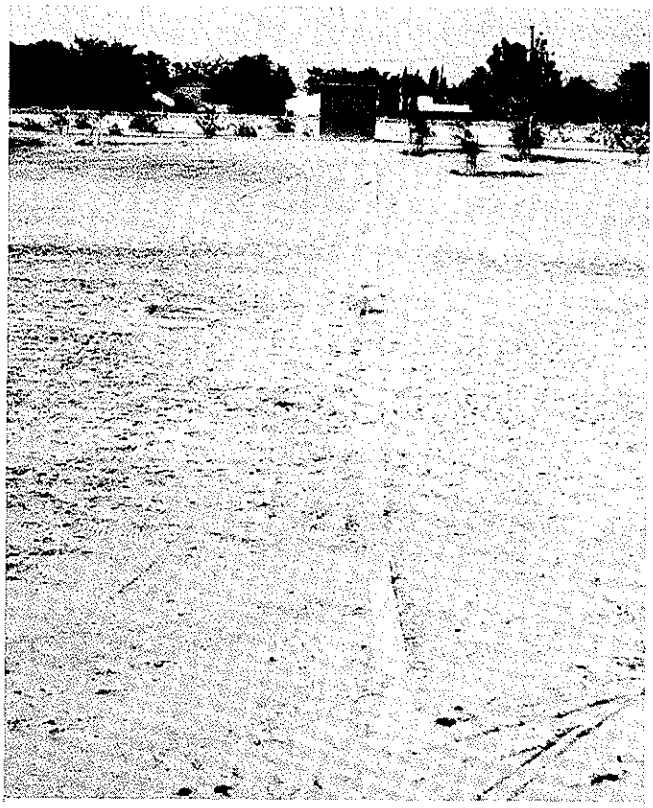
Figure 14. Downstream view, floodway diversion structure, Six Mile Creek, San Antonio, Texas. Low flows are diverted by the sill in the foreground through the culvert to the right.

Some designs use floodway inverts several feet above the natural streambed in lieu of weirs. Alternate designs call for floodwaters to be released into the flood channel once a certain stage is reached. Weirs, gated structures, fuse plugs, stop logs, or spillways can be used for this purpose. These designs do not prevent flooding of the natural stream, but do reduce flood stages.

146. Nearly all floodway and bypass channels have steeper grades than the natural channels do. Steeper grades may create stability problems. The beds of tributaries may be several feet higher than the flood channel invert, requiring grade control to prevent headcuts (knickpoints) from migrating up tributaries. Floodways with steep slopes may require linings, stabilizers, or grade control structures to prevent bed and bank erosion. Selection and design of these features are discussed in later sections. Some of the measures used for erosion control on floodways are shown in Figure 15 and are discussed in paragraphs 175-215.

147. Cost. Floodways can be used to avoid channel excavation in areas where land is expensive or relocation costs are great. Alignments for floodway and bypass channels are usually selected on the basis of cost, which depends on right-of-way width, corridor length, land values, relocation costs, topography, soils, and geology. Costs for land acquisition and excavation costs are site specific so only relative cost comparisons can be made between floodways and channel enlargement. Floodways and bypass channels are usually shorter than the natural channel, so, in most cases, less material must be excavated to construct a floodway or bypass channel than to enlarge the natural channel, and land acquisition costs and maintenance are correspondingly less. Channel alignments for floodways and bypass channels may be selected to pass through easily excavated soils and cheaper land and to reduce road, bridge, and utility relocation expenses that have to be borne by the local sponsor. The ability to use dry construction techniques reduces both cost and environmental impacts of construction.

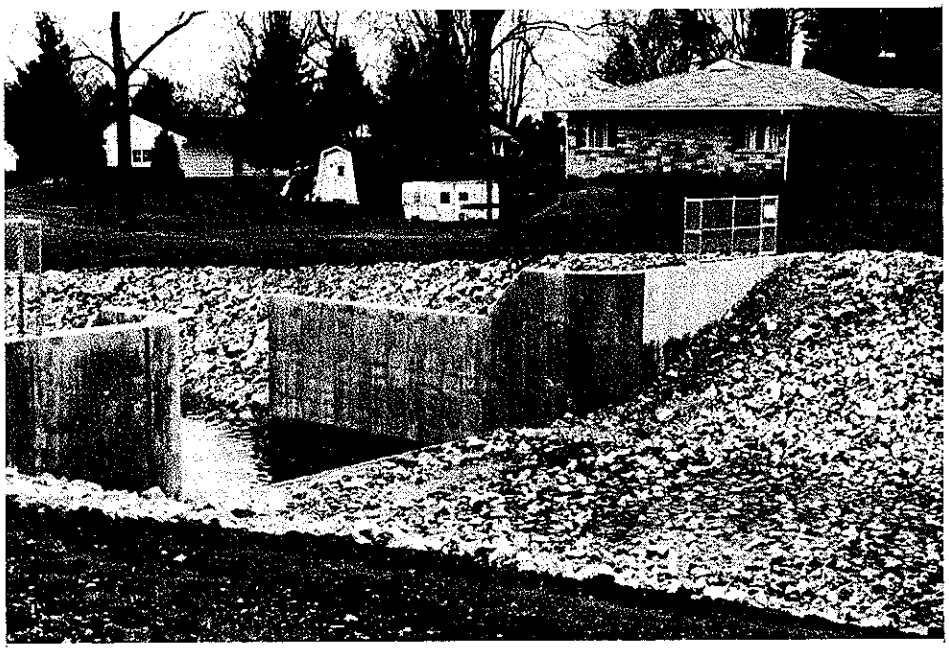
148. Maintenance. Special problems can be encountered in maintaining floodways and bypass channels. When structures are employed to divert normal flows through the natural channel, care must be exercised



a. Stabilizer sill used on floodway diversion channel, Indian Bend Wash, Scottsdale, Arizona

b. Armored diversion channel and sill, Log Pond diversion channel, Newark, Ohio

Figure 15. Erosion control measures used in floodways (photos of Log Pond diversion channel by Huntington District) (Continued)



c. Drop structure, Log Pond diversion channel, Newark, Ohio

Figure 15. (Concluded)

to design, construct, and maintain structures so that they function properly under the prevailing environmental conditions. Weirs, channel blocks with culverts, and floodway inverts with elevations higher than the beds of natural channels are used to divert flow into natural channels. Some examples are shown in Figure 16. When weirs and culverts are used, the most common maintenance problems are sedimentation in the pool formed behind the weir and clogging of the culverts by sediment or trash.

149. Dry floodways and bypass channels that contain flow only during flood events sometimes experience drainage problems that interfere with alternate uses and create maintenance problems. Six Mile Creek floodway, San Antonio, Texas (USAED, Fort Worth 1977) was excavated into a seasonal water table so that the bottom contains standing water much of the time (Figure 14). This promoted rapid growth of water-tolerant vegetation and hindered maintenance. An underdrain system and gabion checks were subsequently added to eliminate seepage and erosion problems.

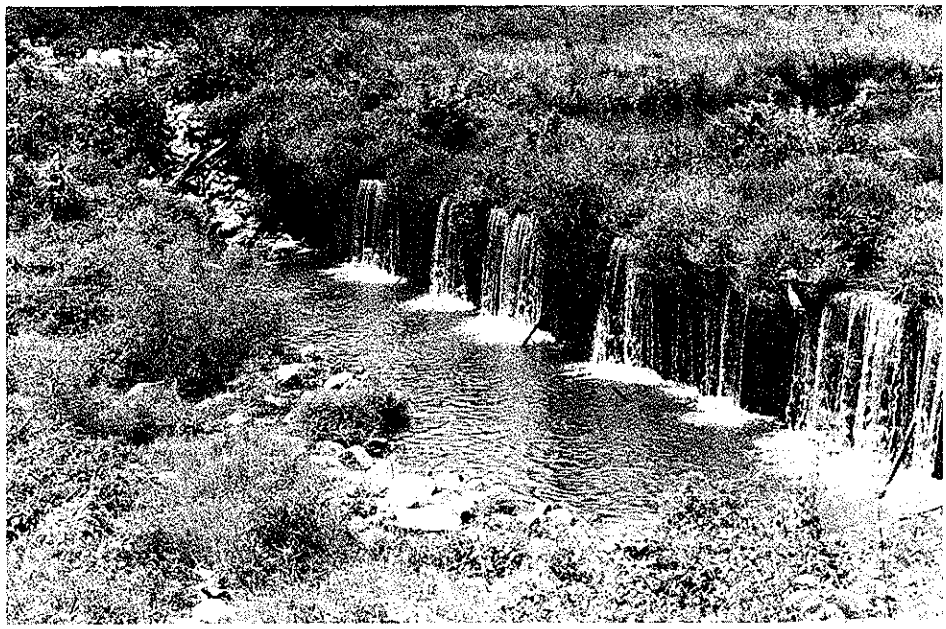
150. Design considerations. Decisions regarding usage and locations of bypass channels and floodways are usually made early in the planning phase, although they may be subject to alteration at a later date for environmental or economic reasons. Major design considerations for bypass channels and floodways include the following:

a. Will the flood channel be used to convey all flows or only flood flows? If the former, then consideration should be given to use of low flow channels or high flow channels, as discussed in the preceding sections. If the latter, then multiple-use options for floodway areas should be investigated (paragraph 144).

b. If the natural channel is to be used as a low flow channel, a means of diverting low flows and restricting flood flows must be provided.

c. The floodway or bypass channel should be sized to convey the design discharge, less the flow diverted through the natural channel, during flood events.

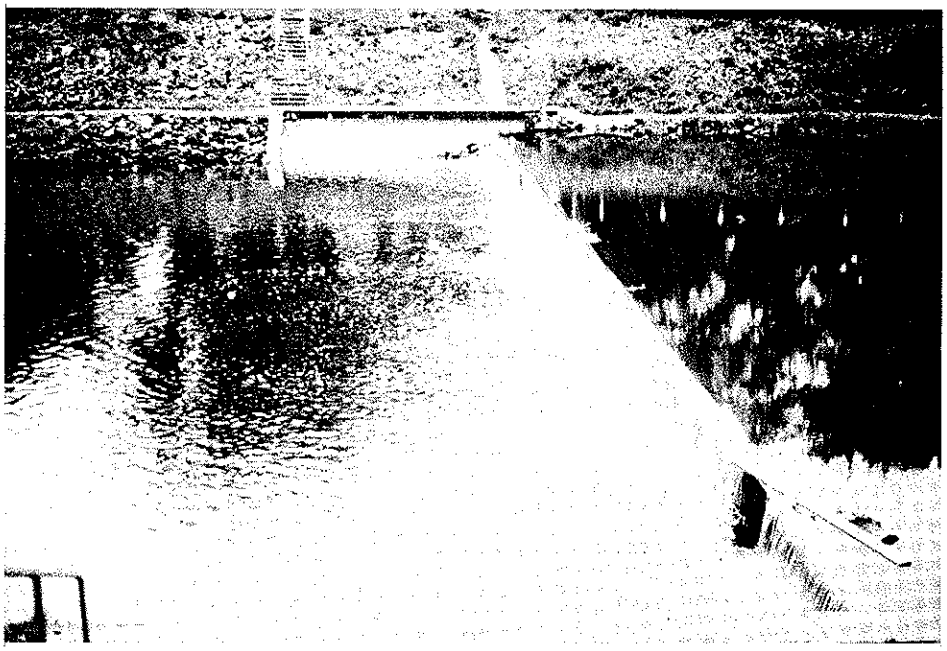
d. Special care should be taken to avoid maintenance problems. Grassed floodways should be designed with side slopes conducive to mechanical mowing (normally 1V:3H or flatter) and with well-drained inverts. Chronic wetness



a. Sheet pile weir, Stanefer Creek near Amory, Mississippi

b. Gabion weir water control structure used on Souris River, Minot, North Dakota, to divert flow through bendways

Figure 16. Examples of structures used in floodways to divert normal flows (Continued)



c. Concrete weir water control structure, Souris River

Figure 16. (Concluded)

encourages growth of hydric species and hampers maintenance. Wet conditions can usually be avoided by constructing the invert above the seasonal high water table or by using tile or gravel underdrains to remove seepage. Sedimentation is a common problem when weirs are used to divert normal flow to the natural channel. Culverts used to control flow into natural stream segments may experience sedimentation and debris blockage. To the extent possible, diversions should be designed to be self-cleaning. Both the flood channel and the culvert should be designed to facilitate regular removal of sediment and debris. Access is probably the most critical issue, and long culverts must be provided with an adequate number of manholes and must be large enough to provide maintenance access for removal of blockages.

e. Construction of grassed channels should be scheduled to allow at least one complete growing season after seeding prior to flow diversion.

f. Determine if erosion control is needed on steep grades.

Pools and riffles

151. Characteristically, flood control channels have been designed and constructed with uniform channel gradients. Although uniform gradients are hydraulically efficient and cost effective, they are environmentally undesirable. Natural channel profiles typically have alternating "lows" and "highs" that are referred to as pools and riffles. Pools and riffles provide a scenic diversity that is aesthetically plea sing, and under normal flow conditions, they provide a variety of water depths and flow conditions that is needed to maintain biologic diversity and vigor (Figure 17). Pools supply resting and hiding places for fish, whereas riffles provide feeding areas and spawning habitat for many species (Corning 1975, Eiserman et al. 1975). The rocky substrate of riffles supports a large variety of invertebrates, including mayflies, stoneflies, and caddisflies. On the other hand, pools tend to support forms that burrow into the muddy substrate (Simpson et al. 1981).

152. Pools and riffles are best developed on gravel bed streams with a heterogeneous mixture of bed material sizes, and have an average pool-to-pool spacing of five to seven channel widths (Harvey 1975; Leopold, Wolman, and Miller 1964; Keller 1978). In meandering streams, pools are associated with scour holes on the outsides of meander bends, and riffles are associated with straight reaches where the thalweg crosses over. Well-developed pool-riffle sequences do not exist in braided or ephemeral streams, or in streams with heavy bedload derived from rapidly eroding banks or disturbed watersheds with high sediment yields.

Figure 17. Pool-riffle sequence in an unaltered stream. In most unaltered streams, pools and riffles occur in an alternating pattern, with a spacing of five to seven channel widths between pools (and riffles).

153. Pools and riffles are permanent bed form features that contribute to the overall resistance to flow. Riffles constitute significant roughness elements at low flows, but are relatively inconsequential at high flows. With increasing discharge, pools and riffles are drowned out, producing a more uniform water surface slope that obscures their locations (Leopold, Wolman, and Miller 1964). Because of their changing resistance with discharge, pool and riffle designs are considered to have an inconsequential effect on flood stages.

154. Although the riffles themselves are permanent features, the sediment particles that comprise them are transient. Several studies have shown that gravel moves downstream even though the basic riffle structures remain unchanged (Andrews 1976; Keller 1971; Leopold, Wolman, and Miller 1964). Clearly, if riffles designed into flood control channels are to last for appreciable periods of time, there must be an adequate supply of gravel upstream to replenish lost gravel, or the riffle

area must be stabilized to prevent gravel loss.

155. Stuart successfully used a dragline to construct gravel piles on a small, relocated trout stream in Scotland (Stuart 1953, as reported in Leopold, Wolman, and Miller 1964). The gravel piles, which were spaced at five to seven channel widths, flattened over time and formed a pool-riffle sequence that was stable for a number of years. Keller (1978) had less success in creating a stable pool-riffle sequence on a small piedmont stream near Charlotte, North Carolina. Gum Branch had been channelized previously and was to undergo clearing and snagging and some bank reshaping to improve flow conditions. Rather than using a uniform cross section, the design employed alternating symmetric and asymmetric cross sections. Symmetric cross sections used 1V:2H bank slopes, and asymmetric sections had a 1V:3H bank slope on one side and a 1V:2H slope on the other. The asymmetric sections were spaced five to seven channel widths and the 1V:3H slope alternated from left bank to right bank to encourage development of a series of point bars and opposing pools. The anticipated morphology did develop but remained stable for only about a year, at which time a large influx of sediment covered the channel and obscured the point bar configuration.

156. CE flood control projects have employed pool and riffle designs in both lined and unlined channels. Pools have been designed into several lined channels in urban areas to provide resting places for fish. The Saw Mill River project (USAED, New York 1974) and portions of the Corte Madera Creek project (USAED, San Francisco 1978, 1980a, 1980b) consisted of V-shaped channels with pools. On Corte Madera Creek, Marin County, California, the 6.5-ft-wide, 4-ft-long pools were spaced 60 ft apart and alternated from side to side. Tamalpais Creek, a small tributary to Corte Madera, has a 10-ft-wide V-shaped channel with two fish resting pools 10 ft long that extend across the channel (Figure 18). Saw Mill River at Chappaqua, New York, contains a series of pools that average about 150 ft in length and are spaced about 150 ft apart (300 ft measured center to center). The pools are 1.5 ft deep at the upstream end and 1 ft deep at the lower end. They increased the overall cost of the 6000-ft channel by an estimated $5000 (1970 price level).

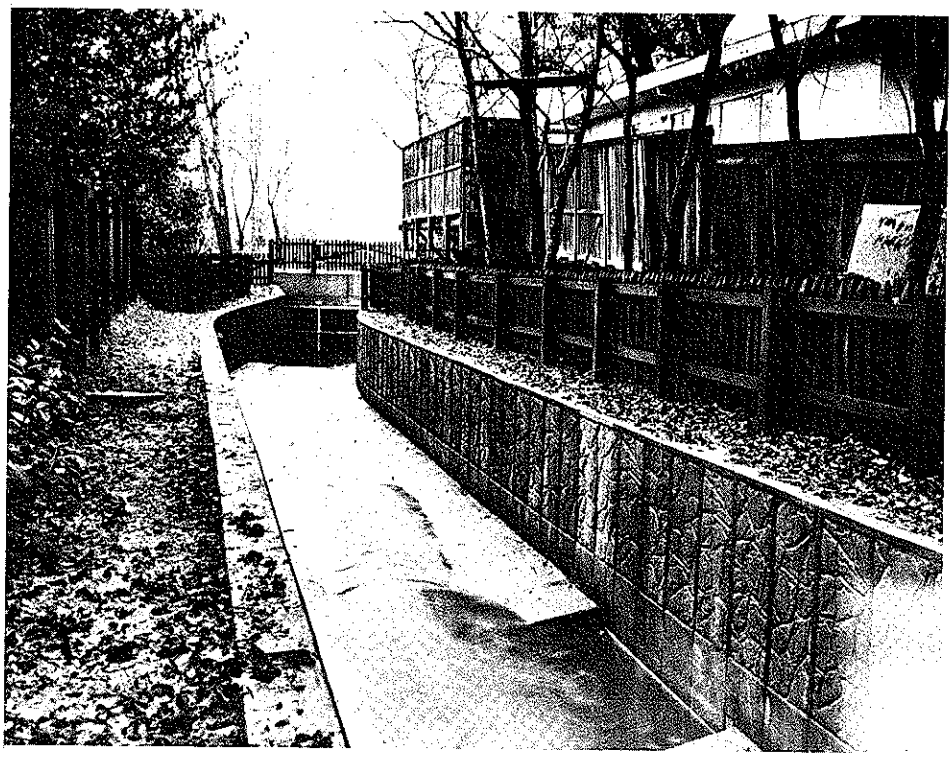


Figure 18. Fish resting pool, Tamalpais Creek, Marin County, California. The fish resting pools, one of which can be seen in the foreground, are 10 ft long and 1 ft deep. The natural stone effect on the concrete channel walls was produced by using a special form liner.

157. Unlined channel designs often include isolated riffles or pool and riffle sequences. Riffles are most commonly made of rubble riprap or gabions. Riffles sometimes double as water control structures or as grade control structures. Costs vary depending on the design and availability of stone. Riffles in Log Pond diversion channel, Newark, Ohio, which contained 25-30 cu yd of 8-in. to 10-in. stone grouted into the channel, cost approximately $150 per riffle (1980 dollars). The gabion riffles used on Tenmile Creek at East Marianna, Pennsylvania, cost $100 per cu yd, or about $5100 (1977 price level). These riffles consisted of single layers of 12-in.-thick gabions placed in the 10-ft-wide low flow channel for varying distances. In a few designs, natural "hardpoints" of resistant material have been left in the channel as a

combined form of riffle and grade control.

158. Although pools and riffles may improve flood control channel aesthetics and water quality to some extent, the primary reason for using them in flood channels is to provide habitat diversity for fish. The initial criteria that determine a stream's ability to support a fishing resource are water quality and permanent flow. Thus, pool and riffle grades are usually inappropriate for floodways that convey only flood flows or for flood channels which convey streams with inadequate water quality. Pools and riffles should not be placed in large channels sized to convey very infrequent events (events with return intervals of 25 years or longer) unless the channels contain low flow channels or subchannels. Pools and riffles are not well developed or do not exist at all on ephemeral streams, or on streams that are very steep, transport large loads of sand, have unstable banks, or have bed materials too coarse to be moved under present hydrologic conditions (Keller 1978; Leopold, Wolman, and Miller 1964). Except for the latter condition, it seems likely that pools and riffles would not be stable if constructed in streams with these characteristics.

159. Pools and riffles should be designed so that the number and location remain stable. Size and shape of pools and riffles are not as critical as spacing and may be varied to suit hydraulic and biologic needs. Spacing is not critical to the stability of pools and riffles designed into lined channels, and may be based on fish needs or other requirements. Pools that are too deep, too wide, or too long may act as sediment traps, however, and require periodic maintenance. Pools and riffles in unlined channels should be designed so that they are self-maintaining. Self-maintenance is fostered by spacing the pools and riffles properly, alternating pools from side to side, and assuring that sediment transport is not radically different from preproject conditions. Based on the success of Stuart's work in Scotland (Leopold, Wolman, and Miller 1964) and on his own research and that of others, Keller (1978) recommended spacing pools and riffles five to seven channel widths apart (measured from the center of one pool or riffle to the center of the next pool or riffle, respectively). However, his research

revealed considerable variability from stream to stream. Harvey (1975) investigated riffle spacing in three streams in southern England and found that the spacing was best correlated with stream width at a range of discharges between the mean annual discharge and bankfull. Spacing varied from a little less than five channel widths to slightly more than seven, with smaller ratios associated with larger widths. These studies suggest that spacing pools and riffles five to seven times the channel width is a valid design approach, so long as the width used is the top width of the subchannel. Thus, pool and riffle spacing must be determined after the subchannel has been sized and shaped.

160. When pools and riffles are used with meandering alignments, it is necessary to construct pools in meanders and riffles in straight sections where the thalweg crosses over. This does not conflict with the recommendations regarding spacing (paragraph 159) because meander geometry is related to stream width and discharge in the same fashion as pools and riffles. For most natural streams, meander wavelength is 6 to 11 meander widths (Table 3). Natural channel meanders have asymmetric cross sections with pools located adjacent to the outside (concave) bank (Figure 19). Asymmetric cross sections that approximate natural cross-section shapes in meanders are recommended for pool and riffle design (Hunt and Graham 1975).

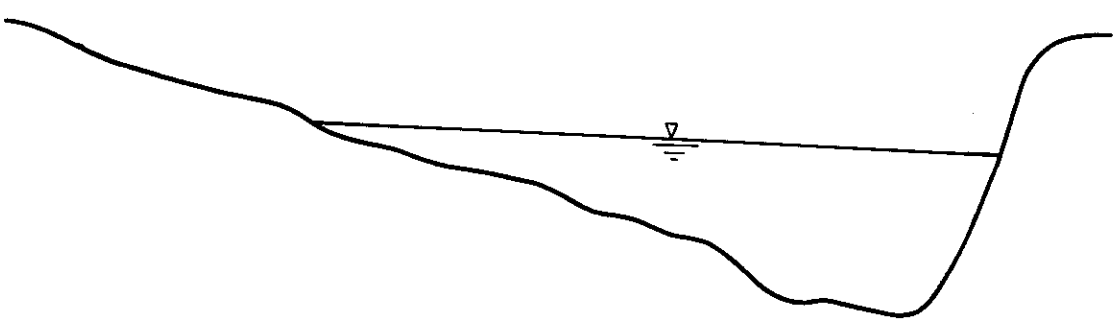


Figure 19. Meander cross-sectional geometry. Natural streams have asymmetric meander cross sections with pools located adjacent to the concave bank.

161. The design of pool and riffle sequences for unlined channels can be summarized as follows:

a. Check stream characteristics to determine if pools and riffles are appropriate environmental features (paragraph 158).

b. Size the subchannel according to procedures in paragraph 128 or 141.

c. Space pools and riffles an average of five to seven channel widths apart, but avoid regular spacings. Alternate pools from side to side. Use meandering alignments if possible, and locate riffles in straight reaches and pools in bends. Although riffle and pool dimensions are not critical, pools should have a minimum low-water depth of 12 in. in most cases and riffles should not project more than 12 to 18 in. above the subchannel invert. Individual pools and riffles should not be longer than three channel widths or shorter than one.

d. If riffles are to be dynamic and self-maintaining, construct them using a mixture of natural stream gravel with size distribution typical of the bed material. Otherwise, construct them of gabions, cobbles, or riprap sized to withstand discharges up to a selected return interval.

Meandering alignments

162. Single channel streams (as opposed to braided or anabranching streams) can have any kind of alignment pattern from straight to tortuously meandering. Few natural streams have truly straight alignments, except for short reaches that are structurally controlled by faults or other geologic lineaments. The degree to which a stream departs from a straight course is measured by its sinuosity, expressed as the ratio of stream length to down-valley distance. A sinuosity of 1.5 is often considered to be a convenient breakpoint between straight and sinuous patterns (Dunne and Leopold 1978). Few flood control channels follow existing stream alignments precisely. In fact, the sinuosity of most flood control channels is reduced by the use of meander bypass channels and floodways. Although some realigned reaches have slightly sinuous alignments, meandering patterns with a sinuosity greater than 1.5 are seldom, if ever, employed.

163. Meandering alignments are not only aesthetically superior to straight channels, but they also may be more stable. Meander geometry has been investigated by many geomorphologists and engineers. Some of

the equations derived from these studies are listed in Table 3. Since meanders are basically sinusoidal, average meander width and length are often described in terms of wave amplitude and wavelength, and are frequently expressed in nondimensional form as multiples of channel width. The radius of curvature of individual bends is usually expressed in channel widths as well (Figure 20). There is no common agreement as to which equations are best. Leopold and Wolman (1957, 1960) investigated

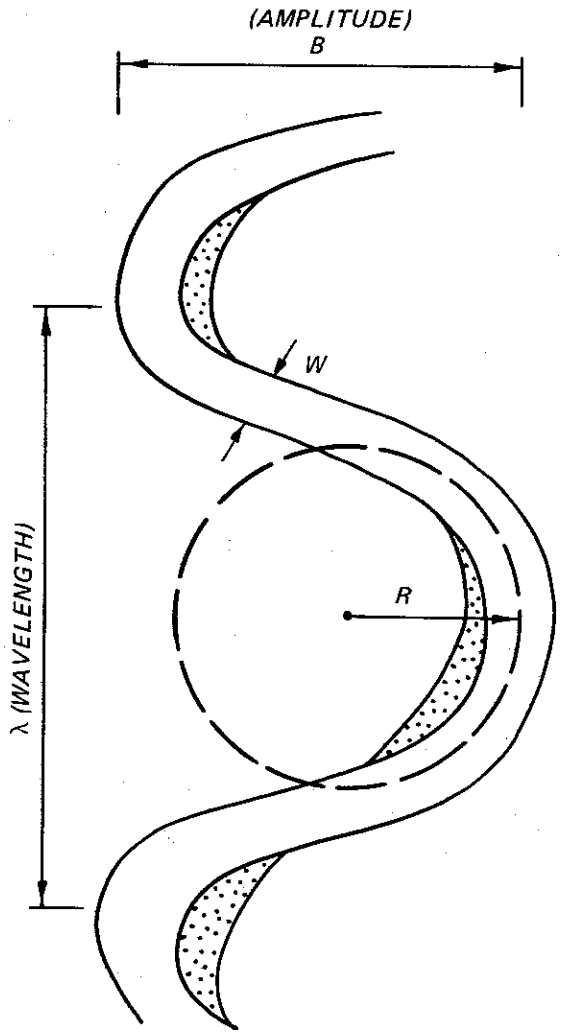


Figure 20. Meander geometry. Wavelength (λ), amplitude (B), and radius of curvature (R) are usually expressed in channel widths (W).

relationships of meander wavelength to discharge and bankfull width. The relationship between wavelength and width was the better of the two. On the other hand, Carlston (1965) found that wavelength was better correlated with mean annual discharge than with bankfull width.

164. Cost. Meandering channels are more expensive to construct than straight channels because of increased right-of-way acquisition and excavation costs. However, environmental benefits and reduced maintenance costs may offset increased construction costs over the life of the project. Although some bank protection may be required on outside meander banks, well-designed meandering channels are more stable, provide a greater variety of flow conditions and aquatic habitat diversity, and are visually more appealing than straight channels.

165. Design considerations. If meandering alignment is desired for a channel of approximately the same size as the natural channel (as with relocated channels or subchannels), the existing meander geometry and slope can be used as a guide. So long as size, meander geometry, slope, and bed roughness of the new channel do not depart radically from the old channel, it ought to possess similar velocity-depth characteristics at similar discharges. Two meanders were built in a Montana stream that was relocated (but not enlarged) during the construction of Interstate 90 (Hunt and Graham 1975). Natural meanders were measured and their geometry was reproduced in the constructed meanders. Three years after construction the meanders were hydraulically and biologically similar to nearby natural meanders.

166. The meanders constructed on the relocated section of Clark Fork River were designed in the field using five criteria, the first four of which were based on natural channel observations (Hunt and Graham 1975):

a. Bankfull stream width was approximately equal to natural channel width.

b. Maximum depth was approximately equal to that in the natural channels.

c. Asymmetric cross section was used with deep flow concentrated along the outer, or concave, bank of the meander.

d. Steep banks were used on the outside of the curves.

e. There was a constant slope along the center line of the channel.

167. Hunt and Graham recommended modifications to this design procedure that include: (a) establishing a typical asymmetric meander cross section based on natural meander characteristics, and holding the cross section relatively constant throughout the meander to simplify construction; and (b) interspersing a relatively flat bed gradient with occasional steep riffle sections to encourage the rapid evolution of a natural pool and riffle sequence. The steep gradient should be skewed across the stream in riffle areas to provide crossover for the thalweg.

168. The stability of the meanders constructed on the Clark Fork River, and their hydraulic and biologic similarity to natural meanders, attests to the validity of using design criteria based on natural channel geometry (regime relationships). A simplified design procedure for meandering alignments applicable to channels with dimensions approximately equal to the natural channel can be summarized as follows.

a. Using field surveys and aerial photographs to determine existing meander geometry (meander wavelength, meander width) and stream length and gradient. An alternative source for meander geometry is to use the equations in Table 3.

b. Considering topography, geology, and other constraints, lay out the new alignment so that meander geometry is as similar as possible to existing geometry.

c. Design an uneven channel gradient with pools and riffle patterns similar to natural stream grades. Riffles should be located in straight reaches, pools in bends.

d. Based on existing meander geometry, establish average cross-section shape for constructed meanders. Cross sections should be asymmetric with channel bottom sloping toward the outside (concave) meander bank and with outside bank slope steeper than inside bank slope. Maximum concave bank slopes should be based on bank stability criteria. A short transition reach should be provided between straight reaches and meanders at the meander inflection point. The average meander cross section can be used throughout the meander between transition reaches.

e. Stabilize outside meander banks with riprap if necessary.

169. Land values, topography, or other considerations often

dictate or severely constrain the alignment of large flood control channels. When some latitude does exist in selecting alignment, optimum meander geometry can be based on regional hydraulic geometry relationships derived from streams with dimensions or discharges similar to the design discharge. If sufficient data to establish these relationships are lacking, then Carlston's formulas in Table 3 that use bankfull discharge or Leopold and Wolman's formulas that employ bankfull width can be used to derive meander geometry. Vanoni (1975) cautions against using meanders with a radius of curvature that is too small. Tight bends cause bank erosion and maintenance problems. An optimum bend radius for most streams is two to three times channel width (Bagnold 1960, Leopold and Wolman 1960), although on streams such as the Missouri that transport a heavy percentage of sand, bends with radii exceeding 10 channel widths are more stable (Vanoni 1975). A minimum radius of three channel widths was used in designing the meandering alignment of Apache Creek (USAED, Fort Worth 1973).

Single-bank modification

170. Single-bank construction is the preferred technique for channel enlargement. The existing channel alignment is followed, and enlargement is confined to one side. Existing vegetation on the opposing bank is disturbed as little as possible, although snags that would interfere with flow or trees that might fall into the channel may be removed. Water quality benefits of single-bank construction techniques are maximized by leaving as much streamside vegetation as possible and by working primarily from the northerly or easterly bank so that the channel remains shaded as much as possible. Aesthetic impacts are reduced if the work is alternated from side to side and if clumps of vegetation are left on the work bank (Figure 21).

171. Equipment used for single-bank construction varies with stream size. Hydraulic hoes and other small equipment are preferable for small streams because of their maneuverability, the smaller access routes required, and reduced right-of-way needs. On large streams, the use of floating dredges reduces the clearing required for haul roads and access since dredged material can be pumped for long distances.

Figure 21. Single bank modification, Swift Creek Watershed, North Carolina. Clumps of vegetation left on the modified bank improve aesthetics.

172. Disturbed areas should be revegetated promptly to reduce erosion and sedimentation in the flood channel. If work areas are left exposed for long periods (e.g., more than 30 working days), temporary cover should be provided during the growing season. Planted and preserved vegetation should be protected from encroachment, especially in agricultural areas. Buffer strips as wide or wider than the channel should be established on both sides of the channel and clearly marked. Fencing of buffer strips is desirable in livestock areas.

173. Cost and maintenance. In most cases, construction costs for single-bank modification should be less than traditional techniques, although frequent crossings, access restrictions that require long travel distances, or extensive hand labor may increase costs considerably. Debris that falls into the stream from the unmodified bank may increase maintenance cost over that for traditional designs.

174. Design considerations. The design procedure for single-bank construction involves selecting the work bank and marking any trees to be preserved on that side; specifying guidelines for any clearing and

snagging to be done on the bank; specifying any restrictions on equipment, access, or work schedules; and developing specifications for revegetation of work areas and designating buffer strips. The procedures can be summarized as follows:

a. Alternating the work bank from side to side and leaving some vegetation with special aesthetic or habitat value on the work bank may further reduce the impacts of single-bank construction; however, equipment maneuverability and access may limit the frequency of changeover. Factors that should be considered in designating the work bank include habitat value of vegetation, aesthetics, shade, and bank stability. Plans should be drawn up by a field team that includes a wildlife biologist and a hydraulic engineer. Any special vegetation to be preserved on the work bank should be specially marked.

b. Specifications for selecting and removing snags from the opposing bank should be developed according to the procedures presented in paragraph 104.

c. Restrictions on equipment, access, work scheduling, etc., should be developed according to paragraphs 110, 113, 118, and 119.

d. Specifications for revegetation of work areas and buffer strips should be drawn up according to paragraph 114.

Features for Bed and Bank Stability and Erosion Control

175. Flood control channels frequently experience erosion and sedimentation problems. Flow depths and velocities in these channels during high discharges are often sufficient to cause general scour of their beds and banks. Local scour is likely to occur around obstructions and bridge abutments, below grade control structures, in meanders, or along bank sections constructed in erodible material. Under low flow conditions, velocities in widened channels may be insufficient to transport sediment delivered from upstream reaches and tributaries. Sediment transport problems are compounded when low velocity environments are created behind structures used for water diversion, water level control, and grade control. Flood control channels that do not follow the alignment of the natural stream usually have steeper gradients than the

stream and may be subject to severe downcutting unless stabilized by lining or grade control structures. This section evaluates the environmental aspects, costs, and maintenance considerations of channel linings and bank protection measures, and erosion and sediment control features used in flood control channels. Although the bulk of the data used comes from CE flood control projects, data from other sources are incorporated, especially in the discussion of bank protection.

176. Environmental benefits of features discussed in this section are largely indirect. Nevertheless, some form of channel lining, bank protection, grade control, and/or erosion control is used on nearly every channel project. Project planners may have considerable latitude in the choice of methods for preventing erosion and controlling sediment. Since each method may have different environmental impacts and benefits, it is appropriate to include a brief review of the most widely used techniques. Henderson and Shields (1984) review environmental aspects of bank protection measures in much greater detail.

177. General guidance for designing features to stabilize channel beds and banks and for controlling erosion can be found in various state handbooks on erosion and sediment control (Amimoto 1978; Beckett, Jackson, Raeder, Inc. 1981; SCS 1973; Virginia Soil and Water Conservation Commission 1980). Although these handbooks are oriented primarily toward construction sites, they contain information about the design of sediment barriers, sediment traps, drop structures, streambank protection, and vegetative practices. The CE report to Congress on streambank erosion (OCE 1981b) and the notes from the Streambank Protection Shortcourse (USAE Division, Huntsville 1982) contain a wealth of information about the design and performance of streambank protection methods and their environmental impacts.

Channel linings and bank protection measures

178. Although flood control channel cross sections usually are designed to minimize erosion problems, lined channels or some bank protection is required on nearly every flood control channel. Channel stability is important for hydraulic, environmental, and economic reasons.

Erosion and deposition may impair project performance, shorten project life, degrade water quality and aquatic habitat, and endanger life and property. The major causes of erosion on flood channels can be summarized as follows (OCE 1981b):

a. General scour caused by excessive flow velocities attributable to increased slope, reduced bed roughness, and/or increased flow depth.

b. Local scour caused by easily eroded bank materials, local velocity increases at constrictions, local turbulence caused by flow obstructions, and hydraulic jumps.

c. Structural instability of banks caused by loss of shear strength or undermining of toe slopes.

d. Overbank runoff.

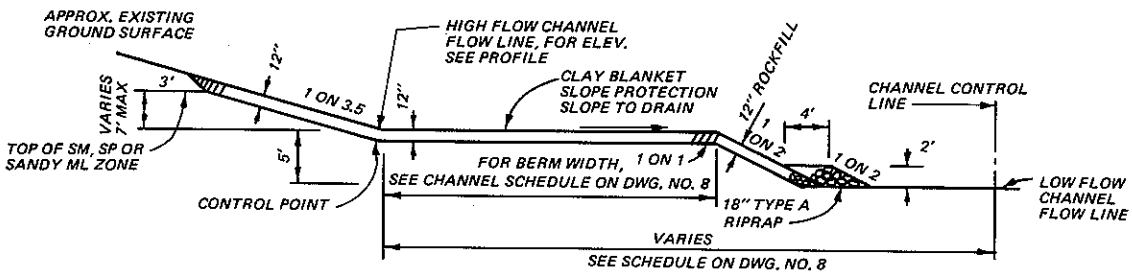
e. Ice and debris gouging.

179. Channels subject to scour are protected by stabilizing erodible soils, planting vegetation, or covering the bed and banks with various materials. Lined channels are usually employed in urban areas where right-of-way is limited and land is expensive. Placement and type of bank protection vary, depending on the anticipated cause of erosion. Banks that are structurally unstable may be protected by bulkheads or rigid linings. Toe slope erosion can often be prevented by fences, jacks, longitudinal dikes, or spur dikes, although these tend to be unsightly and are used mostly in natural streams where severe erosion problems already exist. Lined drains or drop inlets can be used to prevent erosion by overbank runoff.

180. Impacts, costs, and maintenance considerations of flood channel linings and bank protection measures are discussed briefly in the following section, and examples are provided from CE projects. These data are summarized in Table 4. Because guidance for design of channel linings and bank protection is available from several sources, detailed design procedures are not provided here. Instead, major design considerations are identified, and readers are referred to other sources for guidance.

181. Clay blankets. Clay can be used to cover erodible materials in flood channels that are not subjected to velocities exceeding 6 to

8 ft/sec (SCS 1977). Two CE high flow flood control channels have been designed with clay linings that were vegetated for additional protection and aesthetic reasons. The Big Creek Flood Control Project (USAED, Buffalo 1979) will require excavation into a weak shale that is subject to slaking when exposed to wet-dry cycles. The design calls for the high flow channel invert to be lined with a soil layer and sodded. On the Little Blue River Project (USAED, Kansas City 1972), sections of the high flow floodway excavated through sand lenses were lined with clay and planted to grass (Figure 22) (see Table 4 for cost). These sections

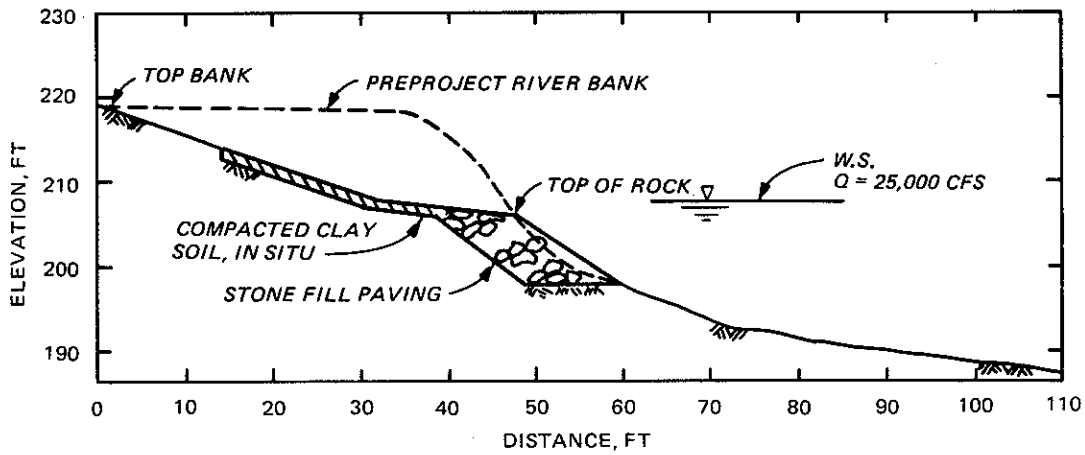


CLAY BLANKET SLOPE PROTECTION

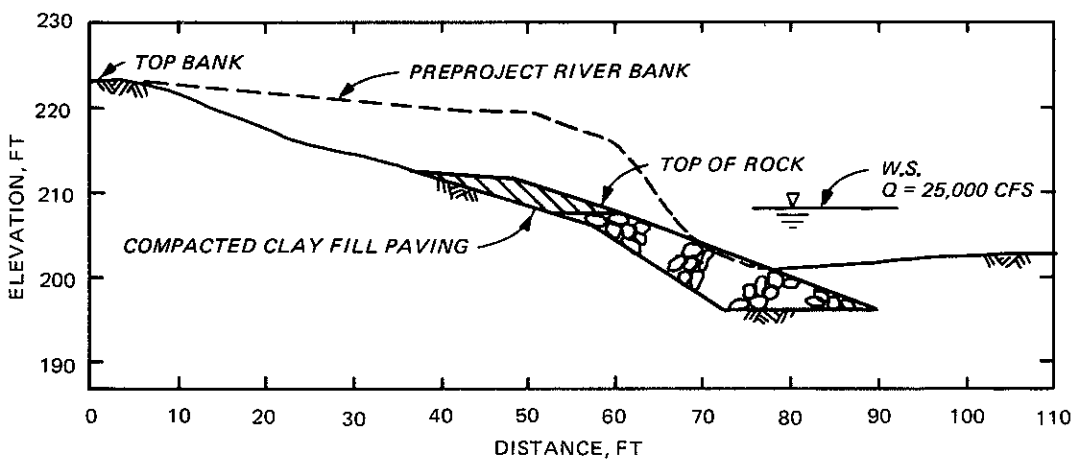
Figure 22. Design drawings of the clay blanket used on the Little Blue River, Kansas City. Clay was used to line channel sections excavated through sand. (USAED, Kansas City 1972)

have performed well and no failure is evident since the project was completed, except for some erosion of the clay blanket by improperly controlled overbank drainage. Clay blankets have also been used for bank protection on the Little Blue River Flood Control Project and on the White River in Arkansas (OCE 1981b). On the latter, upper bank slopes were protected with a clay blanket composed of in situ compacted clays in some places and clay fill paving in others (Figure 23).

182. Design considerations. The major considerations in designing clay liners are specifying physical characteristics of the material to be used as a liner, placement and compaction of the fill, and quality control. Specifications used for the construction of the clay blanket on the Little Blue River are provided in Appendix D. Example design drawings are shown in Figure 22. Permissible velocities for various



a. Upper bank areas with suitable clay content were compacted in situ



b. Other areas required clay fill paving

Figure 23. Compacted clay blanket and clay fill liners used on the White River, Arkansas (OCE 1981b)

soil conditions can be found in SCS Technical Paper No. 61 (1947) and in SCS (1977) Technical Release No. 25.

183. Chemical stabilization. Lime, cement, and lime-cement mixtures have been used to stabilize streambanks. Hydrated lime ($Ca(OH)_2$) has been used to stabilize very plastic, expansive clay soils and silty dispersive soils. Treated soil may be left exposed or covered with topsoil and vegetated. Costs of lime stabilization on the Section 32 Program demonstration projects are given in Table 4. Lime and lime-cement stabilization performed well during the 2-year observation period. Soil cement was used on several sites in the demonstration program with mixed success. Problems encountered in applying soil cement included weather (rain that leached the soil before the cement cured) and inadequate specifications (or failure to follow specifications) during construction (Plack 1982).

184. Design considerations. Soil stabilization with lime or cement is limited to soils with desirable physical and chemical characteristics. Hydrated lime stabilization can be used on very plastic clays to produce a surface that is more resistant to scour than cohesive clay, and on dispersive loessal soils to prevent piping and gullying. Guidance for the design and construction of banks with lime stabilization can be found in Littlejohn (1982). Additional guidance can be found in Gutschick (1978), Haliburton et al. (1975), and Howard and Bara (1976). Detailed testing is required to determine if soils are suitable for stabilization with cement. Plack (1982) provides detailed information about testing procedures and some design guidance. Additional guidance can be found in several publications of Harza Engineering (1964), Litton and Lohnes (1982), and the Portland Cement Association (1971, 1975a, 1975b, 1977, 1979).

185. Vegetation. Vegetation is widely used for channel stabilization and bank protection. From an environmental standpoint, it is the preferred treatment when hydraulic conditions allow its use. However, velocity and inundation constraints are stringent. Woody vegetation is usually restricted to banks, but grass may be used to line intermittent channels or the inverts of high flow channels that are normally above

water. Grass linings perform well when properly maintained and not exposed to excessive velocities, heavy sediment deposition, or prolonged wet or dry conditions. Grass channels are ecologically less diverse than natural channels that support woody species, but grass is environmentally preferable to artificial linings. In addition to its aesthetic superiority, grass provides limited streamside habitat and some organic input to the stream. A dense growth of woody vegetation provides greater resistance to erosion than grass and offers habitat diversity and some shade. However, it requires a longer time for establishment and reduces flow capacity. Resistance to scour can be improved by combining vegetation with other protection measures such as cellular concrete or aluminum honeycomb grids, but at a loss in aesthetic and habitat value and an increase in construction and maintenance costs.

186. Examples. The grassed portions of the Indian Bend Wash floodway (USAED, Los Angeles 1973) (Figure 9b) are excellent examples of a well-maintained vegetative lining, as are portions of the San Antonio River flood control channel (USAED, Fort Worth 1975) (Figure 24).

Figure 24. Vegetative lining, San Antonio River flood channel. This completed reach contains a subchannel which conveys normal flows. The high flow berms and banks are vegetated. Note the river walk (Paseo del Rio) inside the flood channel.

Grass inverts seem to be more prone to scour on the insides of meander bends than elsewhere. Bermuda turf used on the high flow invert of Apache Creek, a tributary to the San Antonio River, was badly scoured by high flows on the insides of meander bends, and some of these meander sections subsequently have been lined with concrete (Figure 25). Sediment deposition and frequent inundation have been problems on the grassed floodway inverts of the Little Blue River Project.

Figure 25. Erosion of grassed channel invert, Apache Creek, San Antonio, Texas. The Bermuda grass turf has sustained considerable erosion on the convex sides of meander bends.

187. Costs. Data in Table 4 indicate that vegetation is usually the cheapest form of erosion protection and can have long life expectancy if appropriately used and properly maintained. Costs for grass linings depend on the type of grass used, seedbed preparation, method of establishment, and whether supplementary irrigation is required. Fescue, ryegrass, native Bermuda grass, and certain other species can be established relatively cheaply from seed, whereas sodding is much more expensive.

188. Maintenance. Maintenance requirements of vegetative linings

also vary. Some species, such as crown vetch and Sericea lespedeza, require little maintenance other than infrequent mowing to prevent establishment of woody vegetation. Other species require regular mowing if they are to perform efficiently and retain their aesthetic value. Careful consideration should be given to maintenance requirements when selecting a vegetative lining for flood control channels.

189. Major disadvantages. The major disadvantages of vegetative protection are its relatively high maintenance costs where regular mowing is required; its restriction to channels with low velocities (4-8 ft/sec for most grasses, Table 5); its susceptibility to damage by grazing animals; and its potential for failure during dormancy, droughts, extended inundation, or periods in which velocities exceed design velocities. Overbank surface drainage must be controlled to prevent rill and gully erosion of vegetated banks. Erosion problems can be prevented by intercepting surface runoff with berms or diversion ditches that discharge into lined drainage ways, culverts, or drop inlet drains.

190. Design considerations. Vegetative protection used on channel inverts and toe slopes must be designed to withstand shear stresses imposed by the flowing water. The toe is the lower part of the bank adjoining the channel invert. On permanent streams the toe slope is below water level much of the time and is subject to erosion primarily by current action. A summary of extensive research on vegetative channel linings by Ree and Palmer (1949) is presented in Table 5. Parsons (1960, 1963) computed allowable shear stresses for Bermuda grass channels and hydraulically equivalent stone diameters (see Table 6).

191. Even when shear stresses in the toe zone are high, suitable bank protection often can be achieved by vegetative means if adequate toe zone protection is provided. Factors to consider for design of vegetative protection include frequency and duration of flooding, species selection, bank geometry, site preparation, and construction scheduling.

192. Hydrologic analysis should reveal the frequency and duration of flooding at various elevations on the bank. Coupled with knowledge of the flood tolerance of vegetative species, this information should allow the project planner to choose the most appropriate plant or

combination of plants for a particular situation. Whitlow and Harris (1979) present information regarding flood tolerance of various plant species. As a general rule, native plants or plants already adapted to the area should be used, for they are likely to be best adapted climatically and most resistant to disease and pests. Plant mixtures may be chosen to provide a diversity of wildlife habitats. Guidance for proper seedbed preparation, fertilization, and seed selection is available in Technical Manual (TM) 5-830-2 (OCE 1981a) or can be obtained from local SCS District Conservationists. Suggested plant mixtures with wildlife habitat value can be obtained from the SCS, or from CE or conservation agency wildlife biologists.

193. Construction should be timed so that it is completed during the optimal planting season and low water conditions. If this is not feasible, specifications should call for replanting as necessary to establish good vegetative cover. Banks should be sloped to a stable grade and a seedbed should be properly prepared and fertilized before seeding. Topsoil removed during grading should be stockpiled for seedbed preparation. Bowie (1981) recommends that vegetated banks not exceed a slope of 1V:2H. If mechanical mowing of vegetated banks is anticipated, slopes should be no steeper than 1V:3H. Mulch should be applied to slopes immediately following planting to preserve moisture and prevent erosion by rainwash. It is imperative that overbank drainage be controlled to prevent gullying of vegetated banks.

194. Gravel and stone. Armor layers that develop by selective removal of fine sediments are common in natural streams. Armor provides good habitat for macroinvertebrates (Bingham 1982, Bulkey et al. 1976) and fish spawning. Aesthetically, flood control channels lined with gravel probably rank between grass-lined and concrete channels, although they may have a natural appearance if the stone is restricted to the channel invert and consists of stream gravel of a wide range of sizes. Three of the flood channel projects surveyed were designed with armored channels. Riprap lining was the preferred alternative for the Namo River in Guam, based on an evaluation of hydraulic, aesthetic, biologic, and economic factors (USAE Division, Pacific Ocean 1973). An uncompleted

portion of the Corte Madera Creek flood channel was designed with a gravel section to serve as a spawning and rearing area for salmonid fish (USAED, San Francisco 1980a, 1980b). The bed and lower bank of Prairie Creek, a flood channel constructed by the SCS in Indiana, were lined with a 6-in. blanket of river gravel (SCS 1975).

195. Riprap is probably the most widely used nonvegetative type of bank protection. It is relatively inexpensive and has long life expectancy. If riprap protection is properly designed and installed, failure rates and maintenance costs are relatively low. Riprap has a number of advantages over other structural bank protection measures (Maynord 1982).

- a. Skills and abilities required for riprap design and construction are widely available relative to more exotic bank protection methods.
- b. Riprap is aesthetically and biologically superior to most other structural forms of bank protection.
- c. It is flexible and does not weaken or fail from minor bank adjustments, due to its self-healing properties.
- d. Suitable rock is often available locally.
- e. It has a more natural appearance than other types of structural protection, especially if soiled and seeded or when allowed to revegetate naturally.
- f. It may be easy to provide toe protection due to its ability to be "launched" in a loose mass.
- g. Expensive filter layers may not be required for some applications.
- h. Upper bank areas can be maintained by machine mowing if the riprap is covered with topsoil and seeded on slopes of 1V:3H or flatter.

196. Maintenance. Stone properly sized to withstand shear stresses imposed by flood flows requires little maintenance other than regular inspection, periodic removal of large woody vegetation, and expeditious repair of failures. The river gravel used on Prairie Creek (SCS 1975) has remained stable through several flows at channel capacity. Total annual maintenance costs for the riprap lined channel of the Namo River in Guam were estimated to be $17,300 compared to $16,900 (1973 prices) for a concrete lined channel.

197. Costs. Construction costs for stone-lined channels depend on local availability of stone of proper size and quality. Generally, they are more expensive than grass-lined channels but cost less than concrete linings. Gabions are sometimes used if they are more economically attractive than stone sufficiently large to resist shear stresses. However, gabions increase construction costs considerably because of the hand labor required for filling and tying the gabion cages.

198. Design considerations. Design of gravel armor and riprap bank protection involves three major decisions: (a) the size gradation of rock needed to withstand erosive forces, (b) the structure of the protection (bank slopes, presence and types of filter, thickness of blanket, manner of providing toe protection, etc.), and (c) where, and to what extent, protection is needed. Design guidance for items a and b can be found in EM 1110-2-1601 (OCE 1970), ETL 1110-2-120 (OCE 1971a), and Maynord (1978, 1982). Item c is a problem on flood channels with meandering alignments and those which have grade control, water control, or habitat control structures. The location of the major stress zone varies with discharge for meandering alignments, and is displaced progressively downstream as discharge increases. Successive meanders complicate the problem. Guidance for placement of bank protection in bendways of small to medium size streams can be found in Maynord (1982) and in Nunnally and Keller (1979). The material presented by Maynord is based on work done by Parsons (1960).

199. Gabions. The survey of recent CE flood control projects failed to reveal any projects that had used gabions for bank protection, although they had been used to build instream structures on several projects. Gabions were used for bank protection on several projects evaluated for the Section 32 Program. Data indicate that gabion mattresses (Figure 26) are approximately twice as expensive as riprap protection, largely due to the additional cost of the cages and the hand labor involved in filling them. Stacked box revetments used on slopes too steep for mattresses (Figure 27) increase costs even more. Factors that influence costs include the size of the gabion cross section, total project length, the need for a filter layer, and the local availability of suitable stone (Schmidgall 1982).

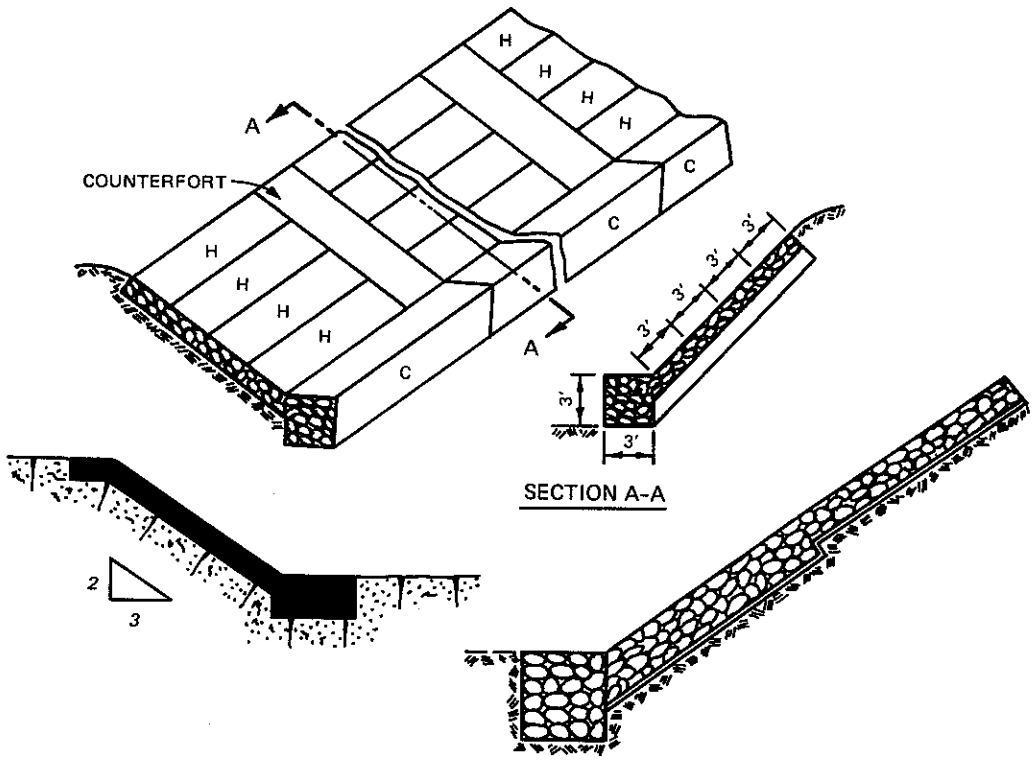


Figure 26. Gabion mattress, typical section. Gabions 9 to 18 in. thick are typically placed on IV:3H slopes with toe protection provided to a depth of 3 ft. (after Schmidgall 1982)

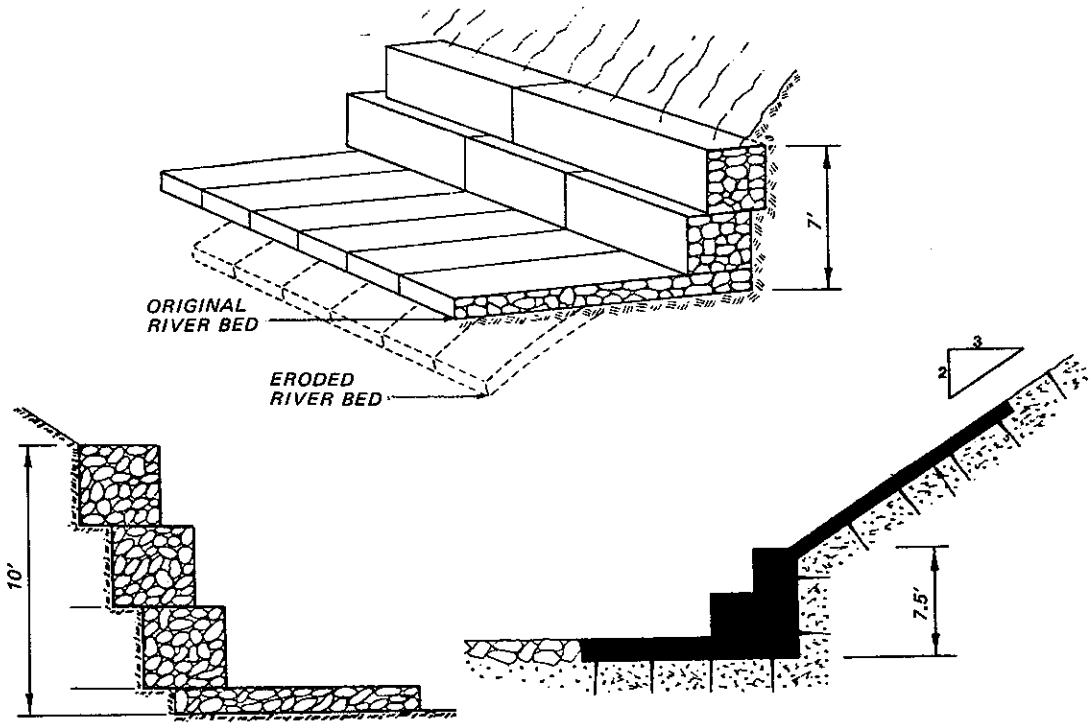


Figure 27. Stacked gabion box revetment, typical sections. Stacked gabion cages can be used on much steeper bank slopes than mattresses. (after Schmidgall 1982)

200. Gabion cages are subject to damage from floating ice and debris, corrosion, abrasion by sediments (especially in steep gravel bed streams), and vandalism. After installation, gabions may be spray-coated with gunite to protect the cages. However, gunite-coated gabions are less attractive. Vinyl-coated wire cages are available that resist erosion longer than regular cages. Failed cages can be hazardous to recreationists. Although gabions are considered to be porous, they can be sealed by deposition of silty sediments so that they behave as nonporous covers. Most problems encountered in the Section 32 Program involved downslope displacement of mattresses, erosion at gabion toes, and erosion at the periphery of treated reaches. If necessary, gabion maintenance can be accomplished by unlacing and refilling or replacing damaged sections.

201. Design considerations. The only CE guidance for the design of gabion structures for bank protection is presented by Schmidgall (1982) and Varga (1982). Additional information is available from suppliers of Bekaert and Maccaferri gabion products. Addresses for suppliers of these and other manufacturered products for bank protection may be found in Keown et al. (1977). Typical sections for mattress and stacked cage revetments are shown in Figures 26 and 27. According to Agostini and Papetti (1978), mattress revetments 9, 12, and 18 in. thick should withstand velocities of 10, 15, and 18 ft/sec, respectively. Model tests performed under the Section 32 Program led to the conclusion that prototype gabion flexibility cannot be accurately modeled.

202. Rigid linings and bank protection. The most widely used rigid channel lining used on CE flood control channels is concrete, but asphalt, grouted riprap, and concrete faced with stone are occasionally used. Unlike riprap, which is flexible and can adjust to bank deformation, rigid structures are more prone to failure by undercutting and piping (Figure 28). Although they have long life expectancy and relatively low maintenance costs, rigid linings and bank structures are generally among the most expensive and difficult types to design and install and have the most negative environmental impacts. Rigid channel linings have generally been restricted to urban areas where land costs are high

Figure 28. Failure of concrete bank paving, Alazan Creek, San Antonio. Alazan Creek is tributary to Apache Creek. The bank paving that was done by local interests failed due to undercutting and leaching.

and to steep channels that experience supercritical flows. Rigid bank protection structures are used mostly to protect bridge abutments and instream structures and to prevent localized erosion problems.

203. Environmental impacts. Environmental impacts tend to be greater for channels with rigid linings than for other types of linings. Concrete lined channels typically have poor water quality and low habitat value. This is due, in part, to their urban setting, but also is attributable to shallow flow, lack of shade, low organic input, and poor substrate conditions (Parrish et al. 1978). Fish habitat can be improved by molding pools in the lined channel and using embedded boulders. Aesthetics of concrete channels are usually very poor but can be improved by treatments such as brushing and use of special patterned form liners and stone facings as described in EM 1110-2-39 (OCE 1969).

204. Costs. Reduced costs of relocation, excavation, and land for lined channels are partially offset by the high cost of the lining. For concrete channels, the cost depends on the local price for concrete,

the size of the lining, the amount of reinforcement required, the amount of anchoring needed, and any special treatment. Concrete-boulder combinations have proven to be less expensive, in some cases, than all concrete channels (see paragraph 126). Special form liners or finishes for aesthetic purposes (Figures 18 and 29) usually increase costs accordingly (see Table 16 for information on costs of aesthetic treatment).

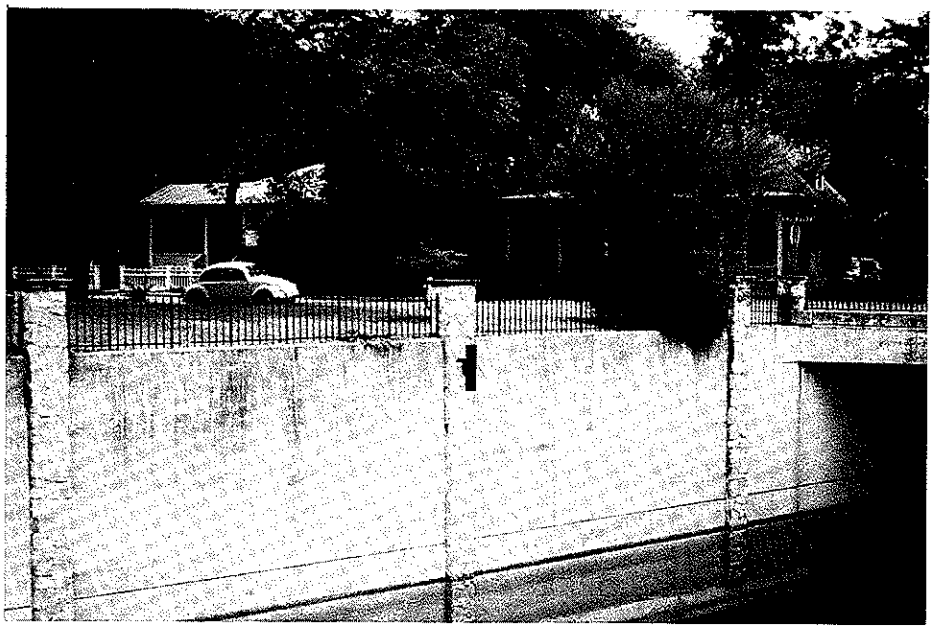


Figure 29. Stone-faced pilasters, San Antonio. These pilasters were constructed by the local sponsor in order to maintain a project motif developed for earlier channel work.

205. Maintenance. Maintenance costs for rigidly lined channels are not radically different from costs of maintaining riprap channels. Maintenance involves periodic inspection, removal of accumulated debris and sediment that might impair project performance, and repair of damaged sections. Failure of concrete channels is most often associated with buoyancy that results from failure to provide sufficient anchoring or adequate toe drainage, or with collapse of channel walls due to piping or sapping. Concrete lined channels are also subject to wear and damage from transported debris and sediment.

206. Design and construction. Hydraulic design guidance for concrete channels is contained in EM 1110-2-1601 (OCE 1970). Most failures of concrete and grouted riprap channels and bank structures appear to be associated with one or more of the following:

a. Failure to provide adequate drains to relieve hydrostatic pressures.

b. Undermining of the toe due to inadequate design.

c. Erosion at the upstream and downstream margins of the structures.

Clearly, these areas should be given special attention during the design phase.

207. Concrete channels are usually poured in place--a time-consuming process that requires extra excavation to accommodate forms. Precast panels were used on Placer Creek, Idaho (USAED, Seattle 1980), to speed construction of channel walls and cut costs. The stream was diverted through a 4-ft-diam pipe during construction of the 3700-ft-long, 10-ft-deep channel (Figure 30). Using precast panels allowed the channel to be completed 3 months ahead of schedule. Precasting may also allow for better quality control, which is an important consideration for special aesthetic treatments.

208. Cellular concrete blocks. Of the many manufactured materials tested in the Section 32 Program (OCE 1981b), only cellular concrete blocks had been used on any of the flood control channels surveyed. Cellular concrete blocks are made of precast unreinforced concrete blocks and have open rectangular holes (Figure 31). They are 4.5-in.-thick, 24- by 16-in. rectangles that weigh approximately 90 lb. Cellular concrete can be used in lieu of large riprap and is comparable to riprap in cost and degree of protection. Compared to large riprap, cellular concrete is lighter and can be hand placed, is more resistant to freeze-thaw breakdown, and is less prone to ice gouging. Once grass is well established, cellular concrete is more aesthetic and easier to maintain. Many of the remaining bank protection measures listed in Table 4 were developed for severe bank erosion problems that usual methods could not control. Many of the streams involved were braided streams, large

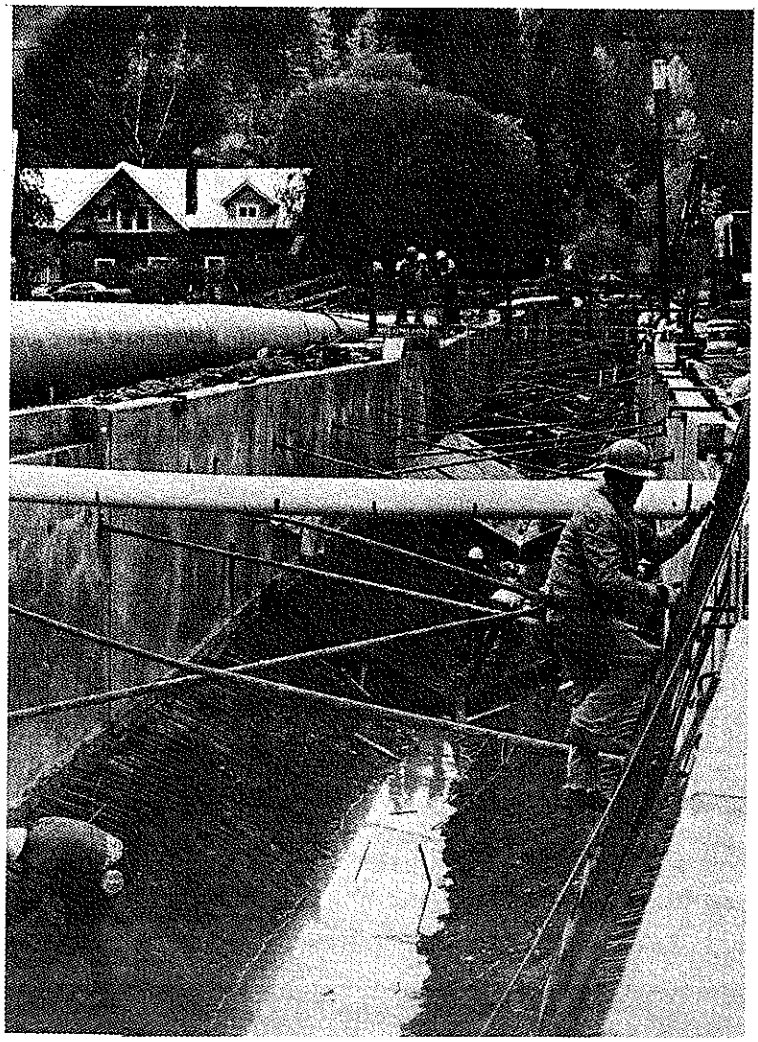
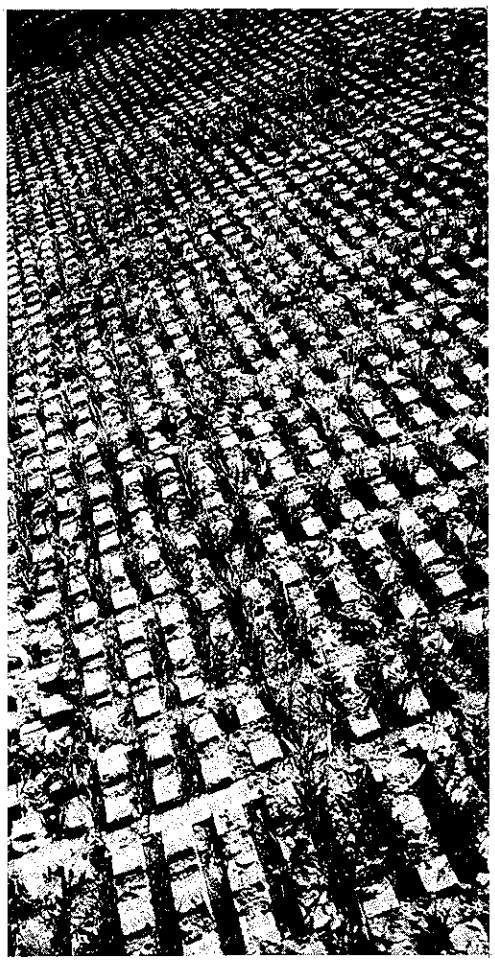
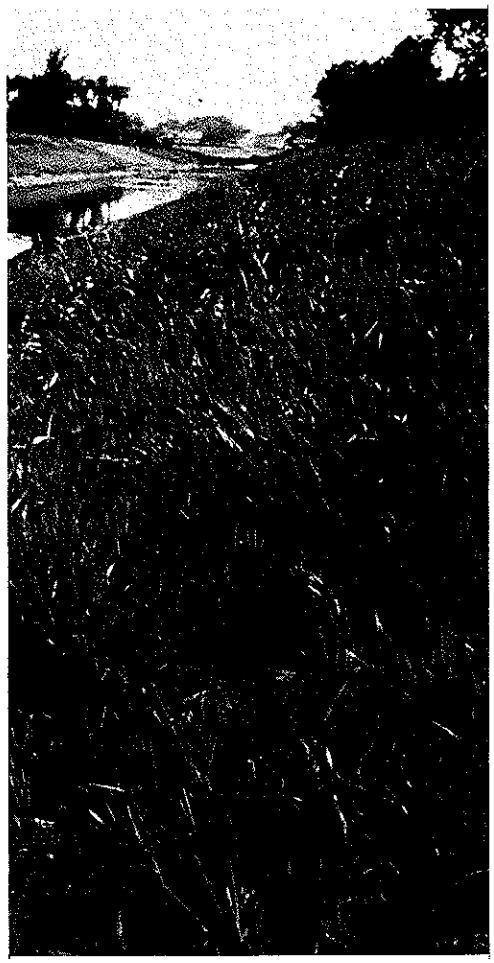


Figure 30. Channel construction with precast concrete panels, Placer Creek, Idaho. Precast panels reduced excavation requirements and construction time. Dry construction was made possible by working during the low-water period and diverting flows through a 4-ft-diam pipe. (photo by Seattle District)



a. This photo was taken shortly after the cellular concrete had been installed



b. The concrete is not visible in this photograph, taken later when the grass was 6 to 8 in. tall

Figure 31. Cellular concrete bank protection, Scajaquada Creek, New York (photos by Buffalo District)

navigable streams, or unstable streams with rapidly migrating headcuts.

209. Design considerations. Proper design and construction of cellular concrete structures is important because failures are often progressive. Linder (1982) reviews important design considerations for cellular concrete. Slopes must be designed to support the additional weight of the concrete, and fine-grained cohesive soils may require a filter layer. Manufacturers' literature states that cellular concrete can be used on slopes as steep as 1V:1H. Revetment edges must be protected from undercutting. Cellular concrete blocks are especially vulnerable to erosion at the toe and at the top of the structure. It is essential to control overbank drainage and to provide toe protection by extending the blocks below the channel invert or by using riprap.

210. Maintenance of bank protection. In addition to the CE guidance for general inspection and maintenance programs (OCE 1967b, 1973), supplementary guidelines for bank protection can be found in Elliott (1982). Because bank failure is often progressive, regular inspection and maintenance for all bank protection is essential to prevent major damage. Periodic inspection not only provides timely information about maintenance needs, but also may provide information about the cause of failure, which could lead to design modifications for future work.

211. According to Elliott, "The first two years and the first major flood are the critical periods in the life of bank protection works," and inspections should be intensified during this time. Critical items that should be given special attention during inspection include the following, listed in order of general importance:

a. Toe deepening.

b. Upstream and downstream bank connections.

c. Destroyed or deteriorated components.

d. Bare areas resulting from differential settlement or hydrologic displacement.

e. Inadequate interior drainage for monolithic structures.

f. Evidence of inadequate overbank drainage.

Elliott stresses the need for a detailed monitoring program that includes repetitive site photography, periodic resurvey of cross sections

with common stationing, and collection of hydraulic and hydrologic data. Such data are essential to program evaluation and feedback to design.

Grade control structures

212. Evaluation. Grade control structures are used to prevent channel degradation and headcuts on streams with radically steepened gradients or lowered beds. Grade control structures include sills, weirs, chutes and flumes, and drop structures. Sills are normally placed at, or slightly above, bed elevation to control scour (Figure 15a). Weirs are used to control water surface elevation (and thereby control the energy gradient). Drop structures provide for abrupt changes in bed elevation, whereas chutes and flumes provide more gradual transition.

213. Sills, weirs, and chutes and flumes are classed as bed stabilizers, and they are often designed as multipurpose features. Sills can be designed to function as riffle areas (Figure 32), weirs can serve as water level control structures (Figure 16), and fish ladders and boat passages can be designed into chutes and flumes. Drop structures, on the other hand, are single-purpose features.

214. Construction and maintenance costs for grade control structures vary with the type and size of structure and with the construction materials used. Small drop structures can be built cheaply from

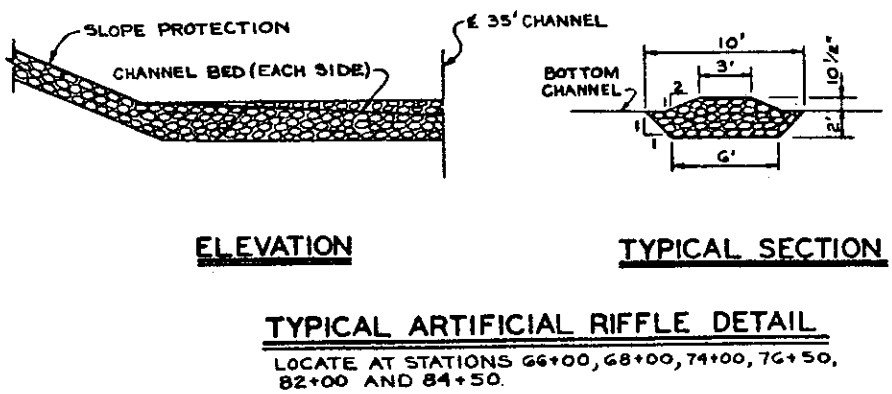


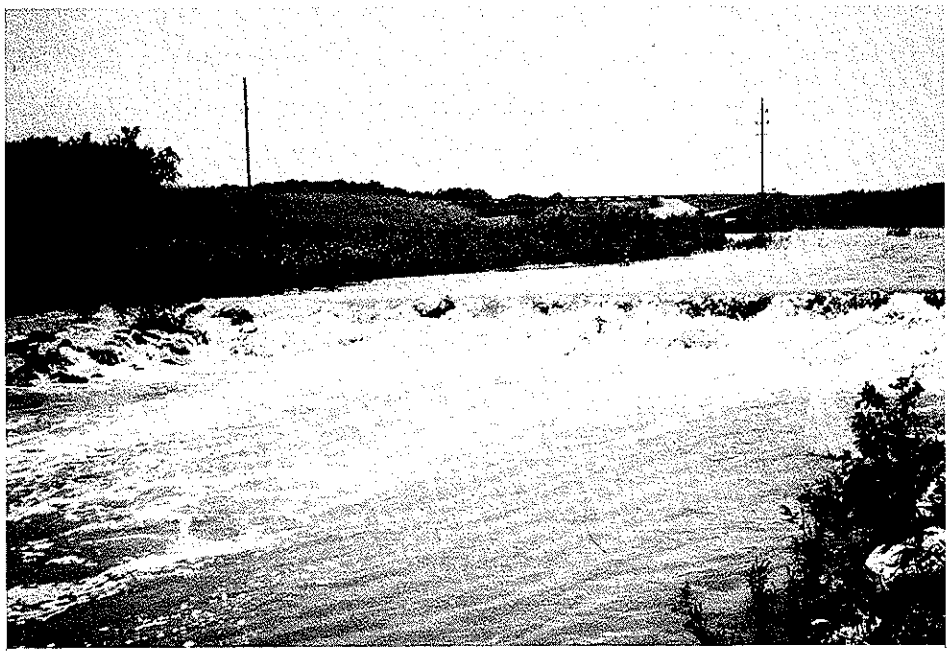
Figure 32. Rock sill used as riffle area and grade control, Log Pond diversion, Ohio. A typical cross section is shown above and a constructed riffle is shown in Figure 15c. (USAED, Huntington 1975)

materials such as corrugated pipe, logs, or sheet piling. Large concrete structures, on the other hand, can cost more than a million dollars (Figure 33). Required maintenance for grade control structures involves periodic checks of the structures, removal of debris and sediment from pools formed behind weirs, removal of brush from riprapped banks, repair of eroded bed or banks below the structure, and repair to the structure itself when damaged or flanked. Although complete failure of grade control structures is rare, partial failures do occur, especially in gabion or riprap structures. Rupture of gabion cages has begun to occur on some of the Souris River structures (Figure 33b). A sheet pile core has allowed these structures to remain functional, although some minor bank erosion is evident immediately downstream. Special designs can sometimes cause special maintenance problems. Narrow-crested concrete weirs located in urban areas are sometimes designed with vertical slots for aesthetic reasons. Most urban streams contain debris (such as automobile tires) that becomes trapped in these slots and has to be removed.

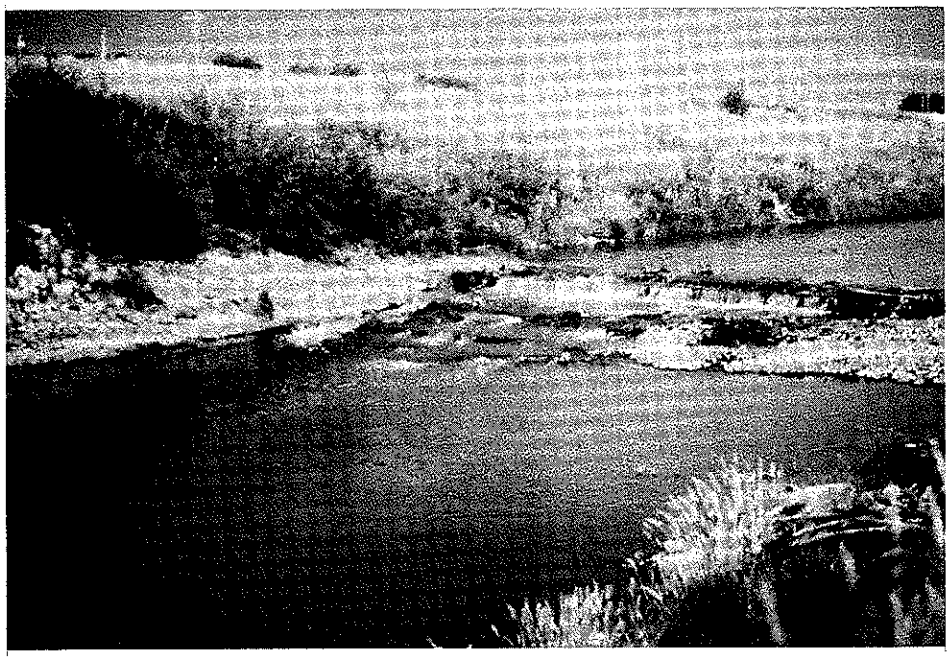
215. Design. The great variety of types of grade control structures and wide choice of construction materials precludes any extensive treatment of design in this report. Hines (1982) discusses causes of streambed degradation in detail and reviews the theory of grade control structures and design fundamentals. Specific applications and detailed design guidance for different structure types can be found in a number of CE and SCS documents (OCE 1968, 1969, 1970, 1972, 1974a, 1978b; SCS 1968, 1977) and published papers (Brevard 1975, Ferrell and Barr 1963, Heede 1966, Linder 1963). Care should be taken to provide for fish passage on streams, where needed, when weirs or drop structures are used. Physical modeling of grade control structures can resolve many problems of design, including durability, hydraulic effects on flood flows, and performance of fish passage facilities at various discharges (Little and Murphey 1981, 1982; Saunders and Grace 1981).

Sediment and debris basins

216. Evaluation. Debris basins are constructed to trap sediment and debris that could otherwise damage or clog flood channels, impair

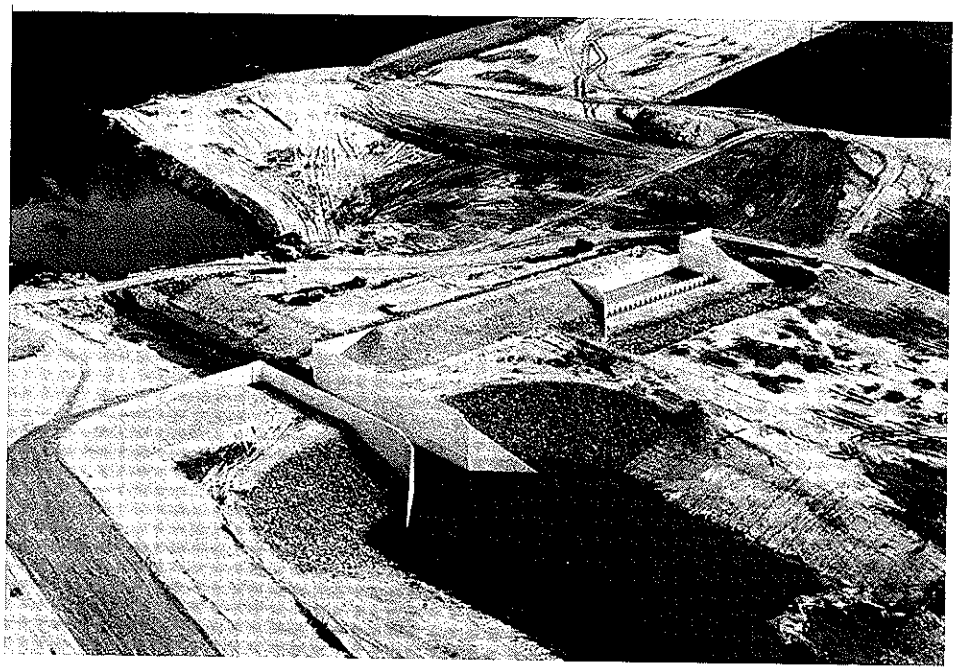


a. Sheet pile weirs, Little Blue River, Kansas City, Missouri



b. Gabion weirs, Souris River, Minot, North Dakota

Figure 33. Examples of grade control structures used on CE flood flood control channel projects. The two-stage grade control structure shown in c. was constructed by the SCS to control headcut erosion. Costs range from as low as $30,000-$40,000 for sheet pile structures (1972 dollars) to as high as $1.5 million (1979 dollars) for a two-stage concrete structure. (Continued)



c. Concrete drop structures, Middle Fork Tillatoba Creek, Mississippi (photo courtesy of SCS)

Figure 33. (Concluded)

aesthetics, and degrade aquatic resources. Debris basins are required mostly on high gradient streams. Sediment basins are used to reduce sediment load and turbidity that can adversely affect fish and other aquatic organisms, water quality, and project aesthetics. Sediment traps are almost essential to the success of any flood control channel project incorporating instream environmental features if the stream carries appreciable coarse sediment load.

217. Numerous examples exist of flood control channels where sediments have obscured low flow channels, fish habitat structures, and pool and riffle grades. On Tenmile Creek at East Marianna, Pennsylvania (USAED, Pittsburgh 1976) a low flow channel was excavated primarily in rock. The upper reach was located immediately below an existing water-supply dam that served as an efficient sediment trap. The low flow channel in this reach contains no sediment and is functioning as designed (Figure 34). In the lower reach, the low flow channel and a gabion riffle were completely inundated within 5 years by an influx of sediment from a tributary stream (Figure 35). A sediment trap on the tributary stream could have prolonged (or might restore) the useful life of the low flow channel and riffle.

218. Costs. Construction costs for sediment traps are limited to the extra excavation needed for the desired trap efficiency. Debris basins are more expensive to build. Debris basins are typically located in upstream areas where headwater streams emerge from steep mountain valleys. They are larger than sediment traps and may have several hundred acre-feet of storage. Because of their required capacity, debris basins are constructed by damming the stream, with or without accompanying excavation. Costs depend on the combined costs of the embankment, excavation, drainage facilities, and spillway.

219. Maintenance. Sediment traps must be cleaned out periodically to maintain their trap efficiency. The frequency of sediment removal depends on trap size, sediment load, and magnitude and frequency of flooding. CE maintenance policies require inspection at intervals not to exceed 90 days and cleaning of debris basins, check dams, and related structures as necessary. Accumulated sediment should be removed

Figure 34. Low flow channel, Tenmile Creek, East Marianna, Pennsylvania. An upstream dam has enabled the low flow channel in this upper reach to remain sediment free.

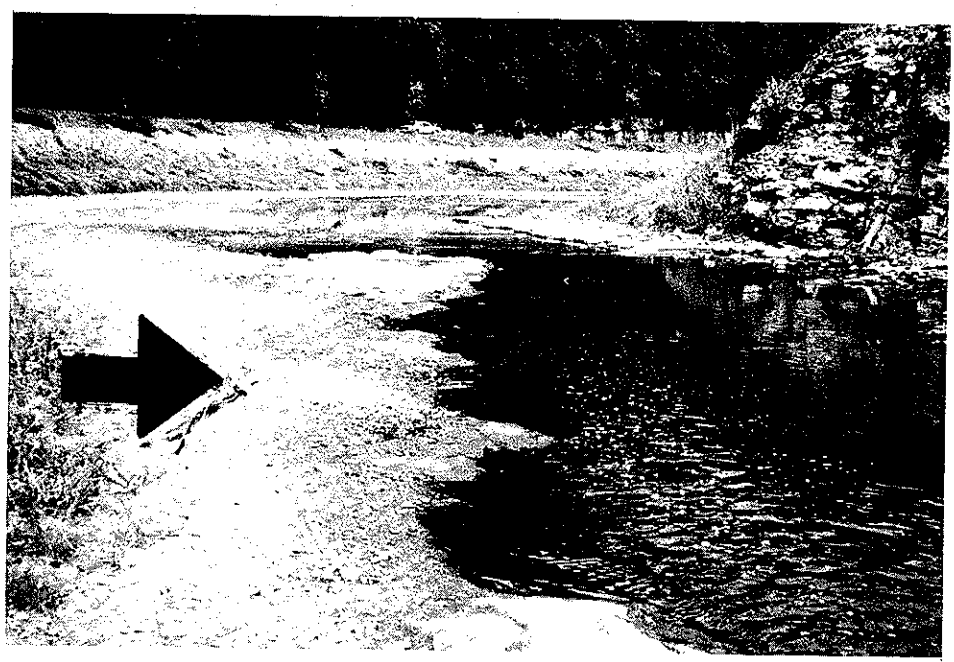


Figure 35. Buried riffle area (arrow), Tenmile Creek. Sediment delivered to Tenmile Creek by a tributary has completely buried a gabion riffle.

from small basins when capacity has been reduced significantly (normally 25-50 percent). Large debris basins may be designed to require little or no debris removal over the life of the project. Maintenance costs may be minimized by designing sediment traps for easy access by large equipment. If the sediment is of commercial quality, its value can further offset maintenance costs.

220. Design. Because of the cost of sediment removal, both access and ease of maintenance should be given priority during design. Technical guidance for the design and maintenance of sediment and debris basins can be found in EM 1110-2-1601 (OCE 1970); Dodge 1948; Moore, Wood, and Renfro 1960; Pemberton and Lara 1971; and Tatum 1963.

Sediment control during construction

221. Streams with good fisheries, water quality, or aesthetics, or streams that could otherwise be damaged by sediment deposition, should be protected from sedimentation during construction. The most common methods of sediment control include dry construction, timing of construction to avoid environmentally sensitive seasons, temporary sediment basins, and immediate revegetation of disturbed areas. Dry construction can be achieved by confining work to the dry season, if one exists, or by diverting low flows through pipes (Figure 30) or temporary bypass channels, or by using barriers to restrict flow to one part of the channel while working on the other (Figure 36). Costs of water diversion during construction vary immensely, as shown in Table 7. Much of the cost variability is related to hydrologic and geomorphic conditions. As the New Gila River, Ariz., project cost indicates, costs are minimal for water control in deserts (Table 7). Instream sediment traps are being used increasingly to reduce sediment damage in areas downstream of channel excavation sites. Sediment barriers constructed of brush, fabric, or hay bales can greatly reduce sediment input during construction from excavated material disposal sites and areas of intensive construction, such as bridge and utility crossings. Disturbed areas can be covered with mulches, fabric netting, mats, or grass to provide temporary cover until permanent measures are in place. General guidance for

Figure 36. Flow diversion for dry construction, San Antonio River. Concrete barriers confine low flows to one side of the channel, allowing dry construction techniques to be employed. Note stone pilasters on previously constructed channel wall.

sediment control during construction can be found in the references cited in paragraph 177.

Features to Improve Instream Habitat and Water Quality

222. Unaltered natural streams are normally rich in habitat complexity with numerous pools and riffles, overhanging vegetation, undercut banks, snags, log and debris jams, and boulders. Channel modification produces more uniform depths and velocities, both at a section and through a reach. Structural elements such as logs, stumps, and boulders are removed, banks are shaped and stabilized, and loss of riparian vegetation reduces shade and organic input. Loss of spawning areas due to gravel removal or sedimentation is a problem on some streams. On others,

spawning runs and fish movements may be blocked by grade control structures or insufficient water depth. Although modified streams will slowly revert to more natural characteristics if not subjected to further disturbance, recovery to original habitat diversity is usually slow and some streams never fully recover (Arner et al. 1976, Griswold et al. 1978, Huish and Pardue 1978). Regular maintenance of modified streams can postpone indefinitely the reversion toward a more natural state.

223. Loss of shade and organic input and loss or reduction in habitat complexity that are associated with channel modifications can be as disastrous to an aquatic community as declining water quality. The occurrence and distribution of fish in streams are influenced heavily by temperature and the availability of suitable shelter from current and predators (Hynes 1970). Gorman and Karr (1978) observed a strong positive correlation between the species diversity of stream fish populations and a habitat diversity index computed from depth, bottom material size, and current velocity. Loss of habitat diversity is also associated with reduced populations and average size of individuals (Griswold et al. 1978, Headrick 1976).

224. Loss of habitat diversity can be partially compensated for and recovery accelerated on some modified streams by using pool and riffle designs or by installing simple structures to increase the variety and amount of suitable fish habitat. Water level control structures have been used to increase pool habitat in modified channels and to raise water levels in floodway and bypass channels so that enough water is diverted through the natural channel to maintain permanent flow conditions and associated habitat diversity. Special gravel-lined sections can be designed to provide substrate for benthic macroinvertebrates or to replace natural spawning areas destroyed during flood control channel construction. Spawning beds damaged by sedimentation from construction activities can sometimes be rejuvenated by cleaning. Fishways can be constructed to allow fish passage around obstacles or through shallow sections.

Habitat structures

225. Conservation agencies have used habitat structures to improve

trout habitat in small coldwater streams for several decades. Use of structures to accelerate biological recovery of enlarged or relocated streams is more recent and less widespread. Several investigators have reported that habitat structures placed in modified channels produced improved conditions, but that the overall stream habitat was still inferior to unaltered conditions (Barton and Winger 1973, Barton et al. 1971, Edwards 1977, Elser 1968, Griswold et al. 1978, Winger et al. 1976).

226. The use of habitat structures in modified channels, particularly flood control channels, presents several problems not encountered in habitat improvement of unaltered streams. Structures placed in modified channels are generally expected to withstand higher velocities, yet cause only minimal effects on channel flow capacity and sediment movement. The consequences of habitat structure failure in modified channels may be more serious, and constructing agencies frequently have limited authority for long-term postconstruction monitoring, adjustment, and maintenance. Structures placed in unaltered streams are intended to increase fish carrying capacity, but structures placed in modified channels are generally for the restoration of an extremely disturbed habitat. Despite these problems, experiences with habitat structures in modified channels have proven successful enough to warrant their continued use in many projects. Information about habitat structures designed for flood control channels surveyed for this report is summarized in Table 8. Project descriptions and summaries of the experience with habitat structures on nine additional modified channels are given in Tables 9 and 10 (Shields 1983).

227. A multitude of designs, materials, and construction methods have been used for habitat structures, but most designs may be placed into one of four categories--sills, deflectors, random rocks, or cover--that have specialized meanings as defined in this section. Each of these types is described and evaluated for its potential for successfully modifying fish habitat in flood control channels. Information about cost, durability, and maintenance is given when available.

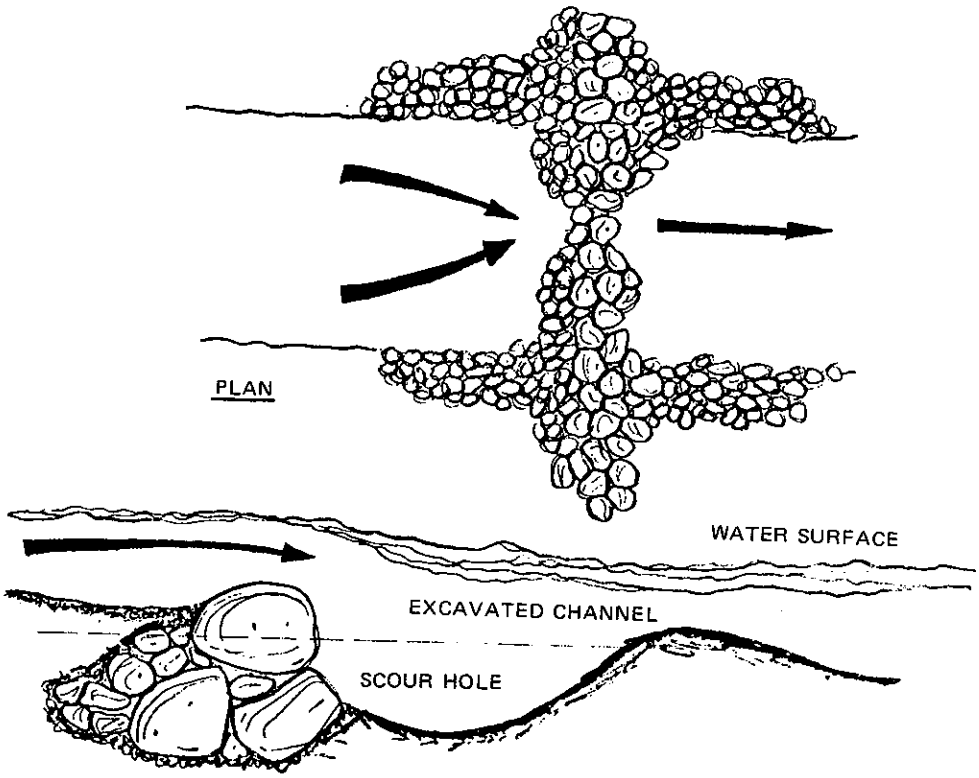
Design of sills

228. Description. Sills are low structures that extend across the entire channel width. They are often designed with a gap or notch and typically have a minimal backwater effect (Figure 37). Sills are designed to produce upstream pools, downstream scour holes, or both. Coarse material removed from the scour hole may deposit a short distance downstream and form a bar or riffle area. Broad-crested sills that are submerged most of the time may themselves act as riffle areas. They may be especially effective if constructed from rock or gabions. Sills tend to be better suited for high gradient streams than deflectors are. High gradient streams generally have little pool habitat. Sills create pools, trap organic debris, and help dissipate excess energy by the fall they provide.

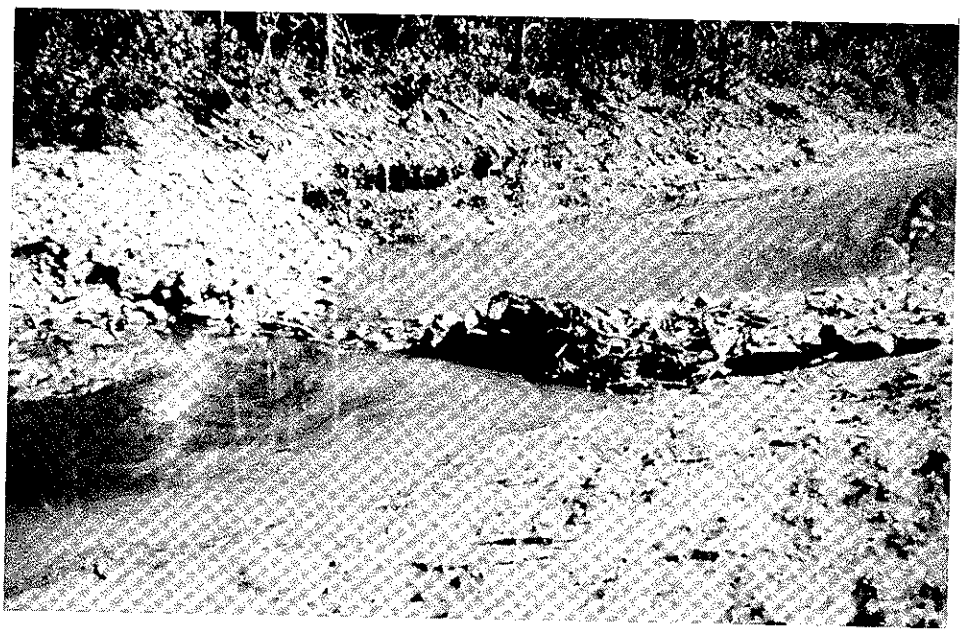
229. Sills may be constructed from logs, rocks, gabions, concrete, sheet metal, or combinations of these materials. Sills may be constructed with sloping crests, central gaps, or notches to concentrate low flow and maintain deep scour holes. This is an important consideration on streams subject to extreme flow variations, as deep pools may be the only fish habitat during low flow periods. Sills constructed 12 in. or more above the channel invert are usually adequate for scouring pools (Forest Service 1969).

230. Problems. Problems encountered with sills include flanking and undermining of structures, structural damage or failure caused by floods or ice, and use of high structures that are susceptible to failure, impede flood flows, and impede fish movements.

a. Flanking can be prevented by properly keying-in sills to the streambed and banks, by sloping sills away from both banks, and by locating them in straight reaches. A minimum key trench depth of twice the height of the sill crest above the invert is suggested (Barton and Cron 1979). Structures are prone to failure by undercutting when the scour hole or plunge pool becomes so deep that the streambed underneath the structure collapses or washes into the pool. This problem can be alleviated by restricting sill height, using a sufficiently deep key trench, and stabilizing the streambed below the structure.



a. Drawing showing how notches help to concentrate low flows and create downstream scour holes (after Barton and Cron 1979)



b. Photo of a constructed sill

Figure 37. Notched sill for habitat development. Sills are low structures that create upstream pools.

b. The larger a stream is, the more likely a sill constructed across it will fail. Despite Gee's (1952) recommendation that log dams be limited to streams with maximum discharges less than 100 cfs and the Forest Service (1969) recommendation that cross channel structures of any kind not be used on streams with discharges greater than 100 cfs or wider than 20 ft, low sills constructed of large rock, concrete, and gabions have been used with at least partial success on channels with capacities as high as 10,000 cfs, mean daily flows of 500 cfs, and channel widths of 120 ft (Edwards 1977, Griswold et al. 1978, Keown 1981, May 1972). However, the life span of structures on large streams may be considerably less than those on small streams. Structures used on several of the projects listed in Tables 9 and 10 were designed to fail before the design flood was reached. Ice damage to structures can be a problem in cold climates on streams large enough to develop ice jams, especially if structures are not submerged at breakup (Barton 1980, Carline and Kloslewski 1981). However, even failed structures may provide some habitat.

c. High structures can reduce flow efficiency in flood channels to unacceptable levels and are more likely to catch debris and be washed out during floods. On low gradient channels, backwater effects from high sills can drown out upstream riffles, especially if the sills are placed in the mid to upper portions of riffle areas. As a rule-of-thumb, pools should not be longer than five channel widths.

Design of deflectors

231. Deflectors are habitat structures that protrude from one bank but do not extend entirely across a channel (Figures 38 and 39). The primary use of deflectors is to scour pools by constricting the channel and accelerating the flow. Deflectors should be located far enough downstream from riffle areas and be low enough to avoid backwater effects that would drown out the riffle area. Material washed out of scour holes is usually deposited a short distance downstream to form a bar or riffle area. These areas of deposition are often composed of clean gravels that provide excellent habitat for benthic macroinvertebrates and spawning habitat for certain fish species.

232. Deflectors may be angled upstream, downstream, or perpendicular to the bank. Deflectors are often triangular in shape and slope toward the channel to provide protection for the near bank. In some

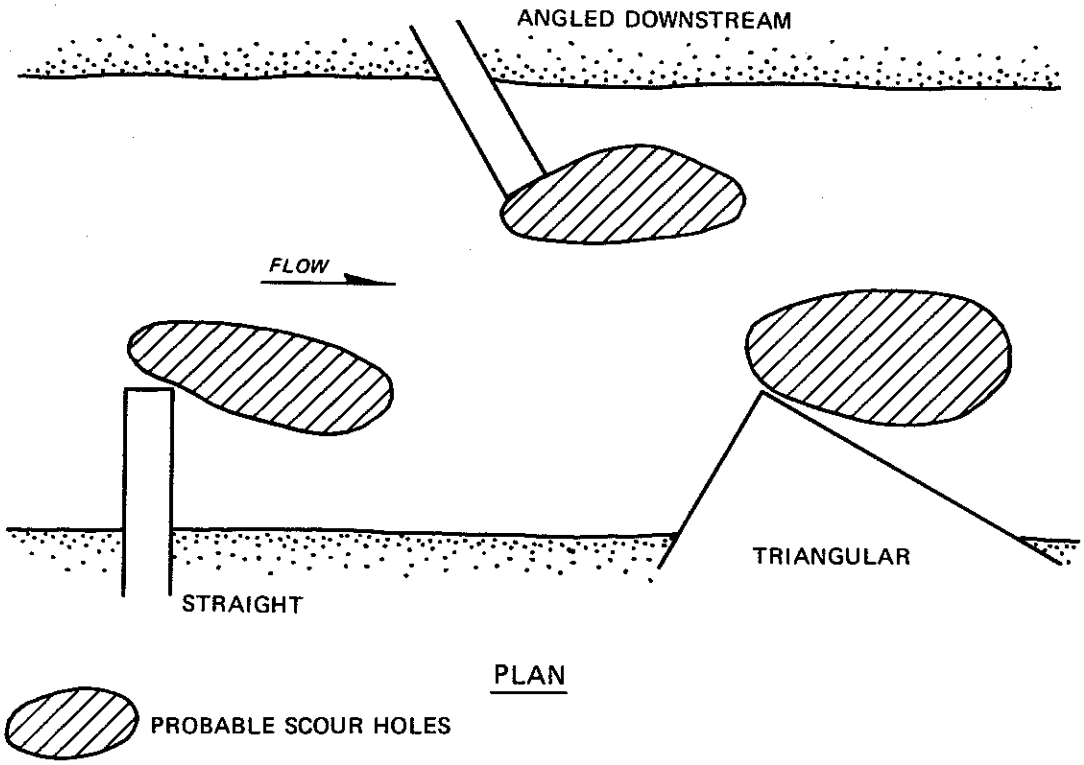


Figure 38. Three types of deflector-type habitat structures. Deflectors are intended to scour pools by restricting flows. Typical layouts include triangular designs and rectangular structures perpendicular to the bank or angled downstream. (Shields 1983) (courtesy of American Society of Civil Engineers)

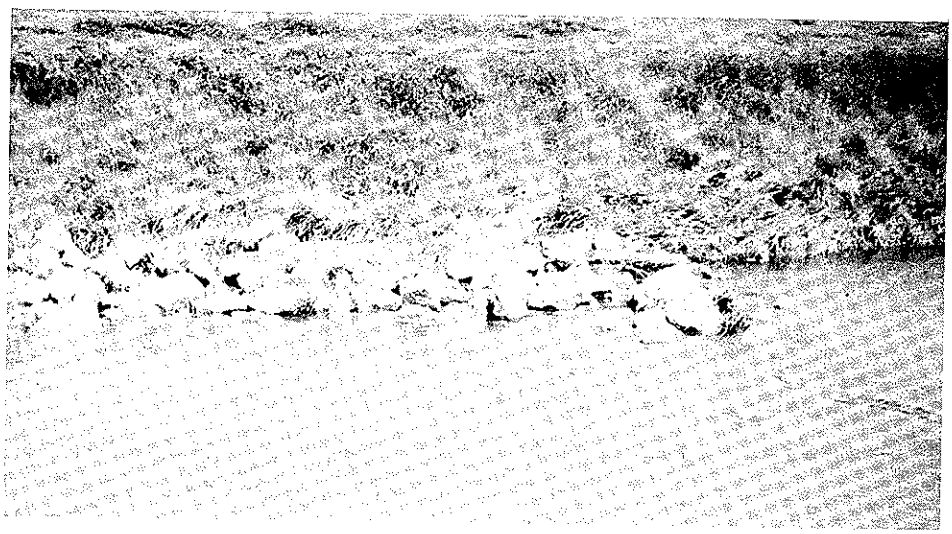


Figure 39. Submerged deflector on Rock Creek, Indiana

cases, banks opposite deflectors may require protection. Deflectors in series are sometimes installed on alternate banks to produce a meandering thalweg and associated physical diversity. Opposing paired deflectors are usually referred to in the literature as a "double-wing deflector," but for purposes of consistency, that type of structure is referred to as a sill in this report. Deflectors should be keyed into the bed and banks in the same manner as sills. They may be constructed of the same variety of materials as sills, although rock and rock-filled log crib structures are most common.

Design of random rock structures

233. Random rocks are large boulders, gabions, or concrete objects placed in a channel well away from either bank to produce downstream scour holes and zones of reduced velocity (Figure 40). In steep channels, rocks may be placed in intermittent clusters to create cascades and "stair-step" pools (Barton and Cron 1979). Research has indicated that boulder cover can increase fish counts in an almost linear fashion, up to some saturation point (Kanaly 1975). Barton and Cron (1979) suggest using one large rock per 300 sq ft of channel. Pattern of boulder placement has little effect on fish numbers, although some researchers recommend placing rocks in groups of two or three (Barton and Cron 1979, Kanaly 1975).

234. Generally, large rocks are effective only where velocities at medium flow exceed 2 or 3 ft/sec. On the other hand, unless channel beds are reasonably stable in floods, the rock may be undermined and buried in the bed. For this reason, random rocks are not usually successful on alluvial streams with beds of sand or fine gravel. Habitat rocks need to be large enough to resist displacement during flood events. According to Barton and Cron (1979), rocks 2 ft in diameter and weighing about 1000 lb will resist current velocities up to 10 ft/sec, and a 4-ft-diam rock will be stable up to a velocity of 13 ft/sec. Rocks used for habitat cover should be durable enough to withstand weathering and abrasion. Dense igneous and metamorphic rocks are preferable to sedimentary rocks such as sandstones and shales.

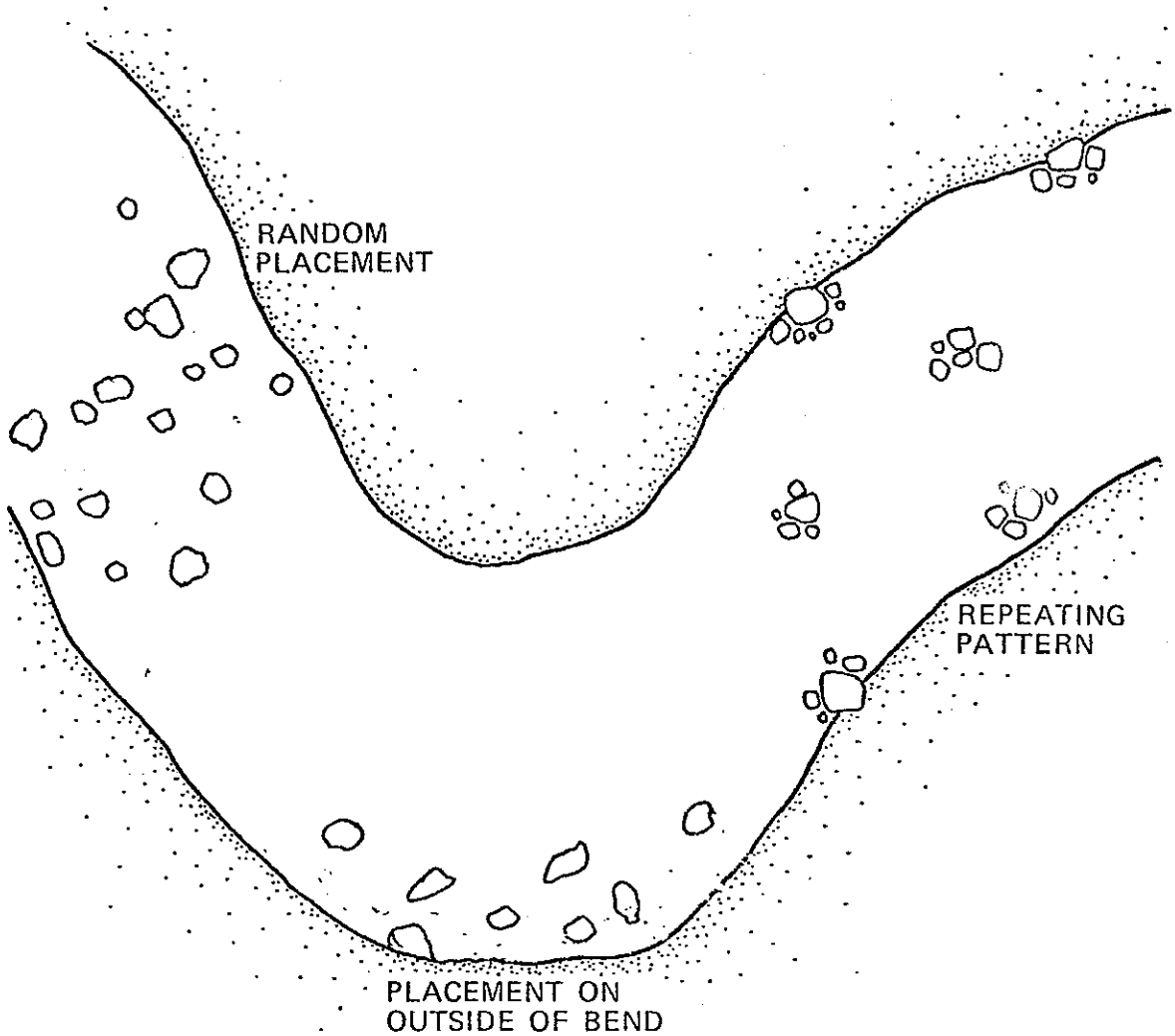


Figure 40. Boulders for habitat development. Boulders may be placed randomly or in clusters of two or three. (Shields 1983) (courtesy of American Society of Civil Engineers)

Design of habitat cover devices

235. Cover devices differ from the three types of structures already discussed in that they generally do not affect flow patterns. Cover devices include floating rafts anchored to the bank, ledges supported by pilings (Figure 41), trees or brush mats anchored to the bank and allowed to trail in the current, logs and vertically separated half-logs aligned with the flow and anchored to the bottom with steel rods, and large boulders or gabions placed in deep pools. Because cover

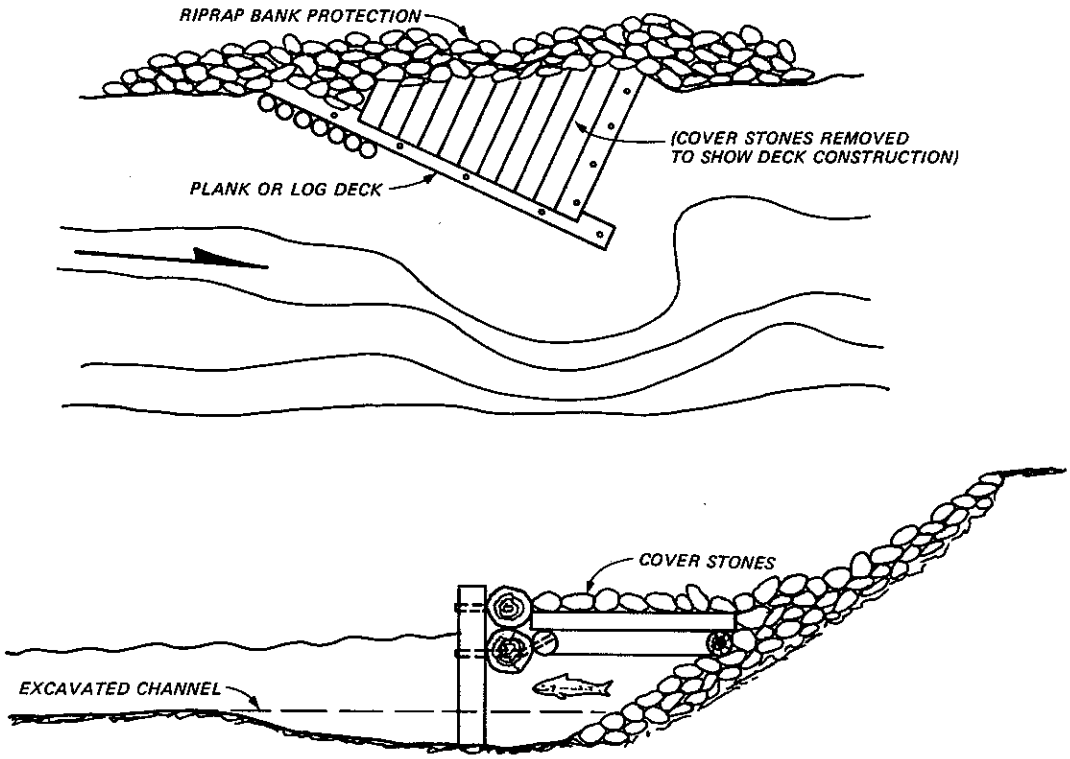


Figure 41. Fixed cover-type habitat structure. In addition to the ledge shown here, fixed cover designs may include anchored trees and brush, half-logs, or gabion structures. (after Barton and Cron 1979)

devices have little or no effect on flow patterns, there are fewer limitations on their use and placement. Habitat cover devices are described in Handbook 2609 11 (Forest Service 1969).

Experience with habitat
structures in modified channels

236. Documented experience with habitat structures in modified channels is severely limited at present. Table 9 provides project data for nine cases where habitat structures were installed in stream channels that were enlarged or straightened. Table 10 gives additional details regarding the structures and an evaluation of their biological effects. Shields (1982) has summarized additional information about most of these projects.

237. In most cases, design procedures were unsophisticated. Conservation agencies usually suggested the use of habitat structures and

the general type and frequency of structures. Construction agencies then formulated structural designs based largely on professional judgment. The observed biological effects for a given structure were dependent on the other components of aquatic habitat--water quality, hydrology, biotic factors, etc.--as well as the design of the structure itself. In the cases shown, the most effective habitat structures created a diversity of velocities, depths, substrates, and illumination conditions that mimicked the natural stream's pool-riffle sequence.

238. Application of the results of the case studies presented in Tables 9 and 10 to the design of flood control channels is limited by a number of factors. For example, there were no long-reach flood control channel modifications designed to convey a low-frequency event. The Fisher River Project was designed to handle the 50-year event, but it consisted of a series of short bypass channels built to cut off bends and provide space in the valley for a railroad embankment (Keown 1981). The SCS projects included did cover long reaches of stream, but the channels were enlarged only enough to speed runoff from relatively high frequency events and provide agricultural flood relief.

239. The most successful habitat structure projects have been on short, realigned (but not greatly enlarged) reaches of coldwater streams. The more complex ecology of warmwater streams, coupled with their often extremely movable beds, presents difficulties for habitat improvement. Furthermore, many CE channel projects are located in the southeastern and midwestern states where these environments are common. A limited amount of information is available regarding the use of habitat structures in unaltered warmwater streams, and such structures were found to be effective in at least two cases (Ebert and Knight 1981, Fajan 1981). However, Fajan (1981) notes problems in using habitat structures in warmwater streams due to economics, channel instability, and large fluctuations in discharge.

Design process*

240. Habitat structure design encompasses several steps, each of

* This section follows recommendations made by Shields (1982) closely. However, some differences exist in the number and order of the steps.

which is important to project success. If habitat improvements are improperly designed, they may fail, be ineffective, increase channel maintenance costs, and impede flood flows. The design process is iterative and involves several steps: determining the feasibility of success; determining habitat deficiencies; selecting the structures; designing layouts; sizing the structures; investigating hydraulic effects and effects on sediment transport; and selecting materials and constructing. Considerable recycling among steps is usually necessary.

241. Determine feasibility. The feasibility of employing habitat structures should be thoroughly evaluated prior to any detailed design. Feasibility will depend on such factors as channel size and slope, flow hydraulics, channel characteristics, water quality and quantity, and stability of the modified channel and its watershed.

a. Channel size and slope. Habitat structures should be avoided altogether on very large or very steep streams. Calhoun (1966) cited several studies that illustrate the discouraging results of the use of habitat structures in some California streams.

b. Flow hydraulics. Flow velocities during normal flow conditions should be sufficient to develop scour holes, but low enough during high flows so as not to wash structures away.

c. Channel characteristics. Channels with hardpan or rock a short distance below the surface are not susceptible to improvement by any device that must scour the channel to be effective. Structures built on streams with low banks are more likely to be susceptible to flanking than those on streams with high banks.

d. Water quality and quantity. Water quality and quantity must be sufficient for the fish species of interest and related organisms.

e. Stability. Habitat structures on unstable streams are easily flanked or undermined by erosion, and sediment may fill pools, blanket rocky substrates and spawning beds, or bury the structures. Similar problems are encountered on streams draining watersheds with excessive runoff and sediment yield. Excessive turbidity following light rainfall, evidence of widespread bank erosion, silt deposition in gravel bed streams, and a paucity of macroinvertebrates and game fish may be indicators of stream or watershed instability.

242. Determine habitat deficiencies. The projected characteristics of the modified channel should be examined in light of the habitat requirements for all life stages of the desired aquatic community. Quantitative methods such as the Instream Flow Methodology (Stalnaker 1980, Stalnaker and Arnette 1976) may be used in certain limited settings to determine desired depths, velocities, and substrates. Habitat indices may be helpful if used judiciously (Binns and Eiserman 1979). Alternatively, the habitat structure plan can be patterned after physical characteristics such as pools, riffles, cover, shade, and substrate of unaltered reaches or of similar unaltered nearby streams. The help of State fishery biologists should be solicited during this phase of the work.

243. Select structure types. Criteria for structure type selection include physical effects and habitat requirements, stream hydrology and hydraulics, bed material, economics and availability of material, and aesthetics.

a. Physical effects and habitat requirements. Tarzwell (1932, 1938) recommended sills for western streams and deflectors for Michigan streams. The steeper western streams need sills to dissipate excess energy, form pools, and stabilize the bed. Deflectors have worked well in Michigan streams, providing pools and shelter, encouraging plant beds, and flushing gravel deposits clean of silt and organic debris.

b. Stream hydrology and hydraulics. According to Nelson, Horak, and Olson (1978), sills are more failure prone than deflectors in channels with extreme flow fluctuations. Deflectors and random rocks are minimally effective in low velocity environments (2-3 ft/sec) since they produce habitat diversity by creating local zones of scour and deposition. However, a notched sill can concentrate normal and low flows to scour a downstream hole even in low gradient, low velocity channels.

c. Bed material. Most types of structures are undermined and buried when placed in channels with fine, noncohesive bed material. Random rocks are particularly susceptible to this type of failure since they are usually not keyed into bed and banks. Sills made of sheet piling and well protected by riprap against undermining and flanking have been used in a few channels with highly erodible beds (Winger et al. 1976).

d. Economics. In situations where several practicable alternatives exist, the final choice may depend heavily upon economics and local availability of construction materials. This is one reason for the popularity of rock-filled log crib structures.

e. Aesthetics. So long as other conditions permit their use, structures built of natural materials and designed to blend with the natural stream environment are aesthetically preferable to concrete or sheet metal structures.

244. Design layout. The location of each habitat structure selected should be determined after the rest of the project has been designed to avoid conflicts with crossings, grade control structures, etc. Structures may be placed at irregular intervals and within sight of prominent viewing places such as bridges and overlooks to add visual interest. Care should be taken to place structures where they will be in the water during low flows. In channels without uniform grades, sills and deflectors should be located so that they will not drown out desirable riffle areas or threaten other desirable habitat. Deflectors normally should be placed in the lower portion of riffle areas whereas sills should be placed in straight reaches near the upper portions of riffle areas where the pool-riffle transition occurs. Structures should be spaced to avoid large areas of uniform conditions. Winger et al. (1976) suggest a minimum spacing of three pool lengths between structures that create pools. White and Byrnildson (1967) recommend a maximum pool length of five stream widths.

245. Rocks may be placed in straight reaches or in meanders. Care should be taken to place large rocks so that they will not produce flow patterns that cause bank erosion problems. Rocks placed on bends should be on the outside in the zone of high velocity (Barton 1980). Barton and Cron (1979) suggest a density of one rock per 300 sq ft, whereas Kanaly (1975) reported that a density of one 7-ft-diam boulder per 750 sq ft provided habitat superior to a density of one per 500 sq ft. Kanaly (1975) found that boulder pattern had no effect on fish density, but Barton (1980) and Pistano and Wiley (1980) recommended placing rocks in groups of two or three.

246. Size structure. Structures should be sized to produce the desired aquatic habitat at normal and low flows with minimal effect on maximum channel flow capacity. Structures should be low enough that their effects on the water surface profile will be almost completely drowned out at near-capacity discharges.

a. Sills. For sills designed to pond water (check dams), the height of the lowest point is usually determined by one of the following criteria: minimum pool depth needed for low water habitat; maximum desired pool length; or elevation of upstream rapids or riffles that should be preserved (Barton and Cron 1979, Cooper and Wesche 1976). Sills constructed too high or too close together may create a series of pools with no intervening riffles or shallows. For sills designed to scour pools, the notch height should be slightly higher than the upstream channel invert. Sills should be designed with the lowest point at the center. Maximum sill height above the channel invert should be no more than one-third the bankfull water depth or 18 in., whichever is less (Barton and Cron 1979, White and Byrnildson 1967).

b. Deflectors. Deflector size may be based on the size of the desired depositional zone and the acceptability of erosion of the opposite bank. In their guidelines for unaltered Wisconsin trout streams, White and Byrnildson (1967) recommend that deflectors extend one-third the stream width into the channel. Bank protection may be used opposite a deflector, but the net result will be a narrower and perhaps deeper channel. White and Byrnildson (1967) recommend that the height of deflectors be 10 in. above the early summer base flow water surface. Barton and Cron (1979) recommend heights of 12 in. to 18 in. above the channel invert.

c. Rocks. Random rocks should be sized to withstand maximum velocities but should be no larger in their greatest dimension than one-fifth the channel width at normal flow (Barton and Cron 1979). The long dimension should be placed normal to the current, and the rock should be large enough to project slightly above the water surface at normal flow. Rock size (minimum diameter for elliptical or oblong rocks) needed to withstand a given velocity may be determined using rules of thumb given by Barton and Cron (1979) or the curves in EM 1110-2-1601 (OCE 1970) relating stone weight to spherical diameter and the weight of an isolated cubical stone to velocity.

247. Investigate hydraulic effects. The effects of the habitat

structure plan on channel capacity and depths and velocities at low and normal flows should be investigated. Hydraulic conditions at low and normal flows should provide the desired aquatic habitat. Barriers to migration such as extremely shallow reaches or vertical drops that are too high for the species of interest to pass over should be avoided. A thorough examination of the hydraulic effects of structures would include physical modeling; however, routine backwater computation such as the Hydrologic Engineering Center HEC-II computer program (HEC 1981) may suffice. For the computer analysis, structures may be modeled as roughness elements, low weirs, or contractions. Scour holes should be included in the channel geometry downstream of sills and deflectors, since a major portion of the head loss occurs as the flow passes through scour holes. Estimating the size of the scour hole that the stream will form and maintain downstream of a structure is difficult, particularly in cases where the channel is active. In such cases, best estimates are based on experience with one or more prototype structures. Scour holes in poorly armored channels should be stabilized by protecting the sides. This will prevent flanking and extreme bank erosion. The stable, rocky substrate afforded by such protection can be a positive influence on the aquatic community (Winger et al. 1976). The effect of a long series of structures on maximum flow capacity may be approximated by increasing the roughness coefficient, but the amount of increase is a matter of judgment. Large boulders placed randomly in channels increase hydraulic roughness. Research by Barton and Cron (1979) indicates that if Manning's n is already 0.045 or greater, one 5-ft-diam rock per 300 sq ft of streambed will not increase roughness significantly. Their data indicate that one 5-ft-diam rock per 60-70 sq ft will increase Manning's n by about 10 percent in a channel with initial roughness of 0.035 and flow depth of 5 ft.

248. Consider effects on sediment transport. Habitat structures are intended to modify patterns of scour and deposition, but the precise nature and magnitude of their effect are difficult to predict. Habitat structure types and sizes should be selected with the sediment load and grain size distribution in mind. When designing structures for erodible

channels, it may be wise to allow the modified channel to "season" through several high flow events before laying out and designing habitat structures.

249. Select materials and design structures. Materials used for habitat structures include boulders, riprap, gabions, sheet piling, fencing wire, reinforced concrete, logs, treated posts, and felled trees. Most situations allow the use of more than one type of material, and final selection may be based on economics or construction methods. In some cases, it may be feasible to salvage large logs, boulders, or rock from clearing and channel excavation for use as habitat structures. When a channel is excavated through rock, an irregular low flow channel with pools, riffles, and undercut banks may be blasted in the bottom. Rock excavated from the low flow channel may be used to build training structures to direct flow into the low flow channel.

a. Logs. Log structures give long service if continuously submerged and are more natural looking than gabions or concrete. Alternately wet-dry logs can give up to 20 years of service, and last even longer if treated (Barton and Cron 1979). Logs and timber should be firmly fastened together with bolts or rebar. Ehlers (1956) evaluated several types of 18-year-old habitat structures installed in a small, unaltered California trout stream and found that log sills proved superior to structures made of loose rock, earth, masonry, and rock-filled log cribs. The most durable log sills were extremely well anchored by piles of large rock at either abutment, both upstream and downstream. Anchoring and habitat were further complemented by good stands of willows and other vegetation at the abutments. Felled trees anchored or cabled to deadmen on the bank provide good cover, although they are susceptible to failure due to ice attack, damage by beavers, and eventual decay.

b. Rock. Rock size required for habitat structures is directly related to the maximum expected velocity in the vicinity of the structure. A range of discharges should be considered since local critical flow conditions may occur at discharges considerably less than a design event. Generally, deflector tips and sill notches are subject to the highest velocities. Debris and ice loads are also a consideration in the overall durability of the structure. Smaller stones may be used in gabions, but use of gabions presents other problems (see paragraph 200).

c. Other materials. Concrete structures may be formed in a variety of shapes (Barton and Winger 1974) and may be a suitable alternative to gabions or rock in some situations. Sheet piling structures similar to grade control structures have been used with some success in erodible channels (Winger et al. 1976). However, sheet piling and concrete tend to be aesthetically inferior to stone or logs. Rigid structures fail quickly when placed on movable beds if their foundations are inadequate (Ehlers 1956).

d. Design. The literature contains design sketches of various structures (Barton and Cron 1979; Barton and Winger 1974; Forest Service 1969; Maccaferri Gabions of America 1968; Nelson, Horak, and Olson 1978; Tarzwell 1938; White and Brynildson 1967). Other considerations for structure design include gravel bedding or filter cloth underneath structures to prevent washout of fine material and resultant undercutting (Tarzwell 1938).

250. Construct. Plans and specifications should be written to allow a team composed of a biologist, a geotechnical engineer, and a hydraulic engineer to make minor adjustments in structure placement and design during construction. This arrangement will help to ensure that desired effects are achieved and initial disturbance is minimized. Remnants of existing good-quality habitat should be preserved whenever possible. The unorthodox nature of habitat improvement requires extremely close supervision of the contractor.

251. Follow up. Habitat structure installation should be followed by regular monitoring, adjustments, and maintenance. A follow-up program is important with flexible construction materials such as rock, because minor design changes can resolve incipient problems and ensure the desired effect. Design uncertainties can be compensated for by follow-up work in some cases, but since additional funds are required for such work, a contingency factor must be accepted in cost estimates. Monitoring and adjustments allow designers to learn from past actions and develop skill for future work.

Water level control structures

252. In this report, a water level control structure is defined as any instream structure that controls water level at a constant or near constant elevation during nonflood periods for aesthetics, recreation,

fish or wildlife habitat improvement, water quality, vegetative control, or related purposes. Water level control structures may have multiple purposes such as grade control and habitat development. Enlarged flood control channels typically have shallow flow depths most of the time, which provide poor aquatic habitat, encourage growth of hydric plant species, and lead to higher water temperatures. These conditions create maintenance problems and massive, nearly empty channels that are unattractive to most people, especially if the channel is paved. Most of these problems can be avoided by placing structures in the channel to raise water levels.

253. Types of structures. Overflow weirs, gated structures, and inflatable dams have been used to control water levels in CE flood control channels. Weirs may be constructed of sheet pile, concrete, gabions, or earth plugs formed by short unexcavated reaches or by compacted excavated material. Typical structures are shown in Figures 16a (sheet pile), 16b (gabion), 16c (concrete), 42 (gated structure), and 43 (inflatable dam). Earth plugs usually require some type of erosion protection and are often scoured and flanked. More permanent structures may be more effective and have a lower cost over the life of the project (Ables and Boyd 1969). Inflatable rubber and fabric dams have been used for water level control on several projects. The Flint River Flood Control/Beautification Project in Flint, Michigan (USAED, Detroit 1974), has an inflatable dam that maintains a 10.3-ft-deep pool for recreational and aesthetic purposes. The dam is water-inflated and consists of two sections, each 50 ft long and 6 ft high when fully inflated, that rest on a 3.7-ft-high concrete sill. The dam is inflated with air during winter and is deflated during floods. It passes a flow of 200 cfs over the crest when fully inflated, and the design discharge is 600 cfs with the dam fully deflated. Inflation is automatically controlled based on upstream water surface elevation. The South Platte River in Denver has an inflatable dam that has been modified with a chute to allow small boats to pass over the structure.

254. Fish passage. When weirs or drop structures are used for water or grade control, provision should be made for fish passage and

Figure 42. Gated water level control structure, San Antonio River. The gates are open in this photo because of flood channel construction activity immediately upstream.

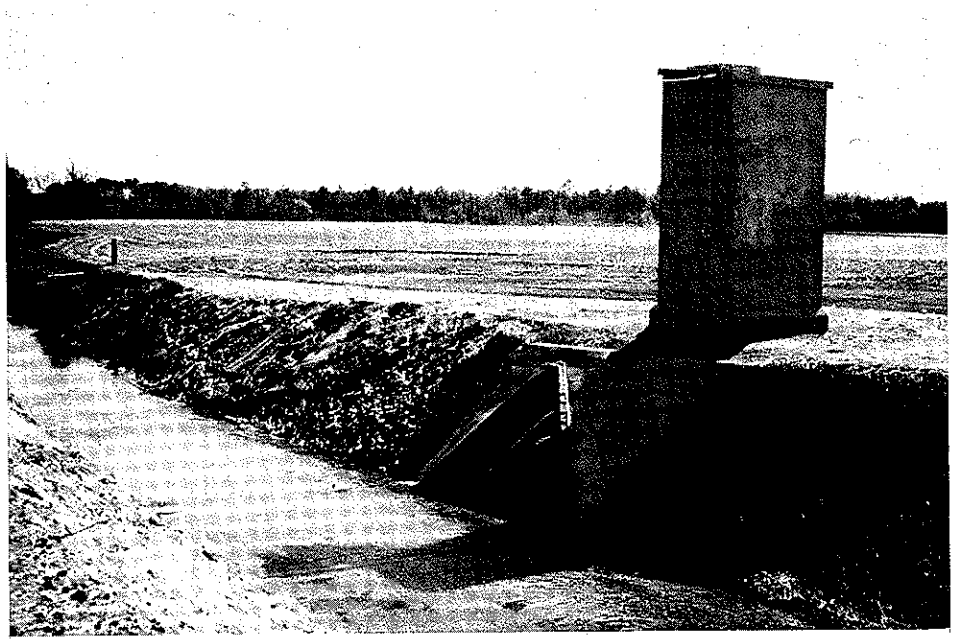


Figure 43. Inflatable dam, Mitchell Creek, North Carolina. The dam, deflated in this photo, can be inflated with water to control upstream water levels for irrigation purposes.

for water flow during low flow periods when flows are insufficient to overtop the structures. (The need for fishways and procedures for their design are discussed in paragraphs 265-284.) Stone, gabion, and sheet pile structures may have sufficient throughflow or leakage to maintain flow downstream of the structure when water levels are below the crest. Two designs that allow for fish passage are described below:

a. The concrete weirs on the Souris River Project were constructed with gated conduits to pass water around the weirs during low flow. The design allows fish to pass through the conduits during these conditions, although they were not designed specifically for this purpose.

b. The SCS design for the Lower Little Black Watershed Project in Missouri and Arkansas calls for four wet-weir concrete structures to pond water for fishery maintenance, to reduce meandering at low flow, and to control willow growth. Each structure will back water up to the next structure upstream, and each has a 1-sq-ft port near the bottom to allow water flow and fish passage from one pool to the other (Figure 44).

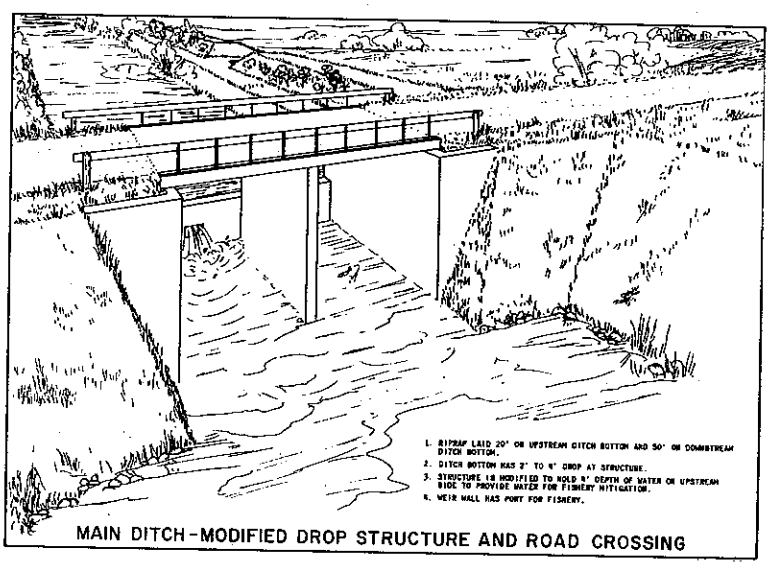


Figure 44. Orifices for fish passage, Lower Little Black Watershed, Missouri and Arkansas. The grade control structures provide for a 2- to 4-ft drop in the channel invert, and openings were provided in the weir walls to allow for fish passage. (SCS 1974)

255. Cost. Costs for various types of water control structures used on CE projects reviewed are shown in Table 11. These data indicate

that construction costs are highly variable and depend on structure size, type of materials used, and complexity of design. Multipurpose structures may be considerably more expensive than simple, single-purpose structures.

256. Maintenance. Upstream sedimentation is perhaps the most serious problem with water control structures. Streams with heavy sediment loads may require upstream sediment traps and/or regular cleaning of pools. Inflatable dams and fully gated structures allow some sediment to be flushed from pools during high flow events. The Flint River Project is located downstream of several impoundments, which minimizes sediment problems. Although vandalism can be a problem with inflatable dams, their low pressures (4 to 5 psi) allow them to continue operating even if punctured or slashed. Commercially available dams are made of materials, such as nylon-reinforced neoprene, that are durable and puncture-resistant under normal operating conditions. If punctures do occur, they are quickly and easily repaired (Shields 1982).

257. Design. Water control structures should be designed, built, and maintained so that they do not block fish movements nor create upstream sedimentation problems, downstream erosion, or reduction of flow capacity under high flow conditions (Shields 1982). These problems can be addressed by the use of gated structures and inflatable dams, but the cost of these structures is sometimes too expensive to justify. Weir structures, on the other hand, can be relatively inexpensive, but may cause any, or all, of the above problems. Careful attention to design and formulation of maintenance procedures can help deal with these problems. Structures can be designed with low profiles to avoid reducing flow capacity during floods. Openings, fish ladders, or other passageways can be used to address fish movement problems. Instream or streamside sediment traps can be used to avoid sedimentation problems, although maintenance is expensive.

258. Ables and Boyd (1969) provide design information for low-water weirs constructed from sheet piling and riprap. The design has been used successfully by the SCS and the CE in channels designed to convey floods with recurrence intervals of 10 years or less. Most of

the channels are low gradient streams in Louisiana and Mississippi. Design guidance for gabion control structures can be found in ETL-1110-2-194 (OCE 1974b). Guidance for the design, installation, and operation of inflatable dams is available from manufacturers of these products and from engineering consulting firms that specialize in their design and installation.

Spawning beds

259. Trout and salmon spawn in gravel riffles. Eggs and newly hatched fry depend on water percolation through the gravel to supply oxygen and remove wastes. Silt clogs the pore spaces and reduces water percolation and survival rates. Channel modification for flood control usually destroys spawning riffles in the modified section and may damage or destroy downstream areas through siltation during construction.

260. Cleaning spawning beds. Downstream spawning areas can be protected during construction by using techniques discussed in paragraph 221. When sediment damage does occur, spawning beds can be rehabilitated by cleaning. If gravels have become cemented together, mechanical loosening by raking, harrowing, dozing, etc., may be required to loosen gravels and flush fine sediments downstream (Forest Service 1969). Mechanical loosening is effective only if flow is sufficient to provide the required flushing action. Mechanical gravel cleaners have been developed and operated by several government agencies (Forest Service 1969; Nelson, Horak, and Olson 1978). These devices have metal teeth to stir the gravel; water jets to loosen silts, sands, and small gravel; and a vacuum to suction the slurry. Cleaning of spawning beds should be attempted only in channels that do not fill with silt quickly.

261. Creating new beds. New spawning beds can be created by trapping existing gravels, introducing graded gravel into channels, or constructing artificial spawning channels. Structures placed in strategic locations can trap gravels in channels that have steep gradients and small scattered gravel deposits. Low sills and right-angle deflectors similar to habitat structures (paragraphs 225-251) may be used. Graded gravel can be placed in flood control channels to create acceptable spawning habitat for trout or salmon populations. The design for the

uncompleted portion of the Corte Madera Creek Flood Control Project (USAED, San Francisco 1980a, 1980b) includes a spawning reach 100 ft long, 6 ft wide, and 3 ft deep (2 ft of gravel, 1 ft of water). Gabion structures will be used to reduce gravel losses during high flows. Lost gravel will be periodically replaced by the local sponsor as a component of regular maintenance. The survey of CE flood control projects found no projects with separate artificial spawning channels. Their use has been restricted largely to salmon streams in the Pacific Northwest. The minimum design consists of a gravel-lined channel, water intake structures, and fish barriers to guide spawning adults into the artificial channel. Adult fish holding areas and rearing habitat may also be included.

262. Cost. Artificial spawning channels are expensive because of the space requirements of spawning fish as detailed in Table 12 (Clay 1961). The 10- by 2000-ft Jones Creek spawning channel built in British Columbia in the early 1950s cost $2.25/sq ft (Clay 1961). The Corte Madera spawning reach is estimated to cost $7.67/sq ft (1978 prices).

263. Design. Spawning beds for trout and salmon can be justified only if flood control channels support, or are accessible to, populations of gravel-spawning fish and possess the characteristics of a suitable spawning site. Bell (1973) provides detailed spawning habitat criteria and methods for evaluating suitability. The most important criteria include an adequate depth of water at spawning time, suitable water velocities during spawning and incubation, adequate water quality (temperature, dissolved oxygen, sediment concentration, etc.), and protection from predators.

264. Construction of spawning beds in flood control channels that meet the foregoing criteria involves trapping stream gravel or supplying properly sized graded stone for the species of interest. Low sills and wing deflectors designed according to the criteria provided in paragraphs 222-251 will trap gravel on steep gradient streams with gravel deposits. Clay (1961) reviews criteria for spawning gravel sizing and gradation for various salmon species. As a general rule, spawning gravel should be from 0.25 to 2 in. in diameter for trout and 0.5 to 6 in. for

salmon. Detailed design guidance for design, construction, and operation of artificial spawning channels can be found in Clay (1961) and Bell (1973).

Fishways

265. Fishways are structures built to allow fish to pass through or around natural or man-made obstructions. The two most common types of obstructions in flood control channels are vertical drops associated with weirs or grade control structures, and culverts or channel sections in which flow is too shallow or swift for fish passage. Fishways are designed to create flow conditions that allow fish to swim through the facility. The need for fishways in channels used for spawning by salmonids or anadromous species is well established. Fishways are also often needed in channels supporting nonmigrating species to allow them access to desirable spawning areas and to permit them to repopulate barren reaches and tributaries following flood events that sweep large numbers of fish downstream.

266. Fishways for vertical obstructions. Fishways over vertical obstacles are sometimes called fish ladders. They can be classified into a few basic types according to the method of modifying flow patterns (Clay 1961). The simplest type, called pool and weir, employs a series of low overflow weirs (called baffles) to impound shallow pools (Figure 45). Fish negotiate the weirs by jumping from pool to pool. A modification of the pool and weir fishway uses orifices in the baffles to pass water and allow fish movement from pool to pool (Figure 44). This type is commonly called a pool and orifice fishway. Both weir and orifice fishways require low drops between pools to allow energy to be dissipated within each pool by turbulence.

267. Different flow characteristics are produced when the orifices extend the full height of the baffles. This design is called a pool and jet fishway. Denil fishways use side and bottom vanes in a steep trough to create countercurrents that slow velocities enough for fish passage (Figure 46). About 1943, Bell designed a fishway that incorporated Denil's principle of creating countercurrents into a vertical slot design. The resulting design is known as a Hells Gate or vertical

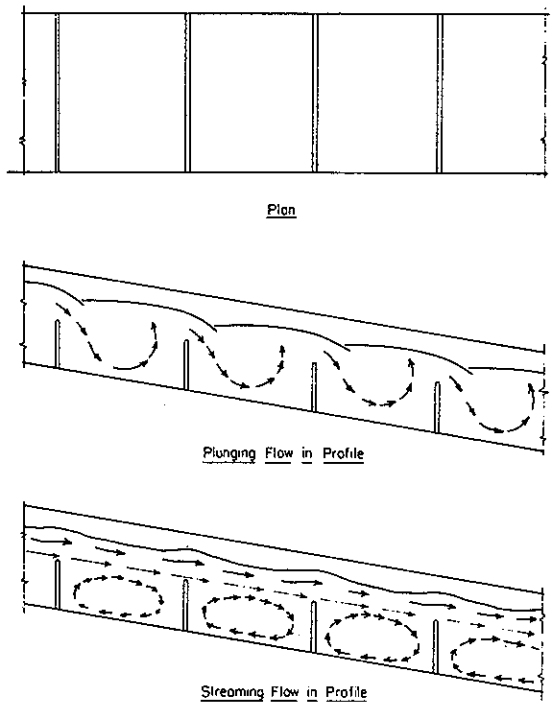


Figure 45. Pool and weir fishway. Overflow weirs are used to impound pools, and fish negotiate the fishway by jumping from pool to pool. (after Watts 1974)

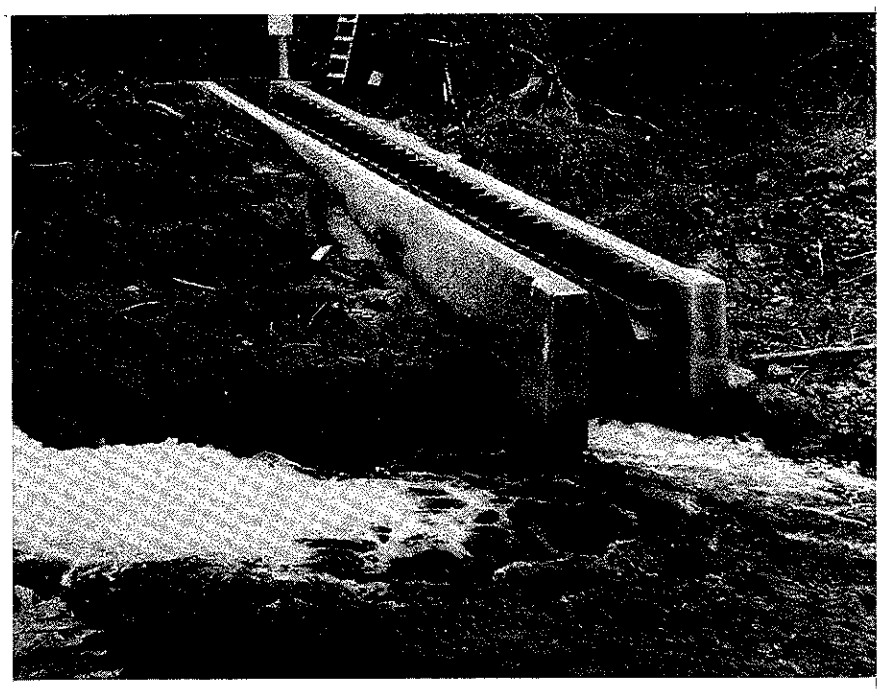


Figure 46. Denil fishway. Side and bottom vanes are used to create velocities slow enough for fish passage. (photo from Clay 1961)

slot fishway (Figure 47) (Clay 1961). The major advantage of this design is that it produces relatively constant flow conditions over a wider range of flow fluctuations than pool and weir designs.

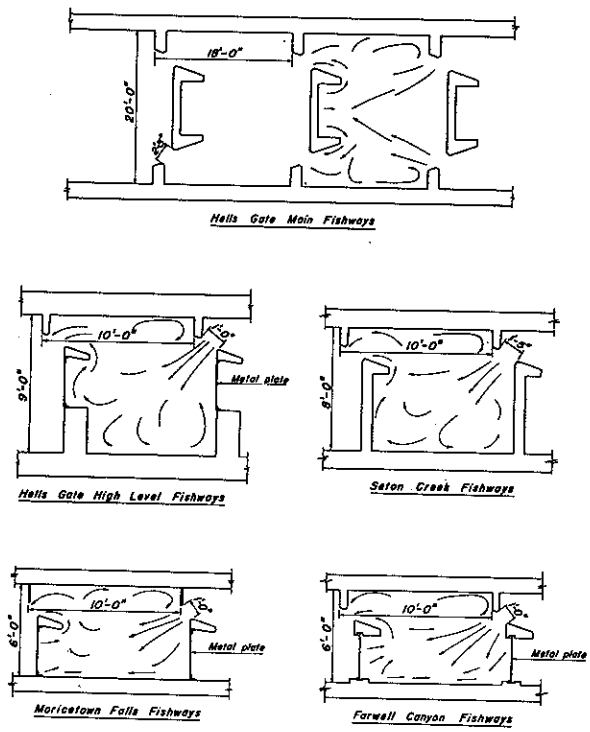


Figure 47. Vertical slot (Hells Gate) fishway. Vertical slot designs work well over a wide range of discharges. (after Clay 1961)

268. One fishway design may be preferable over others for a given hydrologic condition. Pool and weir fishways do not work as well as vertical slot designs on streams with highly variable discharges (Bell 1973, Clay 1961). Vertical slot designs retain relatively constant flow conditions over a wider range of discharges, whereas pool and weir designs may be starved at low flow and drowned at high flows. Pool and orifice and vertical slot designs function better under high bedload conditions than weir and Denil designs that trap more sediment.

269. In addition to increased maintenance problems caused by sediment and debris, Denil fishways have other limitations (Bell 1973, Clay 1961). Width and depth relationships must be carefully engineered to provide velocity control. There is no resting area within the Denil

fishway run, so individual runs are limited to a length of about 30 ft and resting pools must be provided between runs. Its main advantages are that it can be sloped as steep as 1V:4H (although 1V:6H is more common), and it is able to pass large volumes of water that attract fish to the entrance (Clay 1961). Vertical slot designs have several advantages in addition to those listed in the preceding paragraphs. Fish may ascend at any depth, the path is not tortuous, and fish may rest in the pools if they need to (Clay 1961).

270. Culvert fishways. Culverts are usually designed with smooth circular, elliptical, or rectangular cross sections to optimize hydraulic efficiency. Optimization of hydraulic efficiency is usually unfavorable for fish passage. Culverts in flood control channels and their tributaries are sized to convey a design discharge. At normal and low flows, depths are often too shallow for fish passage. During high flows, velocities often exceed the sustained cruising speeds of adult fish. Uniform cross sections above and below culverts provide no resting place for fish, and channel degradation may create a waterfall at the downstream end of the culvert that acts as a vertical barrier to fish movement (Figure 48). Culvert fishways are designed to alter these conditions by increasing low flow depths, decreasing flow velocities, and providing resting areas at both ends and at regular intervals inside long culverts. According to McClellan (1970), almost any type of conventional baffle or ladder system installed in a barrel culvert is effective in developing fish passage. Also, culverts designed to provide passage by reducing invert gradients are generally effective.

271. McClellan (1970) evaluated fish passage in a large number of culverts, some of which were modified for fish passage. He concluded that barrel passage was generally rated as good for culverts not exceeding 50 ft in length and with channel invert slopes not exceeding 5 percent. Fish passage was rated as poor where barrel slopes exceeded 5 percent and no special provisions were made. Baffle design was not a significant factor in performance, and there was no evidence of increased maintenance problems in culverts with fishways in the barrels. Some culverts had structural problems, suggesting the need for close

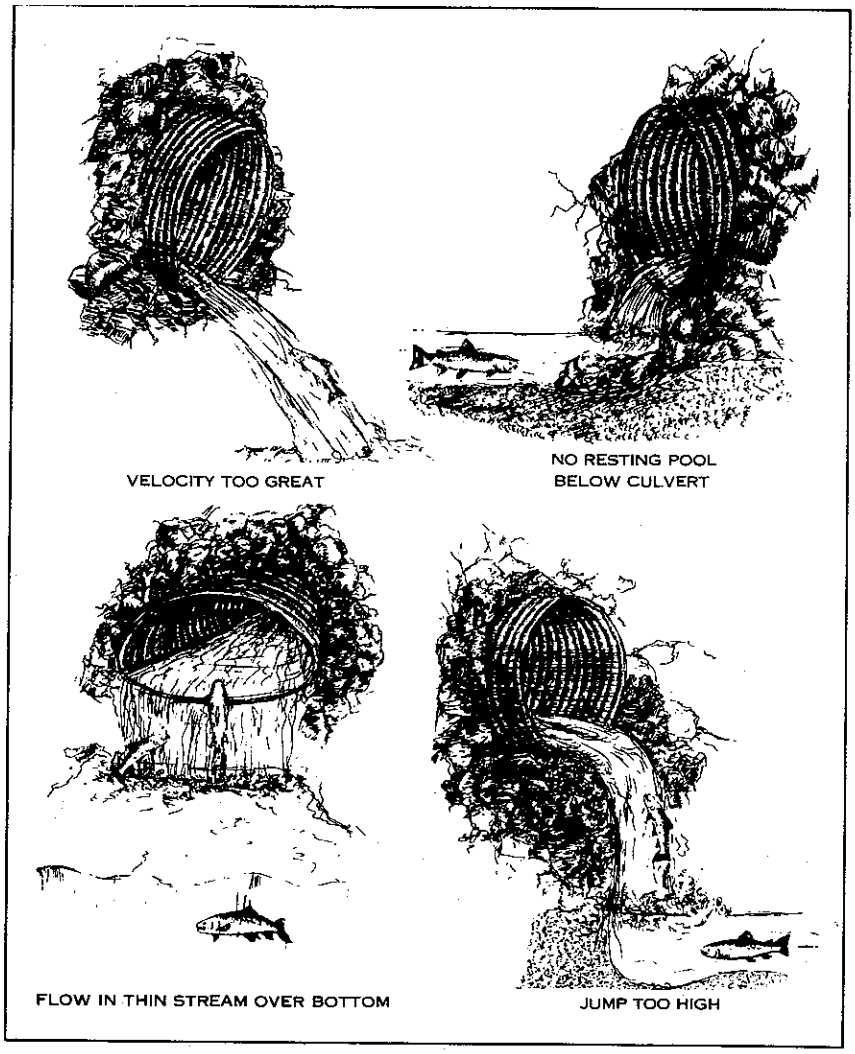


Figure 48. Major types of culvert blockages to fish movements. (Evans and Johnston 1980)

attention to construction supervision and a continuing maintenance inspection program. The most common problem observed by McClellan was the lack of a jump pool on culverts with vertical drops at the downstream end. McClellan concluded that "Any provision of facilities for fish passage in the barrel of a culvert that is not accompanied by consideration of ingress to and egress from the culvert may be of little value."

272. Design for flood control projects. Fishways have been incorporated into four of the projects surveyed. Available data for these projects are summarized in Table 13. The Hayward Creek fish ladder was added after migrating smelt were observed in the drop inlet to a 54-in. culvert at the lower end of the flood control channel. The ladder allows smelt to enter the flood control channel from the culvert. It is a pool and weir fishway with 2-ft-long, 1-ft-deep pools and a drop of 4 in. between pools. No information is available at this time to permit evaluation of the operation or maintenance of the fishways on the three projects that have been constructed. The effect of two long culverts on fish movements in the Bull Creek channel is being studied (Cooper 1981).

273. Design considerations. Several factors must be considered in selecting and designing fishways for flood control channels. The type and size of obstruction is most important. The discussion below is divided into sections dealing with ladder fishways and culvert fishways. Vertical obstructions require ladder-type fishways, and the amount of drop may influence the choice of the specific design. Culvert passage problems can be caused by excessive velocities, insufficient flow depths, excessive length, or elevation differences, each of which may be addressed differently. Flow characteristics and the fish species expected to use the fishway also influence selection and design. Adult fish size and swimming speeds vary among species. These variables and other factors influence decisions regarding type and size of facility and dimensions and layout of structural components.

274. Ladder fishways. Bell (1973) recommends fishways at obstructions with heads as low as 2 ft, but the need for a fishway is better determined by considering the swimming abilities of the fish species of interest. Salmon can negotiate vertical obstacles several

feet high, adult trout are capable of vertical leaps of a foot or more, and shad about 9 in. (Bell 1973, Evans and Johnston 1980). Swimming ability is also a factor in setting maximum weir heights in pool and weir fishways. Evans and Johnston (1980) recommend that individual jumps in series not exceed a foot for salmon and steelhead and 6 in. for trout.

275. Ladder fishway design has been approached as a highly site-specific problem, and the process draws heavily on the experience of the person formulating the design. The design of fishways for grade control and water control structures in flood control channels is subject to the same constraints as the design of fishways at natural obstructions on streams. The structure will be subjected to a wide range of flows, yet, in most cases, it must operate satisfactorily without flow control and have minimal maintenance requirements.

276. Biologic data. The design procedure for fishways is not highly codified, although the ladder design may be relatively standardized for a given fish species and type of design (e.g., vertical slot). Fishway design begins with collection of the necessary biological and hydrological data. The fish species of concern must be identified and data collected to describe their migration patterns, size, swimming speeds, swimming depths, etc. Input from local fish and wildlife personnel is essential at this phase, and they should be involved throughout the design process.

277. Hydrologic data. Required hydrologic data include information on the discharge range over which the fishway is expected to operate, headwater and tailwater curves, and sediment transport. The maximum elevation difference between headwater and tailwater curves within the operating discharge range of the fishway is the total head loss for which the fishway must be designed. If the tailwater curve fluctuates more than the headwater curve, it may be necessary to build the fishway lower at the downstream end to maintain required flow depths during fish movements, and vice versa.

278. Entrance and exit. Once the biological and hydrologic data have been collected, structure design should begin with the location

and design of the entrance and exit ways. Location and design of the entrance is the single most important aspect of fishway design. Fish will not use the fishway unless they are attracted to the entrance. It should not be too high, too far downstream, too far from the main streamflow, or located in an eddy, and it should have sufficient flow to attract fish (Bell 1973, Clay 1961, Forest Service 1969). Exit design is also important, and flow conditions and flow directions should be considered in locating the fishway exit. Additional design guidance is provided by Bell (1973), Clay (1961), and the Forest Service (1969).

279. Ladder design. Design of the ladder may proceed in different ways. The design may begin by fixing a constant pool head, slot or orifice dimensions, and pool size based on experience with the same species on similar sized streams. The design is then checked to see if fishway volume is sufficient to accommodate the peak rate of migration at minimum flow. The number of fish that the fishway can accommodate is equal to

$$C = \frac{V}{n} \times (60\ r) \tag{24}$$

where

C = fishway capacity in number of fish per hour

V = fishway pool volume in cubic feet (volume per pool times the number of pools)

n = the required volume per fish in cubic feet

r = the rate of ascent in pools per minute

Values for n and r vary with species. Bell (1973) and Clay (1961) provide estimates of n for salmonids. Although actual r values are not well established and may vary with such factors as pool shape, fish density, and flow conditions, estimates of r can be calculated from fish swimming speeds or can be based on measured rates of movement of tagged fish. Information on the swimming speeds of adult and juvenile fish of some species can be found in Bell (1973), Clay (1961), and Watts (1974). If the fishway capacity is not sufficient to accommodate the number of fish per hour at peak migration rates, the fishway capacity can be adjusted accordingly.

280. An alternative procedure for the design of a vertical slot or orifice fish ladder that is not so dependent on prior experience is summarized as follows:

a. Determine slot width or orifice dimensions based on fish size. Clay (1961) recommends a minimum slot width of 6 in. for fish 2 lb or less and a maximum of 12 in. for salmon over 2 lb. The Forest Service (1969) recommends orifice openings not exceeding 4 sq ft.

b. Set head loss per baffle. Given the cross-sectional area of the opening and the maximum swimming speed of the fish, calculate head loss per pool from the formula

$$h = \left(\frac{Q}{CA}\right)^2 \times \frac{1}{2g} \tag{25}$$

where

h = maximum head loss per pool

Q = the swimming speed of the fish times cross-sectional area of the opening at minimum flow depth

C = the coefficient of discharge, which varies with the edge shape of the opening

A = cross-sectional area of the opening at low flow

g = the acceleration of gravity

For submerged orifices, h is the difference in water level from one side of the baffle to the other. Unfortunately, little experimental work has been done in determining C values for types of orifices of interest to fisheries biologists. Thus, it may be necessary to calibrate a specific orifice design with a laboratory model. In some situations additional variables such as velocity of approach and hydraulic jumps may have to be considered (Clay 1961). If vertical slot counting stations are to be included in the fishery, they should be designed to eliminate bubbles from the viewing window. Flows approaching, through, and above the counting slot should not cause the fish to be reluctant to enter or to recycle back past the slot once they have passed.

c. Calculate pool volume and dimensions. Pools should be sufficiently large to dissipate energy to avoid excessive turbulence. No proven foolproof method is available for determining minimum pool size, because other variables such as baffle design and slot alignment can

influence velocity and turbulence. The decision is based largely on experience. Clay (1961) cites the recommendations by Bonnyman (1958) that the minimum dimensions for orifice pools should be a length of six times the orifice diameter and a width of four times the diameter, based on a 1.5-ft head loss. Minimum depth should be sufficient to ensure submergence of the orifice at low flow. For the vertical slot design, Clay recommends an absolute minimum pool size of 8 by 6 by 2 ft ($l \times w \times d$) for a 12-in. slot width and a 1-ft head loss. He regards the 2-ft depth as an absolute minimum to be reached only during extreme low flows.

d. Check the fishway volume for adequacy (paragraph 279). If the volume is insufficient, the pools can be made wider or deeper. Since fishway slope is a function of head loss and pool length (a head loss of 1 ft per pool and a pool length of 10 ft produces a fishway slope of 1V:10H), increasing pool length flattens the slope, lengthens the fishway, and may increase fish passage time.

e. For new designs, check the design with a hydraulic model, if possible. The number of uncertainties in fishway design is large enough that hydraulic modeling is needed to ensure that maximum velocities do not exceed maximum fish speeds and that pools are large enough to dissipate energy. The model also may reveal any unstable flow conditions not normally predictable by usual hydraulic analyses.

281. The above procedure is applicable only to orifice and vertical slot fishways. As mentioned previously, design of Denil fishways poses special problems. Guidance for the design of Denil fishways can be found in Clay (1961).

282. Culvert fishways. Design of culvert fishways is less complicated, in most cases, than the design of ladder fishways. The time of upstream fish movements is established, and the expected discharge for that date is determined. The culvert is sized for the design discharge, and barrel velocity is determined for the expected discharge at the time of fish movement. If this velocity exceeds the sustained swimming speed of the fish, the design requires modification. Possible modifications that could be used include addition of baffles or other roughness elements to the culvert invert, reduction of culvert grade, or reduction of the hydraulic radius.

283. It is important to design the culvert installation so that minimum swimming depths are maintained and degradation below the structure is prevented. No special design may be required if the channel is stable below the culvert, although Watts (1974) suggests setting the culvert invert at least a foot below the channel grade. If scour is expected below the culvert or if flow depths are expected to be insufficient for fish movement, a low sill may be constructed at a distance five to seven pipe diameters downstream of the culvert (Watts 1974). The height of the sill may vary depending on its purpose. If the sill is intended primarily for erosion control, a crest elevation equal to the culvert invert elevation might be sufficient. If intended as a tailwater control structure, its elevation could be determined by backwater computations. Alternately, the sill crest could be set at the elevation required to maintain minimum flow depth throughout the culvert (e.g., 8 in. or 12 in. above the invert elevation of the culvert).

284. Regardless of the final design chosen for a culvert fishway, resting areas should be provided immediately below the structure and within the structure itself if it is over 100 ft long. Detailed guidance on all phases of culvert fishway design is available in Evans and Johnston (1980), McClellan (1970), and Watts (1974). The latter reference discusses the use of slot orifice fishways in culverts and gives detailed procedures for their design.

Features for Streamside Aquatic and Wetlands Habitat

285. Realignment of flood control channels results in loss of aquatic habitat for fish, aquatic mammals, and waterfowl. Wetlands habitat is often destroyed by drainage or by placement of dredged material in lowland areas adjacent to flood control channels. Loss of wetlands is of special concern where natural wetlands are limited and where agricultural drainage or urbanization have already resulted in significant losses of wetlands habitat. Several concepts have been used to compensate for loss of aquatic habitat and wetlands (Table 14). Instead of filling severed meanders, they may be preserved as lakes or maintained

as free-flowing stream segments. Small tributary streams may be dammed, and low-lying areas adjacent to streams may be diked and maintained as perennial or seasonal wetlands.

Maintenance of cutoff meanders

286. Oxbow lakes are naturally occurring features in floodplains of meandering alluvial streams that are created when meandering streams change courses. Oxbow lakes are productive habitat for a while, but their eventual fate is eutrophication and filling with sediment. Floodwaters may periodically rejuvenate the lakes, but the associated sediments also shorten their life.

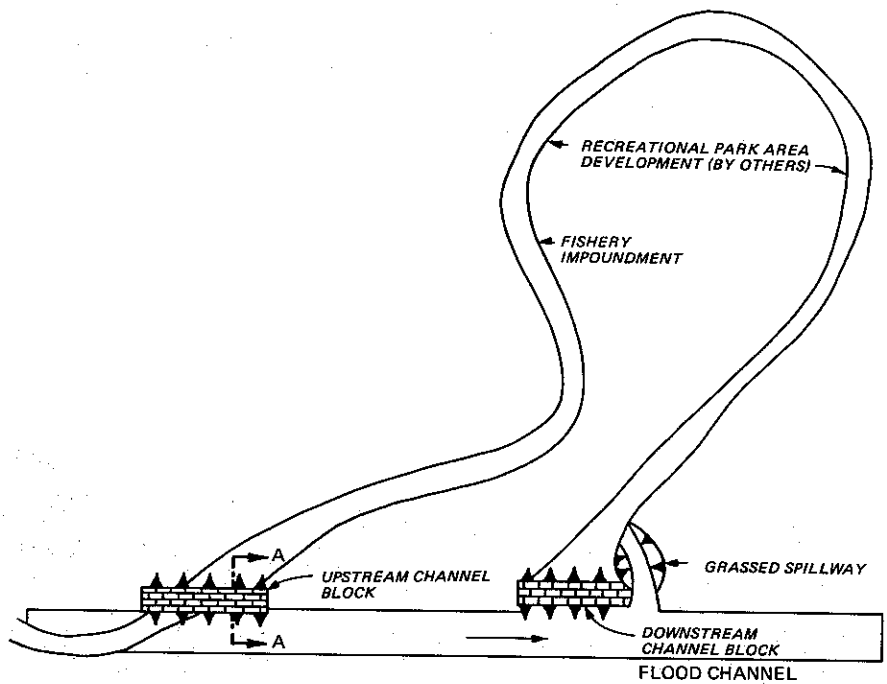
287. Oxbows are also created when channels are straightened. Even if their ends are not plugged intentionally, they soon become blocked as sediments are deposited in the slack-water areas along the flood channel margin. Artificially created oxbows are likely to experience poor water quality unless some means of flushing is provided.

288. Lakes. Severed meanders may be maintained as lake or stream environments. Lake designs usually have channel blocks in both ends of the meander (Figure 49). One block, usually the lower, may be equipped with a pipe outlet or earthen spillway to maintain lake level. Flap-gated culverts may be used to allow water into the oxbow during high flow if the lake does not receive sufficient flow from other sources to maintain the desired water level.

289. Examples. Oxbow lake designs from three CE flood control projects illustrate the variety.

a. Oxbow impoundments on the Little Blue River Project (Figure 49) have channel blocks at both ends of the oxbow. The upstream block has a drop inlet spillway with a 24-in. corrugated metal pipe (CMP) barrel and a 36-in. CMP riser that controls the water level. The lower block is designed with an excavated, grassed emergency spillway (USAED, Kansas City 1972). The design appears to work satisfactorily, although dense growths of aquatic plants have been observed in the oxbows.

b. The oxbow lake design proposed for the Zumbro River Flood Control Project specifies channel plugs placed about 400 ft from the flood control channel. The lower plug will have a 36-in. flap-gated CMP culvert to allow the oxbow to fill during high flow (USAED, St. Paul 1970).



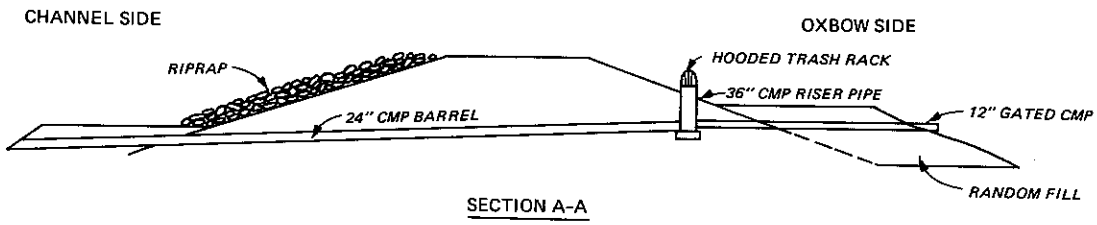


Figure 49. Oxbow lake design, Little Blue River. The upstream channel block has a drop inlet spillway for water level control, and the downstream block includes an excavated, grassed emergency spillway. (sketch modified from USAED, Kansas City 1972)

c. The West Tennessee Tributaries Project (USAED, Memphis 1982) has 21 proposed bendway impoundments (Figure 50) that will be managed for wildlife purposes. Earthen bendway dams will be equipped with gated culverts, base level intake and outlet structure and control valve, and spillways that will allow water level manipulation. Winter pool levels will be controlled by the spillways, and the water level will be lowered during the growing season by raising the culvert gates. The base level intake structure and control valve will permit complete drawdown every 3 to 5 years to control noxious weed growth and undesirable fish species (USAED, Memphis 1982).

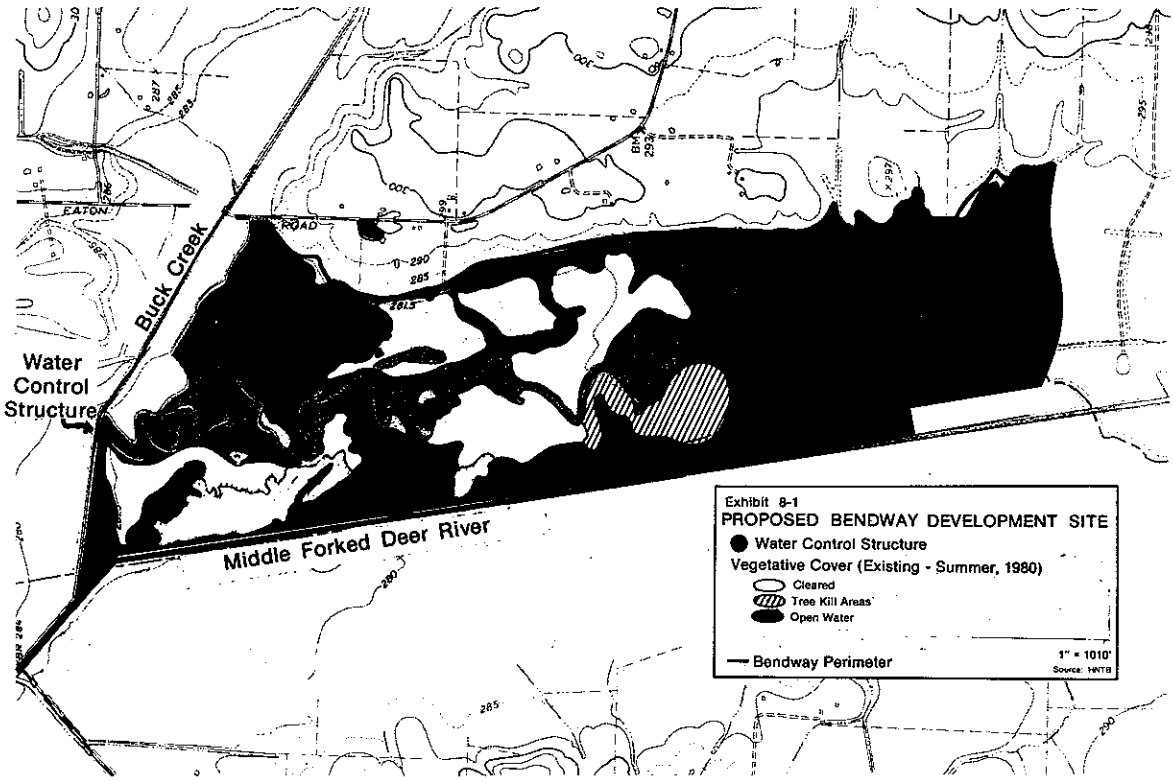


Figure 50. Proposed bendway impoundment, West Tennessee Tributaries Project. Water levels will be controlled by spillways and gated culverts for timber improvement and wildlife management. (after USAED, Memphis 1982)

290. Flow-through bendways. Bendways maintained as stream habitat require some provision to ensure that flow moves through the bendway at all times (Figure 51). The most common designs are to construct the bypass channel invert higher than the bendway invert or to place a water

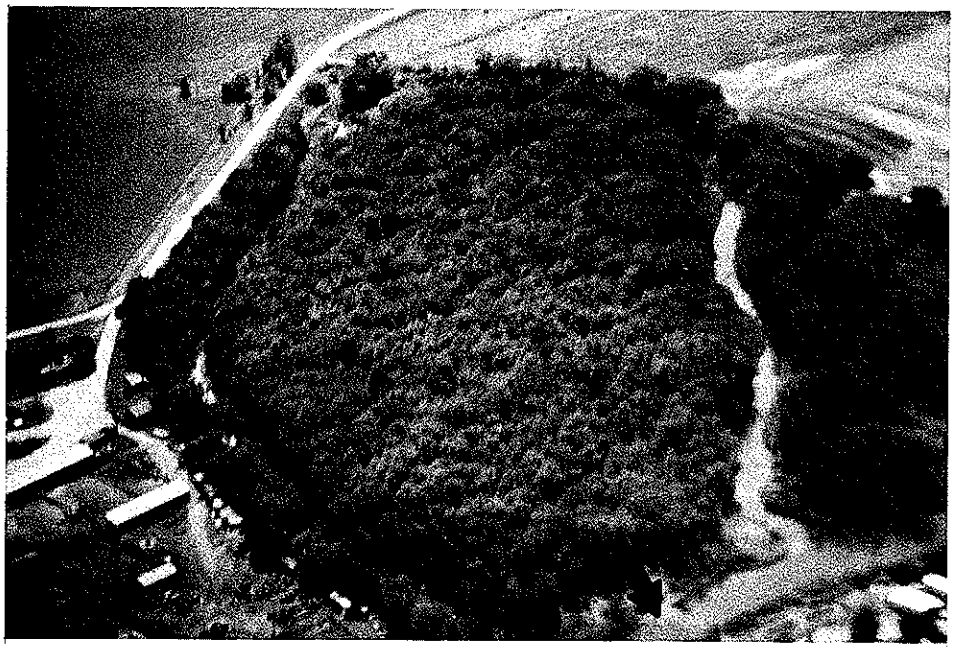


Figure 51. Flow-through bendway, Souris River, North Dakota. A gabion water control structure (arrow) diverts flow through the upper bendway confluence shown on the lower right. Low sills in the bendway near the downstream confluence pond water to increase depth during low flow periods. A closeup view of the water control structure is shown in Figure 16b.

control structure in the bypass channel to raise the water level above the bendway invert. A low sill is sometimes placed in the lower end of the bendway to maintain minimum water depths during the summer.

291. Several CE flood control channel projects have been built with flow-through bendways. Weirs were used to raise water levels in the flood channels and divert low flows through bendways on the Souris River (USAED, St. Paul 1975). On the Little Blue River (USAED, Kansas City 1972), floodway inverts are about 5 ft higher than bendway inverts (Figure 52). In both cases, high flows are divided between flood channels and bendways.

292. Two kinds of water control structures were used on the Souris. The leveed sections in Minot have 10-ft-high concrete weirs and sluice-gated barriers at both ends of the oxbows (Figure 16c). The unleveed sections have sheet-pile core gabion weirs and low sills in the bendway near the downstream confluence (Figure 51). Both designs appear

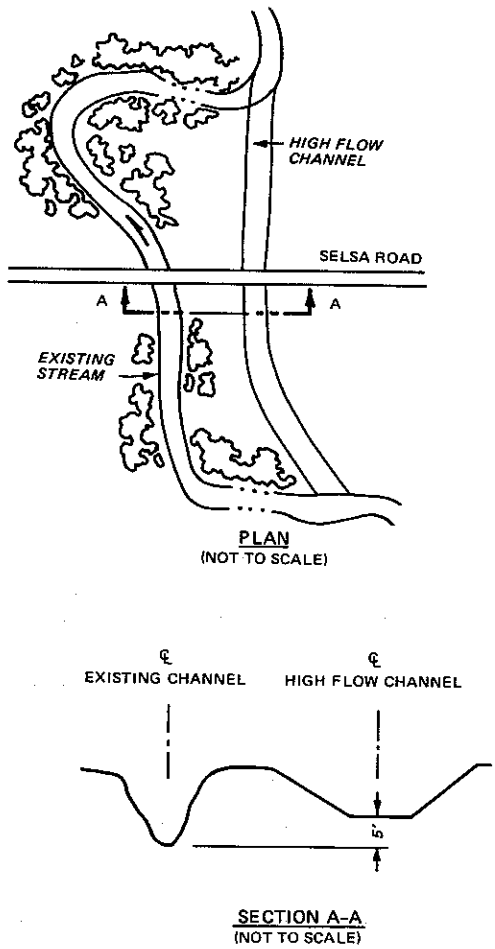


Figure 52. Flow-through bendway design, Little Blue River, Missouri. Floodway inverts that are approximately 5 ft higher than bendway inverts divert low flow through bendways.

to be working well, although minimal flow was observed in some Souris River bendways due to low water levels in August 1982.

293. The foremost problem encountered with flow-through bendways is preventing closure of the ends and eventual sedimentation, even when low flows are diverted through them. Significant sediment accumulations have already developed at the upstream junctions of some of the Souris bendways (Figure 53). Techniques for keeping bendways open include placing culverts at elevations well above the floodway invert and above the zone of heaviest sediment concentration to reduce clogging, adjusting the angle between the bendway and cutoff, and constructing a sediment trap in the upper portion of the bendway.

Figure 53. Sediment deposition at bendway confluence, Souris River, North Dakota. Significant sediment accumulations have already begun to occur at the upper confluences.

Bendway design considerations

294. When bendways of streams with fishery and wildlife value are cut off during flood channel construction, consideration should be given to maintaining the bendway as either lake or channel habitat. Impoundment and flow-through designs share many common aspects. However,

since each has some unique considerations, their design is addressed separately.

295. Impoundments. The first step in the design of an oxbow impoundment is to establish the feasibility, which is largely a function of water quality. Advice from water quality experts should be sought early in the planning process. Cutoff bendways receiving significant pollutant or nutrient loadings from point sources or runoff need to be examined closely. Flushing rates based on inflows and impoundment volume need to be adequate to prevent starvation or eutrophication. Dissolved oxygen problems may be aggravated in shallow impoundments by aquatic weed growth during summer and freezing during the winter. Conversely, narrow, deep oxbows may become stratified and develop anaerobic conditions in the lower layer.

296. Adequate channel blocks and appropriate flow control must be provided. If inflow to the meander from tributaries or local drainage is sufficient to maintain water level, only an outlet structure and an emergency spillway are needed. If inflow is insufficient, a gravity-fed inflow structure or pumped inflow is needed. Water rights should be investigated on any project requiring diversion of water for maintenance of any type of impoundment. Intake structures should be located several feet above the flood channel invert to avoid heavy sediment concentrations that can block the structure. If unlined emergency spillways are used, they should not be excavated in fill material. Design factors that need to be considered include durability, cost, and special maintenance problems. Earthen channel blocks may require erosion protection, especially if constructed on the margins of flood channels. Small hydraulic structures such as culverts are subject to blockage by beavers and floating debris, and flap gates or control gates can be easily jammed by debris. Shallow impoundments may need to be dredged or excavated to acceptable water depths for fisheries management. If they receive heavy sediment loads from runoff or overflow, periodic dredging may be required.

297. Flow-through designs. Feasibility of flow-through designs depends on sediment load as well as water quality. Unless the stream is

relatively sediment free or provision is made to trap sediment and regularly remove it, flow-through designs are likely to have short life and require periodic rehabilitation by dredging. Flow-through designs are also of questionable value on streams with extremely low summer flows.

298. The least expensive design alternative for flow-through bendways is to excavate the flood bypass channel to a shallower depth than the bendway so that low flows are diverted entirely through the bendway. Riprap, gabion mattress, or some other form of bed protection is needed if the channel is excavated into easily erodible material. If the floodway is excavated to a depth equal to or greater than the bendway invert, a low-water weir placed in the flood channel can double as a water level control structure to divert low flows through the bendway and as a grade control structure. If the floodway invert is lower than the bendway at the downstream confluence, bed protection or a drop structure may be needed to prevent erosion of the bendway invert.

299. A better option for streams unsuitable for flow-through design because of sediment load or low flow problems is to block one or both ends of the bendway to keep the water entering the bendway as sediment-free as possible. Model studies (Foster, O'Dell, and Franco 1982) and experiences with navigable streams indicate that upper entrances to cutoff bendways quickly fill with sediment just as natural cutoffs do. This is followed a short time later by the closing of the lower entrance. Model studies of the Red River (Foster, O'Dell, and Franco 1982) indicate that it may be possible to prolong the life of oxbows by sealing off the upper entrance immediately and constricting the lower opening so that it scours on the falling stage. Since most heavy sediments are transported near the channel bed, a sill can be used to exclude much of this sediment from the bendway.

Wetlands

300. Description. Alignment of flood control channels and careful placement of dredged materials to avoid wetlands can minimize losses of these valuable habitats. Even so, lowered seasonal water tables and improved drainage may damage or eliminate wetlands, especially in areas with low relief and high water tables. Replacement of seasonal wetlands

is often easy and inexpensive, requiring nothing more than placing excavated material so that runoff is inhibited or using the material to construct levees around low-lying areas. Culverts of various designs may be used to control the flow of water into or out of impounded areas. Flow control makes it possible to manage wetlands for specific purposes, such as duck habitat or timber production.

301. The West Tennessee Tributaries Project (USAED, Memphis 1982) includes a number of areas that will be managed as greentree reservoirs for timber improvement and waterfowl habitat. Gated culverts will be used to flood these areas during winter and drain them in spring (Figure 50). The plan for Taylors Bayou Drainage and Flood Control Project (USAED, Galveston 1981) includes using dredged material to construct embankments that will pond water in four areas for waterfowl. Water levels will be maintained by adjustable weirs. Local interests acquired and improved 4200 acres of wetlands in lieu of managing two of the disposal areas. Improvements consist of levees, fill, and water control structures. The Texas Parks and Wildlife Department will manage the area.

302. Unlike seasonal wetlands that dry out annually, permanent wetlands remain wet year round (although they may dry up during severe droughts). Permanent wetlands with open water areas provide a distinctly different habitat that may support breeding waterfowl, fish, and furbearers such as otter, beaver, mink, and muskrat. Creation of permanent wetlands may require impoundment of perennial streams, blasting or excavation below the permanent water table, or use of gated culverts to augment meager water sources. Except for the bendway impoundments already discussed, none of the CE projects suveyed included any designs for the creation of permanent wetlands on the project site.

303. Design considerations. The values of wetlands of all types are well established, and opportunities for including wetland features in flood control channel projects are numerous. Alluvial flood plains possess many characteristics that rate highly as site criteria for wetlands--flat topography, relatively impermeable soils, high groundwater table, plentiful and dependable supply of water, and mast-producing

hardwood trees and other vegetation with high habitat value.

304. Many flood plains in the south-central and southeastern United States support bottomland hardwood forests that are naturally flooded in the wintertime and are well suited to development as greentree reservoirs. Greentree reservoirs are inundated for duck habitat during winter dormancy and are drained during the summer growing season to prevent timber kills. Guidance for site selection, design, and operation of greentree reservoirs can be found in the Wildlife Habitat Improvement Handbook (Forest Service 1969). The Final Environmental Impact Statement for the West Tennessee Tributaries Flood Control Project (USAED, Memphis 1982) includes a detailed habitat evaluation and benefit analysis of a greentree reservoir site. Two habitat evaluation methods were employed--the Habitat Evaluation System (HES) (USAE Division, Lower Mississippi Valley 1980) and the Habitat Evaluation Procedure (HEP) (Fish and Wildlife Service (FWS) 1980a, 1980b). Wetlands created by impoundment usually require spillways to control maximum water levels. Adjustable weirs, gated culverts, or stop logs can be used to manipulate water levels for management purposes. Average water depths of 18 to 24 in. are desirable in most cases (Forest Service 1969).

305. Open water areas are valuable habitats for waterfowl and furbearers. Open water areas are often lost when flood channels are realigned through swamps and marshes. In such cases, lost habitat can be replaced by excavating small, open water areas. The deep water helps provide food and cover during dry periods, and disposal banks provide nesting and resting sites, feeding areas, and refuge during floods. The latter can be of utmost importance in the flood plains of low gradient streams. Additional guidance for the creation and management of wetlands can be found in the Wildlife Habitat Improvement Handbook (Forest Service 1969).

Features for Terrestrial Habitat Restoration and Maintenance

306. Many impacts of flood control channel projects on the terrestrial ecosystem are caused by clearing and placement of excavated

material. Riparian vegetation provides the bulk of the food supply and cover for wildlife along streams and valuable corridors for the movement of wildlife in urban settings and in intensive agricultural areas. Excessive clearing along rights-of-way and careless construction techniques damage and destroy important vegetative habitat. The habitat value of existing vegetation and that expected under postconstruction conditions can be assessed with habitat evaluation methods such as HES or HEP (paragraph 304). Maintenance of channel banks and topbank areas usually prevents reversion to a stage that is more ecologically diverse than the maintained condition. Excavated material is often placed in a manner and in locations that disrupt drainage, destroy wildlife habitat, and kill trees.

307. Some techniques for preserving existing terrestrial habitat on flood control channel projects have been treated in previous sections of this report--selective clearing and snagging, modifying alignments to save areas or trees with special habitat value, single-bank construction, and restrictions on equipment access and right-of-way clearing. Additional techniques covered in this section include placement of excavated material to minimize habitat disruption and drainage problems, vegetative plantings for wildlife food and cover, vegetation management, preservation of islands created by cutoffs, and provision of artificial cover and nesting sites. Additional information that may apply to a given project is given by Hynson et al. (1985). A CE Wildlife Management Manual that is currently being prepared provides additional information on preservation of terrestrial habitat that should be beneficial to project designers.

308. Preserving and developing terrestrial habitat on flood control channel projects is a relatively recent concern. Table 15 illustrates the variety of concepts for terrestrial habitat improvement found in the flood control channel projects that were surveyed. Evaluation is not possible since none of the projects has been constructed yet, and specific feature design and detailed cost estimates are not available.

Placement of excavated material

309. The most common practices for disposing of material excavated

from channels have been to use the material as fill for severed oxbows or as windrow material at the angle of repose along one side of the channel, to construct levees and access roads, to fill low-lying areas and wetlands, and to spread the material in agricultural areas. Adverse impacts of these practices include destruction of wetlands, disruption of surface drainage, erosion of fill material, leaching of pesticides and other pollutants, temporary loss of vegetative cover in fill areas, and killing of large trees.

310. Selective placement and treatment of excavated material offers opportunities to reduce impacts and enhance environmental conditions in many situations. In flat areas, excavated material may be piled and shaped to provide visual contrast and recreational opportunities such as sledding or skiing. It may be used in levees or berms to create wetlands (paragraph 300-305) or to control side drainage that might otherwise erode channel banks. Disposal areas may be selected and designed to replace lost wildlife habitat and provide refuge from flooding. In rural areas in Indiana, the SCS has used excavated material to build low windrows to mark the limits of buffer strip easements. These windrows help keep agricultural equipment out of the buffer zone.

311. Environmental considerations that should be included in site selection for placement of excavated material include existing site habitat value and relative abundance of that habitat in the general vicinity, the topography of the site and its potential for flooding, proposed use of the disposal site and its compatability with existing and projected adjacent land uses, and the presence of rare or endangered plants and animals.

Habitat development

312. Habitat development on flood control channel projects is by no means restricted to disposal areas, although they offer excellent opportunity to replace lost habitat with habitat of equal or superior quality. A good example of a project design that includes terrestrial habitat development on disposal areas is the Lower Rio Grande Basin, Texas, Flood Control and Major Drainage Project. The procedure to be used in habitat development was synthesized by Martin (1981) from

several reports about terrestrial habitat development on dredged material disposal sites (Coastal Zone Resources Division, Ocean Data Systems, Inc. (CZRD) 1978; Hunt et al. 1978; Lunz, Diaz, and Cole 1978; Smith 1978; Waterways Experiment Station (WES) 1978). The procedure discussed in the following sections is based largely on Hunt et al. (1978) with minor modifications, and although it was formulated for dredged disposal sites, it is equally applicable to other types of terrestrial sites.

313. Planning. Planning for habitat development includes several steps--site selection, site evaluation, definition of habitat goals, and selection of plant species and method of propagation. After sites are selected based on initial considerations discussed in paragraph 311, their physical and biological properties should be analyzed. The analysis should cover topography, elevation, dimensions, plant and animal species, and detailed soil characteristics. Functional relationships between the site and surrounding areas should be established.

314. Terrestrial habitats can be developed to benefit target species or to promote species richness. Plant species selection depends on which goal is selected. Native plant species that are hardy, well-adapted to site conditions, and have high habitat value should be used. CZRD (1978) presents information about 100 plant species that provide food and cover for wildlife, including brief descriptions of the plants and their life histories, soil and habitat requirements, brief guidelines for establishment and maintenance, diseases and insect problems, and habitat value.

315. Hunt et al. (1978) provide tables to help in selecting propagule type for various species based on factors such as cost, ease of handling, ease of planting, etc., and guidelines for collecting and storing propagules. Seeds are cheap and readily available for most grasses and herbaceous plants. Woody species are usually transplanted. Many native species preferred for their habitat value are not ordinarily available from commercial sources and may have to be transplanted from nearby locations. A list of private and agency sources for various plants in each state is provided in Hunt et al. (1978). Sources of

native seeds and plants are given in a recent publication of the Soil Conservation Society of America (SCSA 1982).

316. Construction. The construction phase includes placement of fill material, seedbed preparation, and vegetative establishment. Topsoil should be stripped from disposal sites and stockpiled prior to placement of excavated material. After excavated material has been deposited, the site may require grading, replacement of topsoil, soil treatment, and fertilization prior to seedbed preparation. Guidance for these steps can be obtained from the local SCS office. Seed may require scarification or stratification before planting to improve germination and growth. Timing and planting techniques vary with species. General planting methods are discussed by Hunt et al. (1978).

317. Maintenance and management. Habitat sites may require longer development times and closer monitoring and maintenance than other project components. Martin (1981) estimates that 10 years will be required to develop habitat lands on the Lower Rio Grande Project suitable for transfer as wildlife habitat. Procedures developed for monitoring and management should address the physical condition of the site and vegetation. Guidelines for maintenance and management can be found in Hunt et al. (1978).

318. Fencing of habitat areas to exclude domestic livestock reduces pressure on these resources, especially during the critical early stages of establishment. The Lower Rio Grande Project includes plans for 200 miles of fencing to project brushland and grassland habitats. Fencing must not interfere with wildlife movements. Guidance for fence construction can be found in the Wildlife Habitat Improvement Handbook (Forest Service 1969).

Preservation of cutoff islands

319. Islands created when bendways are severed are ideal habitat sites. They are usually well vegetated with species adapted to the site conditions. The isolation afforded by the surrounding channels is an asset, particularly for development of wildlife refuges. The habitat value of existing vegetation can be assessed using the habitat evaluation methods described in paragraph 304. If existing habitat value is

low, a management plan can be developed that allows replacement of species with low habitat value by species with higher habitat value. The value of cutoff islands as terrestrial habitat is enhanced by the close proximity of water and aquatic habitat in the bendway and flood channel.

Artificial cover and nesting areas

320. Otherwise acceptable areas often provide poor habitat because of lack of desirable nesting and den sites and cover. Removal or thinning of underbrush may destroy critical cover for birds and small animals. Animals and birds that are cavity nesters, such as squirrels, woodpeckers, and wood ducks, often have difficulty finding suitable den trees. Even when care is taken to preserve existing den trees, supplemental nesting facilities may be necessary. Loosely piled brush provides good cover for small mammals and ground-dwelling birds. Detailed specifications for nest box and brushpile construction, placement, and maintenance can be found in the Wildlife Habitat Improvement Handbook (Forest Service 1969).

Aesthetic Considerations and Features

321. The visual impact of a flood control channel project is probably the factor that most influences its acceptance by the public. While it is true that aesthetic values are very personal and highly variable, beneficiaries of flood projects are likely to be more tolerant of aesthetic degradation than persons not directly affected. However, experience with modified channels has shown that they often possess qualities that are considered to be aesthetically inferior by most people. The foremost factors that contribute to aesthetic degradation are:

a. Large channel size in relation to natural streams and other landscape components.

b. A straight ditchlike appearance resulting from uniformity of cross section, alignment, grade, texture, and color.

c. Use of nonnatural materials in channel construction and bank protection.

d. Loss of natural riparian vegetation.

e. Empty looking channel caused by narrow and/or shallow flow conditions except during high flow.

f. High turbidity, heavy algae growth, and other indications of poor water quality.

g. Caving or eroding banks.

322. Negative aesthetic impacts can be reduced by designing flood channels with a more natural appearance. This can be accomplished, in part, by designing channels with meandering alignments, asymmetric cross sections, low flow channels, and pool and riffle grades; by disturbing vegetation as little as possible and revegetating disturbed areas with native species; by using natural materials rather than man-made materials where possible; and by using special treatments and innovative landscape design to improve visual effects. Landscape architects can provide invaluable input to an interdisciplinary design team. EM 1110-2-38 (OCE 1971c) specifically encourages curved alignments for flood channels for aesthetic reasons and stresses the need for preserving major trees and vegetation, scenic points, and historical features. It also suggests contouring and landscaping excavated material disposal areas, special aesthetic treatments for concrete channel walls, and use of wood fences or colored, vinyl-clad woven wire fences to improve project aesthetics. These and other aesthetic treatments used on CE projects are described in the following sections.

Description of aesthetic features

323. Aesthetic treatments for lined channels, paved surfaces, and concrete. CE projects surveyed for this study used several types of aesthetic treatments for lined channels, but most of these were found in a relatively small number of projects designed by a few Districts in the south-central and southwestern United States. Many streams in these areas are intermittent, and most others have highly variable flow. Flood channels are frequently lined and stand empty, or nearly empty, most of the time, exposing the channel bottom and sides.

324. Concrete is the most widely used channel lining, and the most common treatment is brushing the surface while wet to provide a textured finish. Special form liners are often employed to produce

special textured effects (Figure 18), and color is sometimes added to the concrete to further enhance its appearance. Stone columns (pilasters) and natural stone facings have also been used effectively on some projects to improve aesthetics of concrete channels (Figure 29). Murals have been painted on wall surfaces on a few projects. Local artists were invited to paint murals on the channel wall of Tujunga Wash (USAED, Los Angeles 1975), and they responded with a colorful display of art depicting local history (Figure 54). Indian Bend Wash floodway is a good example of the use of a wide variety of pavings and finishes to achieve aesthetic effects in differing circumstances (Table 16) (USAED, Los Angeles 1973).

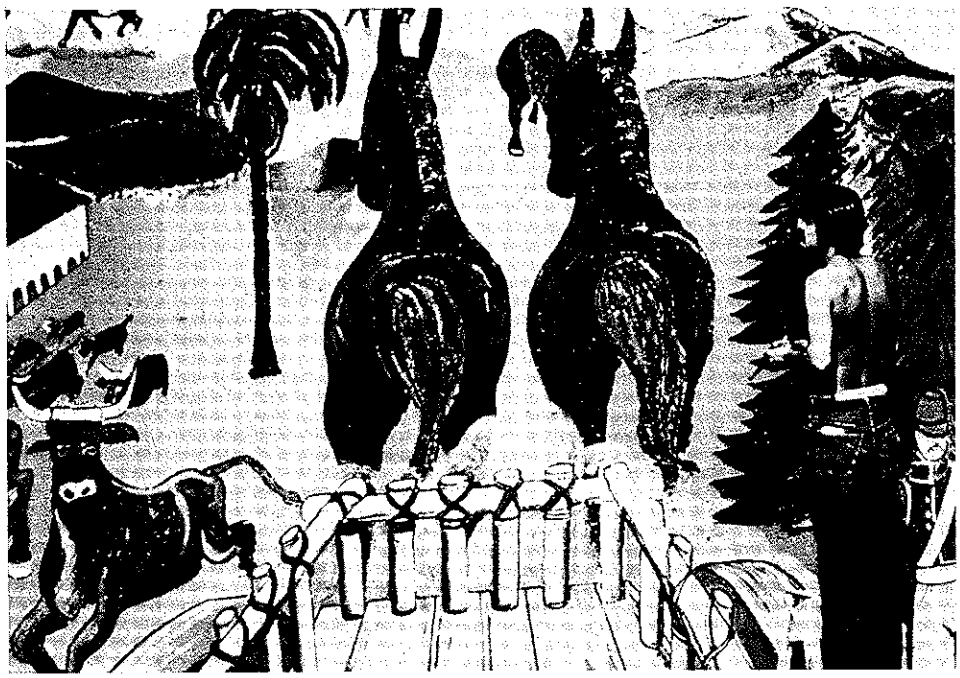


Figure 54. Decorated flood channel wall, Tujunga Wash, Los Angeles, California. Local artists were allowed to paint murals on the channel walls. (photo by Los Angeles District)

325. Water displays. Urban flood channels are often used as focal points for park and greenway systems. Waterfalls, cascades, fountains, and reflecting pools have been used to improve the visual effect of channels in parks that are used primarily for passive recreation. Reflecting pools designed for the Duck Creek Project (USAED, Fort

Worth 1970) were to be impounded by grouted sills about 1 ft high that would also serve as a base for stepping stones. The water display for the Flint River Project (USAED, Detroit 1974) is the focal point of the urban park in which it is located (Figure 55a). Water for the display is provided by an Archimedes' screw (Figure 55b). Decorative fountains, lakes, and ponds built only for aesthetic or recreational reasons are not eligible for inclusion on flood channel projects under current CE policy.

326. Preservation of trees and vegetation. It is CE policy to plan channel alignments "to preserve major trees or vegetation, scenic points, or historic buildings that may be adjacent to channels and floodways" (OCE 1971c). Care should be exercised to protect trees from damage by heavy equipment during construction. Heavy equipment traffic can damage root systems and scar tree trunks. Large pecan and cypress trees along the San Antonio River were protected by placing shims around them (Figure 56) and requiring contractors to pay for damages incurred during construction (USAED, Fort Worth 1981). The cost of tree protection was approximately $1700 per tree (1981 price level), which is a fraction of the aesthetic value placed on the trees by the local sponsor, the San Antonio River Authority.* Tree wells may be needed if excavated material is to be placed around trees. Because tree wells may be expensive ($3500 in 1978 dollars) for the Corte Madera Project (USAED, San Francisco 1980a, b), other options should be considered for disposing of excavated material. Mounding of excavated material can add visual contrast to monotonously flat landscapes (Figure 57). In some locations, mounds can also provide recreational opportunities for sledders and skiers.

327. Grass, trees, and shrubs. Grass, trees, and shrubs are used for beautification on most CE flood channel projects. Costs for establishing ground cover vary with type of cover, method of propagation, extent of seedbed preparation, and fertilization. Table 16 shows the range of costs for representative designs. Costs for trees and shrubs

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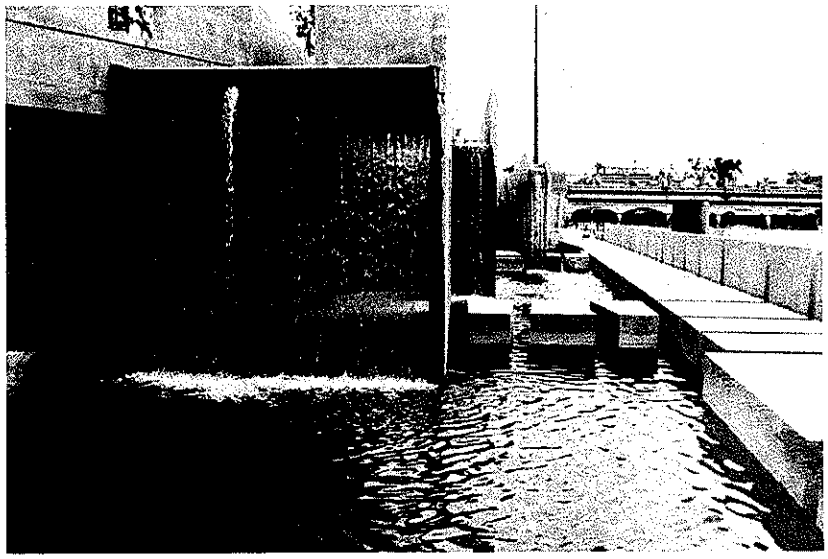
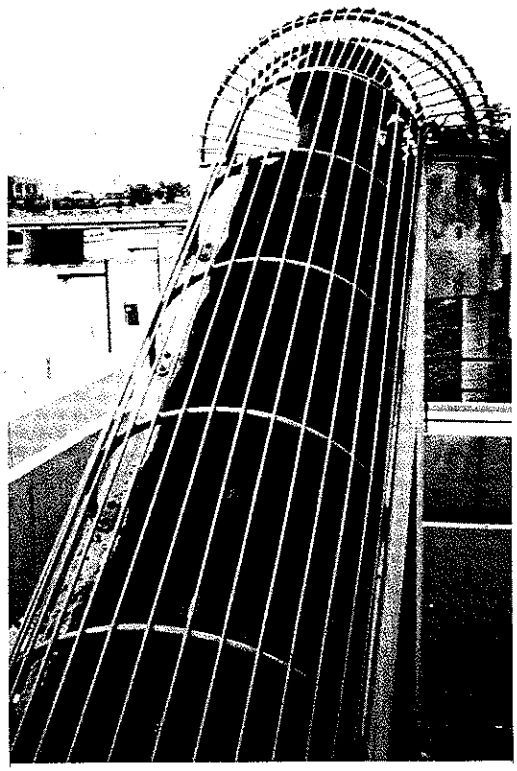
* Personal Communication, August 1983, R. Cate, San Antonio River Authority, San Antonio, Texas.



a. Water for the waterfalls



b. Archimedes' screw

Figure 55. Water displays, Flint, Michigan

Figure 56. Tree protection, San Antonio River, Texas. Shims were placed around the trees to protect them from construction damage. (photo by Fort Worth District)

Figure 57. Mound of excavated material, Souris River. Spoil mounds can add visual contrast to monotonously flat landscapes.

used in the surveyed projects are not included because the tremendous variety in species and sizes makes it difficult to summarize costs in a meaningful way. Standard sources such as Lehigh (1983) and McMahon (1980), which are published annually, are available for estimating landscaping costs. Good maintenance is critical to the success of any landscaping effort. Appendix D contains the proposed landscaping maintenance requirements for Walnut Creek Flood Control Project (USAED, San Francisco 1979).

328. Irrigation. Permanent irrigation is required for turf in park areas located in deserts and semiarid regions. Irrigation costs vary with the type of system and location. In some cases, costs may be reduced by using the channel as a source of irrigation water. Even if permanent irrigation is deemed to be unnecessary, it is often advisable to water grass and trees until they become well established. Temporary irrigation is sometimes best accomplished by watering from a truck. Some contracts specify performance criteria, such as survival rates of 80 percent after 2 years.

329. Special considerations. Special circumstances sometimes warrant innovative designs to achieve maximum aesthetic impact. Vines and climbing plants planted near fences can lessen the visual impact of the fence. The Chartiers Floodway, Pennsylvania, adjoins a historic property with a house that dates from the Whiskey Rebellion of 1794. The normal planting scheme was altered to allow fruit trees, grape vines, and other domesticated plants typical of the period to be planted on the project right-of-way adjoining the historic property (Figure 58). Also, in the same vicinity, special architectural treatment was provided for the sidewalls of the stilling basin just downstream from a major drop structure.

330. Planters. Specially constructed planters can be used in intensively used park areas to highlight and protect expensive plantings. Costs of the planter pockets along the San Antonio River (shown under construction in Figure 59) varied in size and shape, but one approximately 80 ft × 10 ft × 5 ft (l × w × h) cost about $29,000 in 1981 dollars (USAED, Fort Worth 1981). Planters have also been used on the

Figure 58. Special landscaping, Chartiers Creek, Pennsylvania. A rail fence and domestic plants typical of the colonial period were used to reinforce the historic setting of the Neville House.

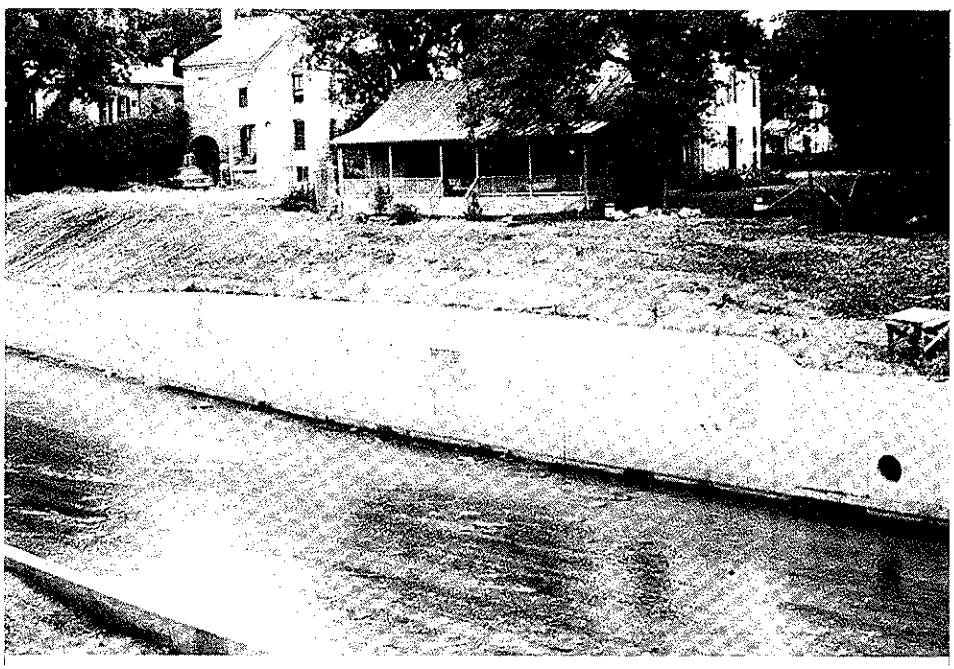


Figure 59. Planter pockets (under construction) on the San Antonio River. Planter pockets are used to highlight and protect expensive plants.

Flint River (USAED, Detroit 1974), Tujunga Wash (USAED, Los Angeles 1975) and South Platte River Projects.

331. Fencing. Fencing is employed on flood channel projects to restrict access to certain areas for security purposes, improve safety, restrict livestock, and mark project boundaries. On urban projects, substitution of colored, vinyl-clad wire and wood for ordinary wire fencing is encouraged (OCE 1971c). The redwood fence on Tamalpais Creek (USAED, San Francisco 1978) is a good example of effective use of wood to enhance project aesthetics (Figure 18).

332. Architectural treatments. Architectural facilities for flood channel projects should be designed to blend harmoniously with other project components and the surrounding environment. The rough finishes and natural earth colors used on Indian Bend Wash promoted a desert theme and helped integrate natural and man-made features. On the Souris River, the appearances of structures varied with location. In nonpark areas, buildings for pumping stations were traditional in appearance, whereas more aesthetically pleasing designs were used in park areas (Figure 60).

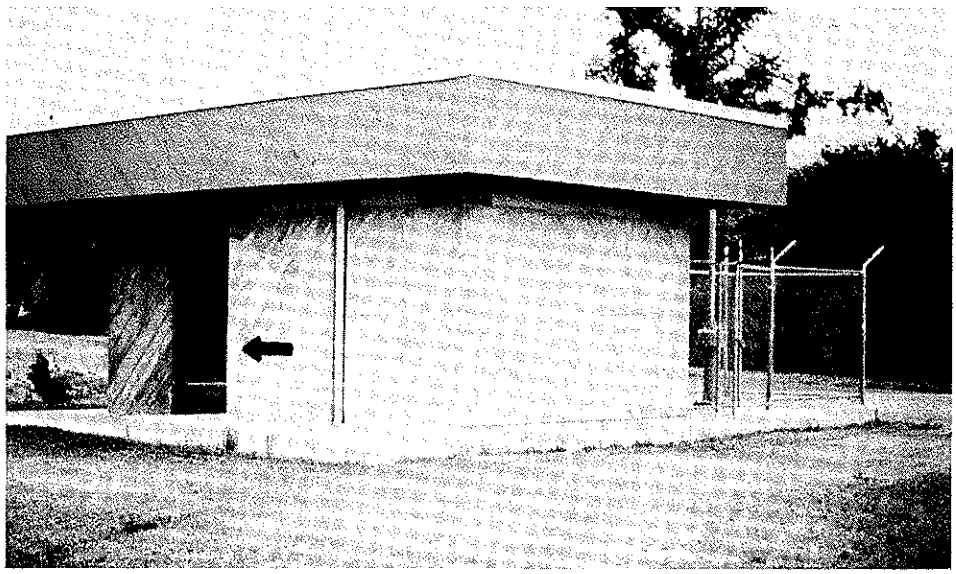


Figure 60. Pumping station architecture, Souris River, North Dakota. A special building design and colored, textured concrete were used in park areas. The object in the left corner (arrow) is a fireplace for public use.

333. Bridges and low water crossings. Pedestrian bridges and channel crossings can be aesthetic assets if they are attractively designed. Reinforced concrete and wood are the most common construction materials for bridges. A "breakaway" pedestrian bridge was designed for the South Platte Greenway (Figure 61) (Shoemaker 1981). One end of the structure is anchored with a cable (Figure 62). During floods, the wooden structure floats off its abutments and swings downstream. After the flood subsides, it is hoisted back onto its supports. These bridges have not yet been tested by a flood. Some of the bridge designs used on CE projects are illustrated in Figure 63.

334. Low water crossings for hike and bike trails are used primarily in flood channels that are often dry or convey very low flows much of the time. Many of these crossings are built directly on the flood channel invert, such as the one at Indian Bend Wash, Arizona (Figure 64). Others, such as the stepping stone design discussed in paragraph 325, are constructed for aesthetic effects. A similar design was used on Apache Creek in San Antonio, Texas (Figure 65). In addition to the aesthetic benefits, raising the crossing above the channel invert allows it to be used during low flow. If such crossings are heavily used, measures may be required to exclude users from the crossing and channel area when high flows are imminent.

Design of aesthetic features

335. Aesthetic response is a highly personal reaction to a perceived image. Nevertheless, there usually is some general agreement as to what is very attractive or very ugly. "The real problems exist within the ambiguous middle range of the natural beauty continuum" (Newby 1971). Designers should try to make flood control channel projects as attractive as possible to ensure a generally positive aesthetic response. A landscape architect is a valuable and sometimes necessary member of the channel design team.

336. All landscape components possess properties that contribute to their visual impact. The most important of these are color, form, line, texture, scale, and spatial character (Sheppard and Newman 1979, Smardon 1981). Color refers to an object's light-reflecting properties;

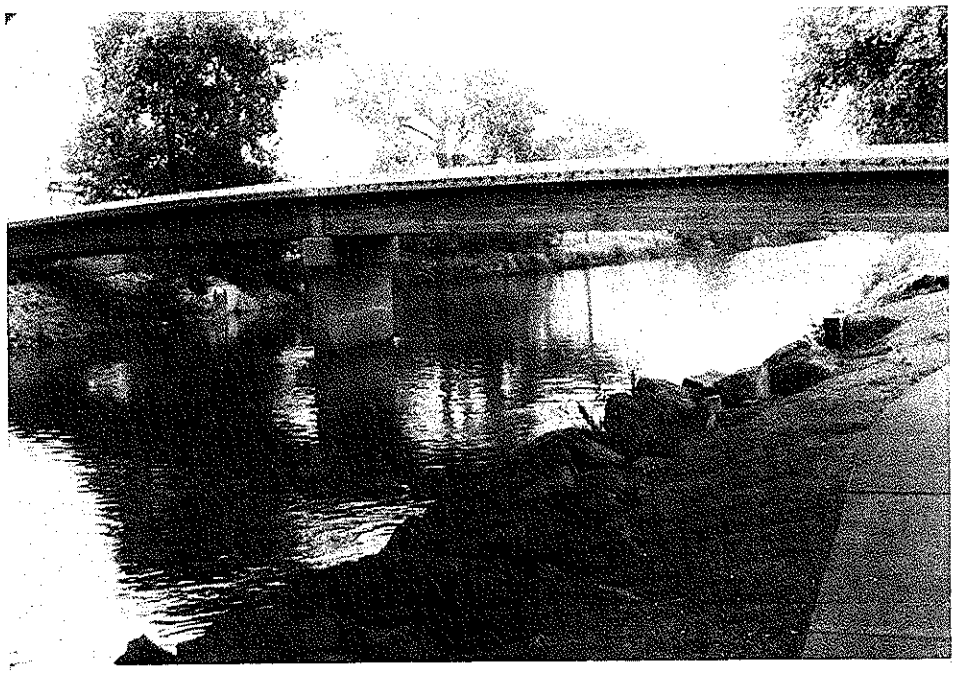
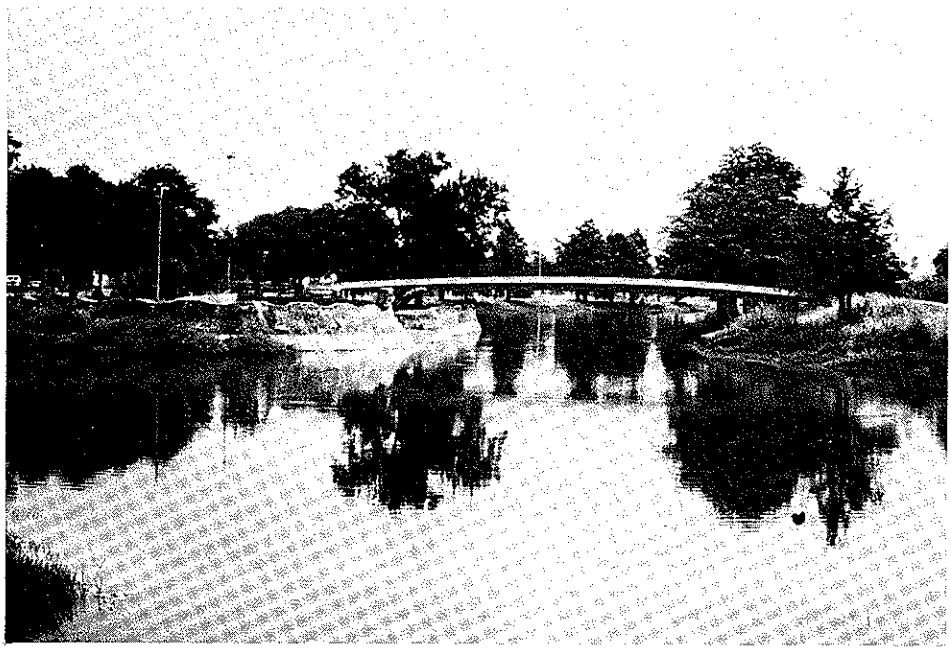


Figure 61. Floatable bridge, South Platte River, Denver. The wooden bridge, which is below the design water surface elevation, floats off its abutments during floods.

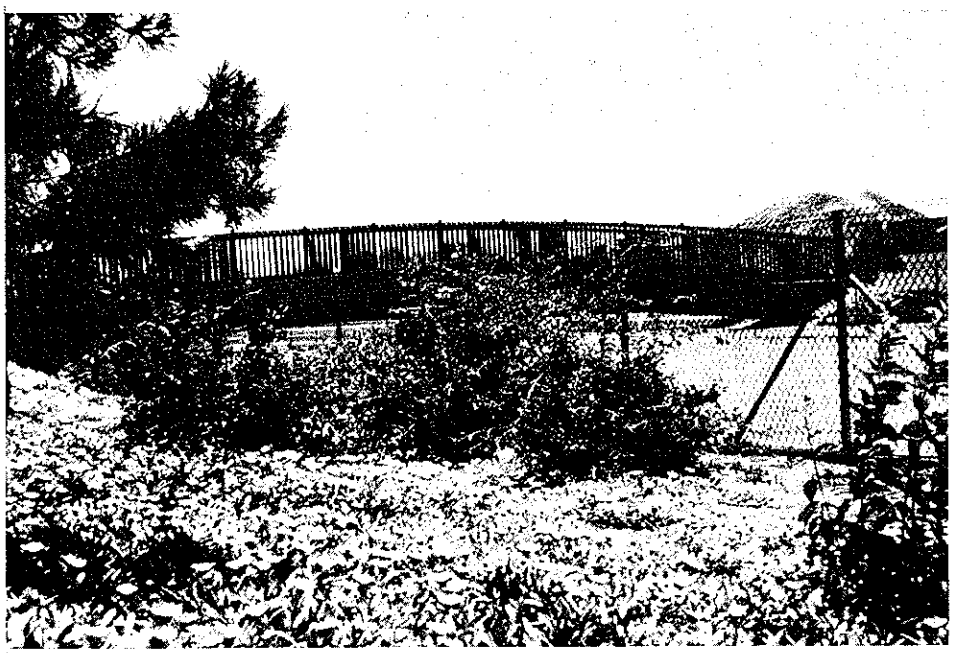
Figure 62. Floatable bridge over South Platte River, Denver, is anchored with a steel cable

a. Sandy Lick Creek, Dubois, Pennsylvania
(photo by Pittsburgh District)



b. Apache Creek, San Antonio, Texas

Figure 63. Pedestrian bridges on CE flood channel projects (Continued)



c. Tujunga Wash, California (photo by Los Angeles District)

Figure 63. (Concluded)

Figure 64. Low water crossing, Indian Bend Wash, Arizona. This trail crosses the floodway channel invert which carries flow only during flood events.

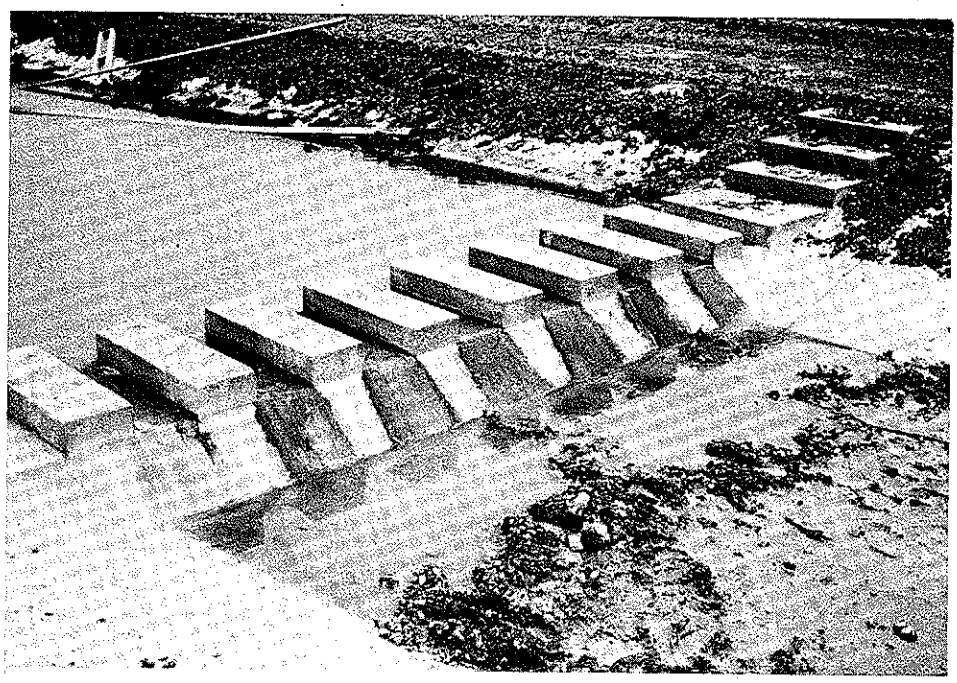


Figure 65. Low water crossing, Apache Creek, San Antonio. The stepping stone design is built on a low sill that serves as a water control structure.

form, to its shape; line, to the path followed by the eye when viewing an object (usually evident as the edge or outline of an object); texture, to the aggregation of small forms or color mixtures into a larger pattern; scale, to the proportionate size relationship between an object and its environment; and spatial character, to the object's placement or arrangement in three-dimensional space (Sheppard and Newman 1979). All of these properties can be manipulated, to some extent, in project design to increase positive visual effects. However, scale may be constrained more than the other properties because of its dependence on object size and the limitations on choice of size for most project features.

337. Channel linings, paved surfaces, and concrete. Vegetation is usually the most aesthetically appealing cover for channels, banks, and large open areas. Natural materials such as gravel or cobble may be used effectively in channels that require nonvegetative linings, if velocities are not too high, and for paved areas. The aesthetic effect in channels is best if linings can be restricted to channel inverts and toe slopes. Natural materials possess colors, forms, and textures that are aesthetically superior to ordinary concrete. The appearance of concrete can be improved dramatically, however, by using natural earth colors such as browns, tans, and siennas and by texturing the surface or using special form liners to create appealing patterns. Guidance for aesthetic treatments of concrete is available in EM 1110-2-39 (OCE 1969).

338. Water displays. Water is an extremely important aesthetic component of the landscape (Litton et al. 1974). Leopold (1969a, 1969b) has indicated the importance of rapids and falls in evaluating the scenic beauty of river landscapes. Project designers can capitalize on this by using falls, fountains, cascades, and reflecting pools as focal points. Sills and deflectors can be used to create turbulent cascades in flood channels that may add considerably to their attractiveness while serving as needed energy dissipators. Water displays rely primarily on the manipulation of form, line, texture, and spatial character of water for their effect. Water displays generally require several feet of head and continual flow. Grade control and water level control

structures are good locations for water displays.

339. Topographic modification. Landscaping involves modifying site topography and vegetation and placing structures to achieve desired visual effects. Topography can be modified by placement of excavated material and site grading. Excavated material may be molded into the topography or it may be used in flat terrain to create hills or mounds for aesthetic or recreational purposes. When feasible, all disposal areas should be contoured and landscaped to avoid unsightliness (OCE 1971c).

340. Ground cover. Ground cover, usually grass, should be planted as quickly as possible after final grading to control erosion and improve aesthetics. Good seedbed preparation and proper fertilization are essential for successful establishment of good ground cover. Advice on cover selection, seedbed preparation, and proper fertilization for specific site conditions can be obtained from the local SCS office. Detailed guidance for establishment of turf is available in TM 5-830-2 (OCE 1981a).

341. Trees and shrubs. Trees and shrubs can be selected and placed for maximum enhancement of color, form, line, texture, scale, and spatial character. Though circumstances vary at each site, general concepts to be considered in selecting and placing shrubs and trees are as follows:

a. Uniform spacing should be avoided, as it leads to monotonous views.

b. On large projects, maximum benefits are derived by concentrating plantings in areas of intensive use, high visibility, and superior aesthetic quality. Inaccessible and infrequently used areas can be allowed to undergo natural succession.

c. Newly planted shrubs and trees should be staked and may require protection from rabbits, beavers, or other animals. Stakes should be loosened as plants grow to prevent girdling.

d. Exotic species not in general use in the project area should be used with caution. Exotics may not adapt well to local climatic or edaphic conditions. Exotics that do adapt well and reproduce successfully may present special maintenance problems or become nuisance species.

e. If irrigation systems are not installed, plantings should be watered for a period long enough to ensure survival. Performance criteria guaranteeing minimal survival rates after a specified period may be desirable.

f. Trees and shrubs planted within flood channels should be selected, placed, spaced, and pruned so that they will not hinder flood flows. Hydraulic criteria used on Indian Bend Wash included the following: low ground-hugging cover, with shrubbery restricted to floodway fringes where design flood depths would not exceed 2.5 ft; blockage by trees limited to 3 percent of the flow width at any given section; trees aligned with flow and spaced a minimum of 60 ft apart; and trees pruned so branching occurred above flood level. Plantings on levees must conform to EM 1110-2-301 (OCE 1972a).

342. Fencing. Fencing can be designed to blend with the setting or to provide a major visual element. Blending is accomplished by choosing colors and/or substances that are natural in appearance and will not contrast sharply with surroundings. Colored vinyl-clad wire fencing and certain types of wooden fencing are commonly used for this purpose. If the fence constitutes a major visual element, ornamental iron or ornamental wooden designs may be used.

343. Architectural design. Structures should be designed and placed to blend harmoniously with other landscape elements and with the surrounding environment. Subdued earth colors, generous use of wood, and textured finishes are common components of structural design on some of the most attractive projects. Small structures within flood channels may be designed for removal prior to flooding, assuming that sufficient warning can be given. Permanent structures within floodways should be secured against flotation, made as floodproof as possible, and designed and located so that hydraulic resistance is minimal. The following guidelines were used on Indian Bend Wash.

a. Columns or poles were limited to a thickness of 24 in. and were included with trees in computing the allowable 3 percent obstruction limitation.

b. Obstructions were streamlined in the direction of flow.

c. Walls, fences, railings, and pedestrian bridges transverse to the flow direction were avoided insofar as possible.

d. Roofs of ramadas and other structures were designed with a minimum clearance of 2.0 ft above the maximum design water surface elevation.

e. Movable facilities such as picnic tables, benches, trash bins, etc., were secured or anchored to prevent displacement.

344. Bridges and low water crossings. Trail crossings for flood channels should be designed to be attractive as well as functional. Where feasible, low water crossings are cheaper and less visually intruding than bridges. Low water crossings often can be designed to produce negligible impacts on flood flows. Crossings may be placed on the flood channel invert (Figure 64) or raised slightly. The most commonly used raised designs are stepping stone designs (Figure 65) and culvert designs. Bridges normally should be higher than the design water surface elevation and should be designed not to trap floating debris. Floating bridges, such as the one used on the South Platte River, are exceptions. The Landscape Architecture Catalog File contains advertisements for prefabricated pedestrian bridges that float (Kerr 1983).

Recreation Features

345. National policy requires full consideration of recreation as a project purpose during the planning of water resources development projects (OCE 1982a). Well-designed recreational features can have a powerful positive effect on public perception of a channel project and of the CE as an agency. Project benefits may also be derived from recreation. Current CE policy limits Federal participation in recreation facilities

> ...to what may be termed basic recreation facilities. These are defined as man-made improvements to facilitate public use and enjoyment of project resources and include access roads and parking areas; picnic areas and campgrounds; beaches and bathhouses; playgrounds and game fields; boat launching, temporary mooring facilities, and sport fishing; hiking, snowmobile, horseback riding, and bicycle trails; and similar improvements for use of the general public

> which are not ordinarily provided by private enterprise or on a commercial or self-liquidating basis

(OCE 1982a). ER 1105-2-20 specifically identifies certain types of recreation facilities as ineligible for Corps participation, although they might be appropriate to a project. In addition to revenue-producing facilities such as motels, retail establishments, stables, etc., the following items are ineligible for inclusion in flood channel projects:

a. Decorative fountains and statuary.

b. Decorative lakes or ponds only for recreation or aesthetic purposes.

c. Elaborate playground equipment such as spray pads, wood and stone replicas of forts, castles, etc.

d. Decorative promenades.

e. Bleachers and dugouts.

f. Courts, except for general, all-purpose areas.

g. Golf courses.

h. Clubhouses.

i. Swimming pools.

j. Chairlifts.

k. Administrative buildings.

l. Visitor centers.

m. Amphitheaters.

n. Exhibit halls.

o. Shower buildings.

346. Recreation facilities on flood channel projects are cost-shared on a 50-50 basis with local sponsors. Many projects constructed or designed during the 1970s included extensive recreation facilities. In decreasing order of frequency, the projects surveyed for this study included hike and bike trails, picnic areas, playgrounds and game fields, nature study areas and nature trails, lakes for fishing and boating, wading and swimming pools, equestrian trails, overlooks, fishing facilities, amphitheaters and bandstands, campgrounds, plazas and pavilions, boat ramps, and canoeing/rafting facilities (Table 17). Indian Bend Wash included almost all of these items and many of the facilities on

the preceding list (paragraph 345), which are not allowed under present policy. It is clear that no project with a recreation component similar to that of Indian Bend Wash could be built under present policies. This section is confined to discussion of recreation facilities especially suited to flood channel projects and to unusual or innovative designs recommended for environmental reasons. General guidance for the planning and design of recreation facilities is provided in EM 1110-2-400 (OCE 1971b).

Trails

347. Discussion. Trails are the most popular recreational feature on CE flood channel projects. Trails intended for use by hikers and bikers are most often constructed of asphalt or concrete, although other materials are sometimes used. Table 18 lists the types of materials used and some representative costs. On the other hand, equestrian trails are usually graded soil and are correspondingly cheaper to build. In cold climates hiking, biking, and equestrian trails can double as snowmobile trails during winter.

348. Ancillary facilities that are often associated with hike-bike trails include parking and access areas, benches, picnic tables, water fountains, comfort stations, lighting facilities, and fencing. Equestrian trails have many of the same facilities, but also require staging areas with watering troughs.

349. Design considerations. The appropriateness of trails for channel projects is attested to by the fact that almost every project with a recreation component has a trail system. Foot and bicycle trails are used to interconnect recreation areas, connect project facilities to outside areas, tie into existing trail systems, and provide safe walking and riding in a pleasant environment. Trail design and operation should preclude conflicts between different types of users (e.g., equestrians, hikers, and bikers). Fences may be required along trails that pass through industrial neighborhoods or other areas where user safety could be a problem. Barricades should be provided in hazardous areas, and bollards (post and chain barriers) may be required to exclude off-the-road vehicles and other motorized vehicles from trails intended for

pedestrians and cyclists. Trails for motorized vehicles, such as trail bikes and snowmobiles, should be located far enough from sites used for unrelated activities that noise will not be a problem. Trails that tie into existing trail systems should be compatible in appearance and constructed to equivalent standards. Standards for trail construction can be found in National Park Service (1968) and Bureau of Land Management (1965).

350. Surfaces. Walking trails are generally surfaced for all-weather use. Wood chips or gravel can be used in normal traffic areas. In heavy-use areas and on dual-purpose hike-bike trails, asphalt or concrete is suggested. Hard-surfaced walkways and bike trails seemed to have fairly standard designs with compacted subgrades, a layer of gravel or slag, and a 2- to 4-in. layer of concrete or asphalt. An innovative grassed-bituminous trail consisting of 6 in. of slag or crushed stone over a compacted subgrade was proposed for Chartiers Creek (Figure 66).

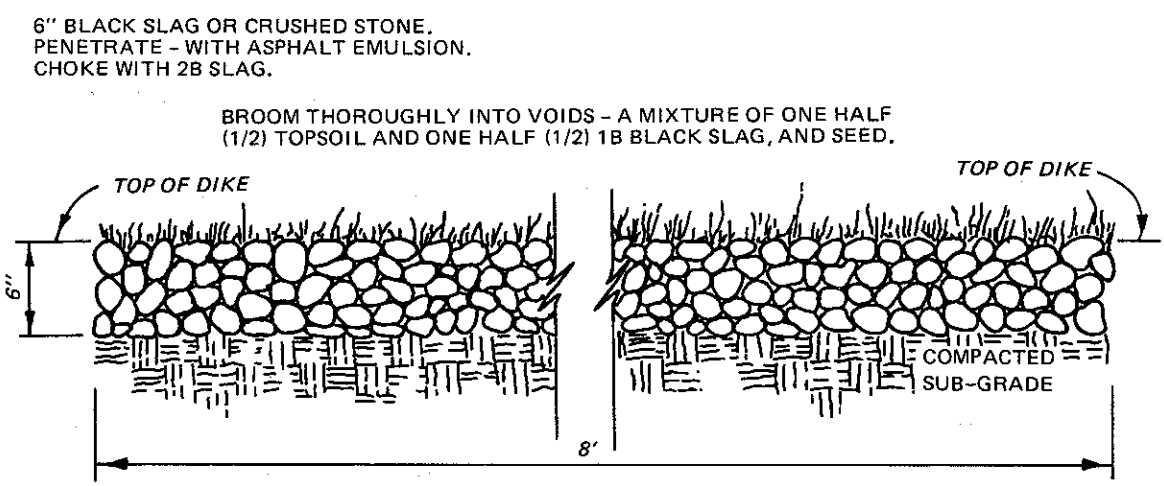


Figure 66. All-weather trail design, Chartier's Creek, Pennsylvania. This unique design consisted of grass planted on a surface paved with slag. (USAED, Pittsburgh 1973, 1974)

The slag was to be penetrated with asphalt emulsion and choked with 2B slag. A mixture of half topsoil and half 1B black slag and seed was to be brushed into the voids to establish the vegetative cover (USAED, Pittsburgh 1973, 1974). The contractor was not able to implement the concept successfully, even though it had been used sucessfully in a

local park. When the contractor reached the final stage at which the mixture of topsoil and grass seed was to be swept into the voids, no voids were left, and a rough bituminous path was the result. The walkway in the park supports about a 50 percent cover of grass that is natural in appearance and does not require mowing. Equestrian trails are usually constructed of graded soil. A good system of signs that provide directions, distances, and locations for major points of interest can enhance the value of a trail system. Well-designed signage also can help establish a motif and improve project aesthetics.

351. Extensive trail systems usually require grade separated crossings at street and road intersections for safety reasons. Underpasses that parallel channel alignments are common (Figure 67). Bridges or low water crossings are used where trails intersect channels. Design of these facilities is discussed in paragraph 344. Consideration should be given to access by handicapped persons in designing hiking trails in urban areas.

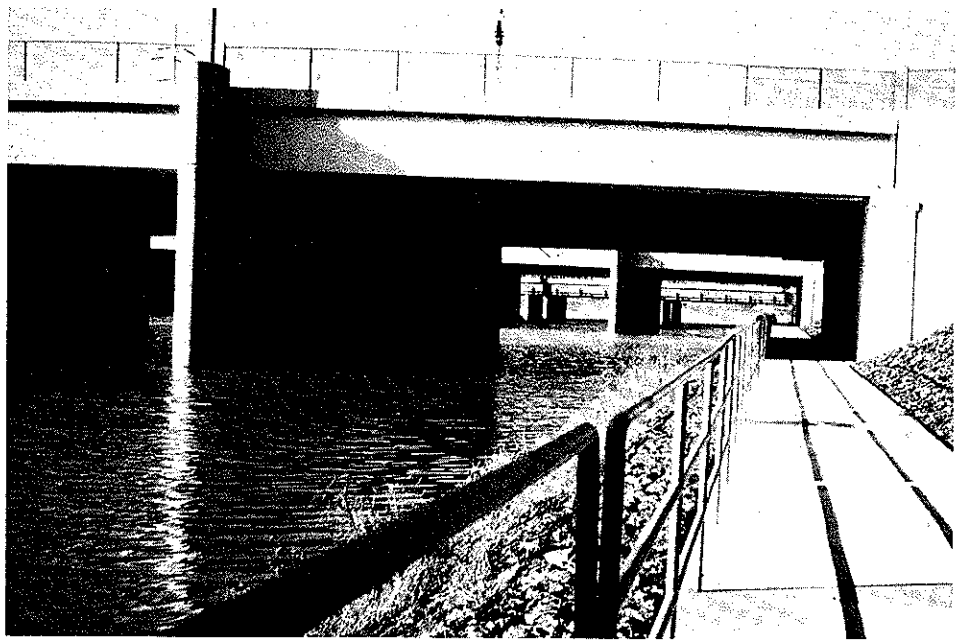


Figure 67. Trail underpass, Fourmile Run, Maryland. For safety reasons, most trails require grade separated crossings where they intersect major streets or thoroughfares.

Playgrounds and playing fields

352. Discussion. Playgrounds and sport facilities are popular components of many flood channel projects that incorporated public parks and greenways. These parks often contained swimming pools, tennis courts, ball diamonds, soccer and football fields, and other facilities built for specific games. Under current CE policy, such facilities are ineligible for Corps participation. General purpose play areas and playgrounds are eligible so long as the playgrounds contain no elaborate equipment (paragraph 345).

353. Design considerations. Local sponsors of urban flood control projects often request recreation plans that include playgrounds and game areas. Though current policy no longer permits construction of special purpose facilities such as tennis courts and softball diamonds, general-purpose playing fields can be constructed. Children's playgrounds can also be included so long as they do not employ very elaborate designs. Playgrounds and playing fields are well suited for projects that include parks and campgrounds.

Nature areas and trails

354. Discussion. Severed bendways, cutoff islands, and wetlands maintained in their natural state and areas developed for wildlife habitat are often used as nature study areas. Trails constructed in nature areas are usually primitive in design and require little more than vegetative clearing and marking, although if they experience heavy use, wood chips, gravel, or other cover may be required to prevent erosion. Nature areas are sometimes designated as wildlife conservation areas and may be fenced for protection. Facilities found at nature areas range from none in some cases to parking areas, restrooms, interpretive displays, and signs identifying features of interest.

355. Design considerations. Locations that are best suited for development as nature areas are natural areas that support unusual or unique ecosystems, which possess a variety of natural conditions (geology, soils, etc.), or which are rich in biological diversity. Nature trails with interpretive displays and signs identifying features of interest have increased value as outdoor classrooms and learning resources.

Trails, signs, and structures should not detract from the natural theme of nature areas. "Rustic" designs are often favored (Figure 68).

Fishing access areas

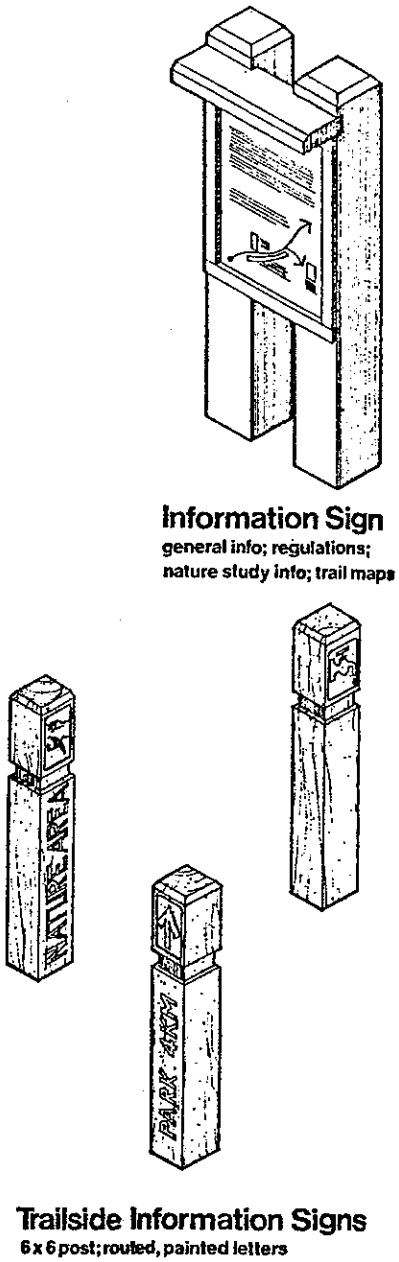
356. Discussion. Fishermen are often attracted to weir pools, stilling basins, and other locations with deep water or good fish habitat. Developed fishing access areas encourage fishing activity while protecting banks and streamside vegetation at other locations from traffic. The Chillicothe Local Protection Project (USAED, Huntington 1975) included $15,000 (1973 price level) to build three simple structures at popular bank fishing sites (Figure 69). The design for the Hocking River at Logan, Ohio, includes an eight-car parking lot and a 1000-ft streamside trail for fishing access (USAED, Huntington 1978).

357. Design considerations. Fishing access areas are usually located at easily accessible pools or structures that attract fish. Access areas may include parking space, boat ramps, water supply and sanitary facilities, trails, and structures. Fishing structures can consist of platforms, piers, or bulkheads such as the one shown in Figure 69. For safety reasons, fences or railings should be provided along platforms or steep banks.

Boating, canoeing, and rafting

358. Discussion. Recreational boating is a popular activity on many flood control channels. If heavy boating use is anticipated, channels should be designed to provide adequate access, suitable low flow depths, and as few obstructions as possible. Minimum dimensions of low flow channels that will accommodate rowboats and canoes are discussed in paragraph 128. Sills and fish habitat structures should be designed so that they will not present obstacles and danger to boaters during low flow conditions, and safe portages should be provided around obstacles such as drop structures and weirs. Appropriate warning signs are needed upstream of such structures. Boating is normally prohibited when discharges exceed a certain amount.

359. It is often possible to modify dams and other structures to allow passage of canoes and rafts. A fabridam located on a reach of the South Platte River downstream of a proposed CE channel project was



a. Wooden signs with routed painted letters blend well with natural settings such as nature areas and trails (after USAED San Francisco 1979)

b. Platte River Greenway trail sign

Figure 68. Information signs

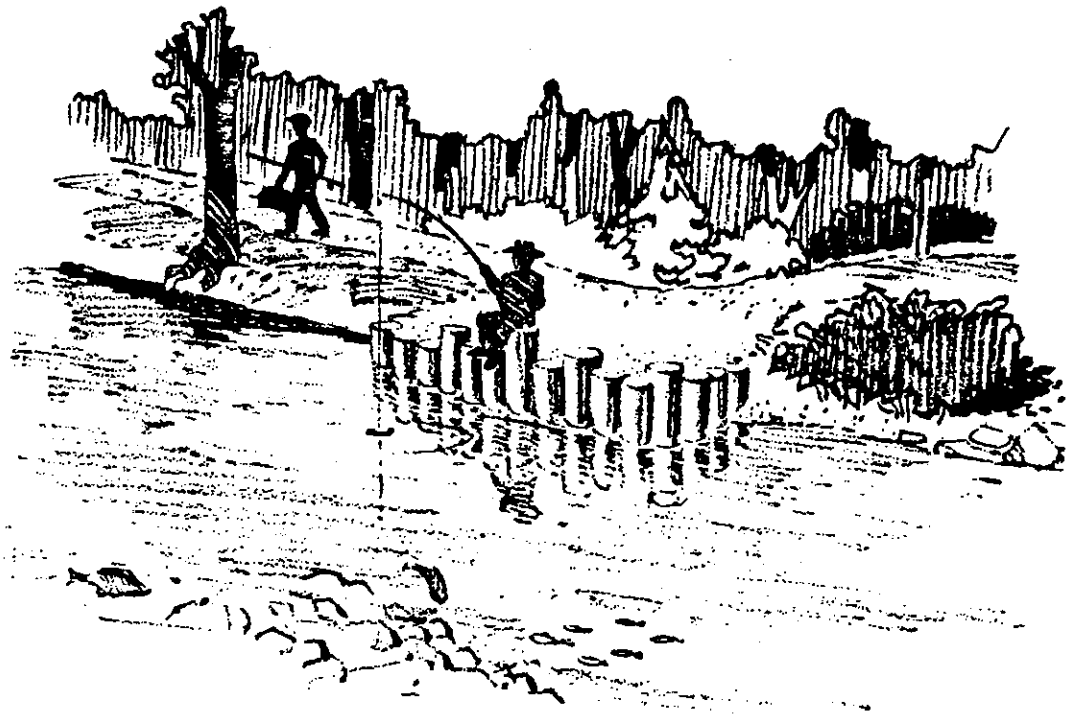


Figure 69. Bank fishing structure. Three of these bulkhead-type structures are planned for the Chillicothe Local Protection Project. (USAED, Huntington 1975)

modified in 1977, at a cost of $140,000, to allow passage by skilled boaters. The boat chute is a concrete and metal slide hinged at the base and resting on the inflatable rubber dam (Figure 70). A second boat chute, designed to accommodate novice boaters and inner tubes, was constructed further downstream on the South Platte in 1975. The Confluence Park chute consists of 12 pools and weirs dropping a total of 10 ft over a run of 330 ft (Figure 71). Flow is regulated by a fabric dam at the upstream end. However, the flow regulation is for water rights stipulations, not boating. "Carry-down" boat ramps are provided at numerous access points along the stream.

360. Recreational boating on streams has increased in popularity in recent years. A 1980 survey of whitewater boating in Colorado revealed that boating use days on the South Platte River through Denver increased from 1500 days in 1976 to 2900 days in 1980 (Environmental Research and Technology 1980). This indicates that facilities such as the

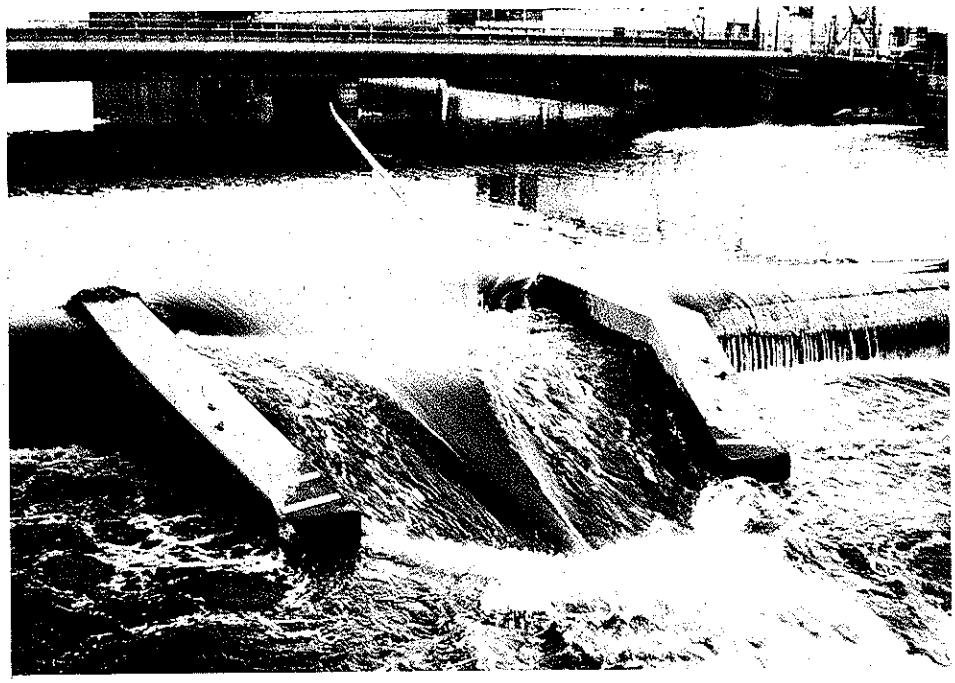


Figure 70. Zuni boat chute, South Platte River, Denver. The rubber fabridam has been modified with a concrete and metal slide to allow passage of canoes and rafts.

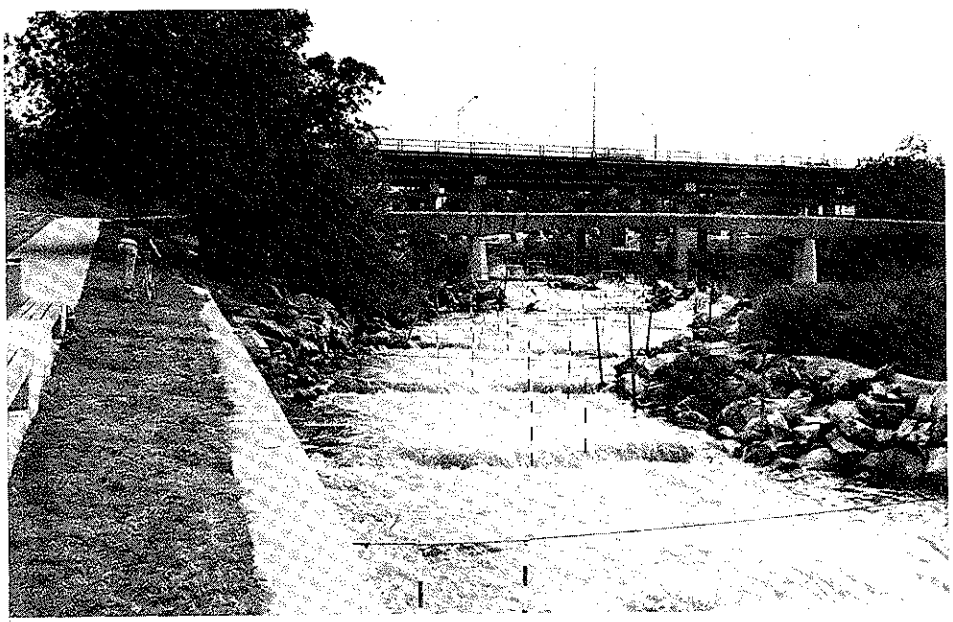


Figure 71. Confluence Park boat chute, South Platte, River, Denver. Confluence Park chute consists of a series of 12 pools and weirs that drop 10 ft over a run of 330 ft. Poles mark a kayak slalom course.

Confluence Park boat chute included in CE projects could attract large numbers of users. Flood control channels are often well suited for boatways because of public control of streamside areas.

361. Design considerations. Studies should be undertaken to ensure that flows and water quality are adequate before boatways are planned for flood channels. A whitewater boat chute similar to the one on the South Platte can be provided on flood channels with moderately steep reaches that fall several feet over a relatively short distance. Boat chutes are simple to design, consisting of a series of low rock sills (notched or unnotched) or paired flow deflectors that drop 6 to 12 in. each. Paddleways can be developed on streams with low gradients. If necessary, water depths can be increased by using low flow subchannels or by constructing a series of water control structures to create pools that extend from the base of one structure to the crest of the next structure downstream.

362. Development of successful whitewater streams and paddleways requires that weirs, drop structures, and other barriers be bypassed or modified for boat passage, or that safe portages be provided around those that cannot be modified. Appropriate warning signs are needed upstream of boating hazards, obstacles, and boat chutes. For safety reasons, all boating is usually prohibited when discharges exceed a certain amount. Provision should be made for indicating unsafe discharges. Clearly marked staff gages or removable warning signs should be located at all boating access points. A sufficient number of access points with adequate parking must be provided for launching boats.

Scenic overlooks

363. Description. Scenic overlooks are often planned for accessible sites with attractive views. Parking areas are usually provided at overlooks, and some also have picnic facilities, restrooms, and associated facilities. Overlooks are relatively inexpensive compared to some other recreational facilities, but they can effectively enhance project visitation.

364. Design considerations. Overlooks should be located at sites that provide attractive views of flood channels and the surrounding area.

Overlook parking areas should contain a minimum of 10 spaces (10 by 20 ft), but no more than 30 (OCE 1971b). Additional facilities that may be included are buildings, covered observation platforms, benches, restrooms, water supplies, trash receptacles, and signs or displays that describe the nature and extent of the project.

Campgrounds and picnic areas

365. Discussion. Picnic areas are the second most often included recreational facility found on CE channel projects. Although some picnic areas contain little more than tables, benches, and trash cans, others include shelters, grills, restrooms, parking areas, lights, etc. Small picnic areas are often placed at scenic overlooks and at attractive areas along trails. Large picnic areas are most often associated with urban parks and campgrounds.

366. Few campgrounds were found on the projects surveyed for this report, despite the fact that they are listed as one of the basic recreation facilities that facilitate public use and enjoyment of project resources. One reason is that so many of the flood channel projects are found in urban areas where other types of facilities are in greater demand and are more appropriate.

367. Design considerations. Water resource projects often contain an abundance of sites suited for development as picnic or campground areas, and these facilities are popular visitor attractions. Facilities located in flood-prone areas should have floodproof designs or be removable during flood season, as in the design for Mississippi River State Park (USAED, Memphis 1974). Guidance on selecting numbers and types of facilities based on anticipated use and on layout and placement of facilities is available in EM 1110-2-400 (OCE 1971b). Additional guidance can be found in American Camping Association (1965), National Recreation and Park Association (1961), and State of Michigan Department of Natural Resources (undated).

Historic sites and structures

368. Description. CE regulations require that significant historic sites or resources be considered in formulating recommendations for project authorization and implementation (OCE 1982c). Where

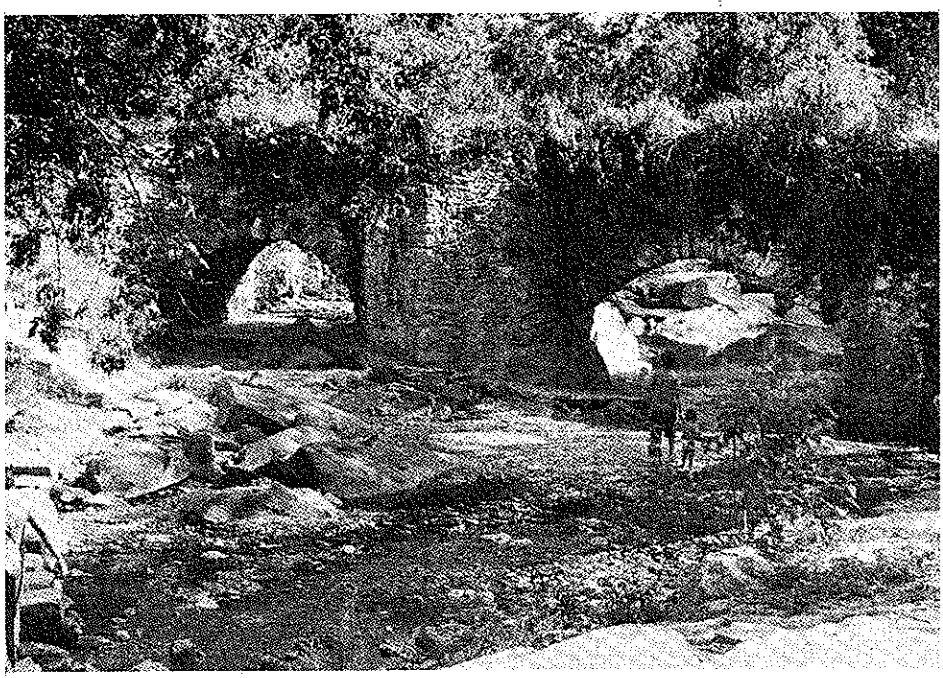
historic sites exist and can be preserved, they can often be incorporated into aesthetic and recreational plans as centers of attraction for local citizens and tourists. The San Antonio River channel contained the remains of the raceway and foundation of an old grist mill built in 1868 (Figure 72). The site, known as Guenther's Upper Mill site, is located

Figure 72. Guenther's Upper Mill site, San Antonio. The old mill site is located in the King William Historic District.

in the King William Historic District, which contains several buildings listed in the National Register of Historic Places. Many houses in the neighborhood have been restored. The flood channel for this reach was designed to minimize disturbance of historic properties in the area and included reconstruction of the mill's raceway and foundation within the flood channel (USAED, Fort Worth 1981).

369. One of the San Antonio River channel improvement projects was implemented to save a historic structure. Espada Acequia is an old Spanish irrigation aqueduct threatened by channel erosion from Six Mile Creek which passed under the structure (Figure 73). A floodway was

a. Circa 1900



b. Circa 1977

Figure 73. Espada Acequia, San Antonio, an old Spanish aqueduct that was being threatened by channel erosion (photos by Fort Worth District)

built to carry flood flows directly to the San Antonio River, while normal flows are diverted through the original Six Mile Creek channel. The headwall of the diversion culvert was veneered with native stone to blend with the old aqueduct and its surroundings (Figure 74) (USAED, Fort Worth 1977).

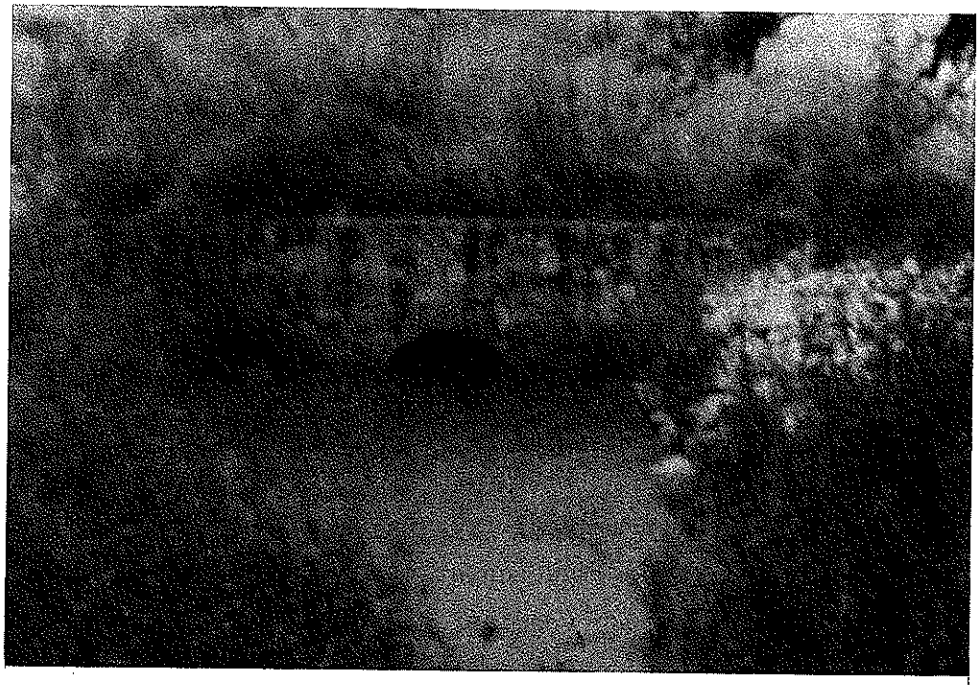


Figure 74. Native stone veneer, Espada Acequia. The culvert headwall was veneered with natural stone to complement the old stone aqueduct.

370. Design. Guidance for consideration of historic preservation in Civil Works planning studies is provided in ER 1105-2-50 (OCE 1982c). This regulation defines historic property or historic resources as any prehistoric or historic district, site, building, structure, or object included in or eligible for inclusion in the National Register. Historic resources must be taken into account in formulating recommendations for project authorization and implementation. Preservation of significant historic properties through avoidance of effects is preferable to any other form of mitigation (OCE 1982c).

Environmental Considerations in Maintenance

371. Official CE policy for inspection and maintenance of CE flood control channel projects is found in Section 208.10, Title 33 of the Code of Federal Regulations, ER 1130-2-303, Maintenance Guide (OCE 1967b), and ER 1130-2-339, Inspection of Local Flood Protection Projects (OCE 1973). These regulations provide guidelines for project maintenance to ensure efficient and reliable performance. They do not address environmental concerns regarding maintenance.

372. Although local interests are normally responsible for performing CE flood channel maintenance, the CE can influence environmental aspects of maintenance by design of maintenance-related features. Accordingly, design of channel projects should include consideration of maintenance requirements and environmental effects of maintenance policy. In addition, the CE often plays a regulatory role for maintenance of non-Federal projects.

373. The major environmental impacts of channel maintenance are associated primarily with destruction of streambank and streamside vegetative cover, especially woody vegetation, and interference with biologic processes and recreational uses. Many undesirable impacts can be reduced by careful scheduling, minimizing use of heavy equipment, and practicing selective vegetative maintenance.

Scheduling

374. Frequency and timing of maintenance can affect environmental quality. Vegetative maintenance of channels and banks should be performed no more frequently than is required to maintain a hydraulically efficient channel. Measurements made on small channels (up to 50-ft bottom width) by Pickles (1931) and Wilson (1973) indicate Manning roughness coefficients in the range of 0.45 to 0.50 for summer foliage after 1 year's growth (vegetation 3 to 4 ft high). These measurements indicate that the hydraulic efficiency of flood channels designed with roughness values in the range of 0.35 to 0.40 probably would not be seriously impaired by vegetative regrowth in less than two growing seasons. As a general rule, vegetative clearing of channel areas is

probably not needed until channel roughness has increased by 25 percent above the design value. Except in parks and built-up urban areas, vegetation outside the flood conveyance zone may require little or no maintenance other than for access required for channel inspection and maintenance.

375. Proper timing of all channel maintenance can reduce impacts to fish and wildlife and inconvenience to sportsmen and recreationists. Maintenance should be scheduled to avoid fish spawning and migration periods, nesting seasons, prime hunting and fishing seasons, and periods of heavy recreation use.

Equipment access

376. Permanently maintained travelways and access routes should not be included in a project unless essential, and their number and size should be minimized. The need for permanent equipment access can be reduced or virtually eliminated by relying on manual labor and small equipment that is easily manuevered. When hand maintenance and selective removal of vegetation is not feasible, equipment such as mowers mounted on hydraulic booms may be used to mow areas that are difficult to access or that might be damaged by heavy traffic. If hydraulic dredges can be used to remove sediment accumulations, the dredged material can be pumped long distances to disposal or collection areas. In many cases this is superior to the near-channel disposal required for draglines and other types of equipment. Extremely small dredges are commercially available.

Vegetative maintenance practices

377. Vegetative maintenance practices that promote vegetative diversity are preferred. Special care should be taken to avoid disturbing sensitive areas or valuable habitat; dens, burrows, and nesting sites should be avoided. Brush removed from channel areas can be used to provide habitat for small mammals and ground-dwelling birds. However, any brush or other debris deposited on the floodplain should be securely anchored. Hynson et al. (1985) discuss environmentally desirable vegetative maintenance practices for flood control channels and levees. Additional information is provided in the section on selective clearing and snagging (paragraphs 102-121).

378. When vegetation is incorporated in channel designs, funding and effort for adequate and thorough maintenance should be allocated. Ornamental plantings frequently must be replanted, so planting contracts should specify a certain survival rate and require removal of dead plants. Poorly maintained vegetation can be detrimental rather than beneficial to aesthetic and ecological resources. Proposed landscaping maintenance requirements for the Walnut Creek Flood Control Project are presented in Appendix E (USAED, San Francisco 1979). However, if plantings are intended to promote wildlife, often no maintenance is needed once they are well established.

PART V: SELECTION OF ENVIRONMENTAL FEATURES

379. General environmental objectives should be established simultaneously with other project objectives early in the planning process. Several options may exist for achieving a specific environmental objective, as illustrated by Table 19, which is designed as a matrix for selecting environmental features. Columns are environmental objectives and rows are environmental features. Cells containing an X indicate that the environmental feature on that row generally may be an appropriate way to achieve the environmental objective in that column. For example, the aquatic productivity of channels may be increased by incorporating features such as pools and riffles, single-bank construction, bed armor, habitat structures, water control structures, fishways, substrate construction, oxbow and bendway maintenance, scheduling of work to avoid environmentally sensitive periods, and vegetative buffer strips.

380. Although environmental objectives guide the selection process, stream and watershed conditions may influence the successful operation and maintenance of environmental features and must be considered. Table 20 provides a quick way to assess the suitability of an environmental feature. Environmental features are listed across the top, and stream reach and watershed characteristics are listed on the left side. Cells with an X indicate that the environmental feature represented by that column is probably inappropriate for the stream characteristic or watershed conditions represented in that row. Cells with slashes indicate that the feature may be inappropriate, depending on the specific design and precise stream characteristics. For example, instream habitat structures generally are inappropriate for streams that have characteristics such as braided channels, high bedload transport, steep gradients, high discharge, intermittent flow conditions, poor water quality, or no existing fishery, or that drain arid watersheds. In addition, some instream habitat structures may be inappropriate on streams with high suspended loads, bedrock or sand beds, low slopes, discharges between 1,000 and 10,000 cfs, highly variable flows, or

warmwater fisheries; streams that freeze over; or streams that drain urban, agricultural, semiarid, or highly disturbed watersheds. Habitat structure designs that depend on scouring for their effect usually will not work well on bedrock streams, whereas many kinds of designs will not last on mobile, sand bed streams due to undercutting and flanking. The likelihood of success in using a particular design may be difficult to assess unless the environmental feature has been tried under a variety of conditions. The use of Table 20 requires that sufficient data be collected to adequately characterize the stream and its watershed. Section IVA of Appendix B outlines the types of data that should be collected to assess existing conditions and provide the data required for project planning and design.

PART VI: SUMMARY AND RECOMMENDATIONS

Summary

381. Channels modified for flood control often experience severe environmental degradation. The most common problems include erosion and sedimentation that result in property loss, threaten structures, and reduce channel and reservoir capacities; loss of riparian vegetation and the shade, habitat, and organic matter that it provides; loss of aquatic habitat and reduced habitat diversity due to reduced channel length, removal of cover, alteration of substrate, and more uniform flow depths and velocities; loss of terrestrial habitat and reduced diversity caused by extensive clearing, spoil disposal, and altered drainage; and a modified channel that is often aesthetically inferior to the original channel.

382. Many of the impacts encountered in flood control channel modification can be attributed to a failure to recognize that streams do not exist as separate, isolated physical entities that can be manipulated without concern for what happens in adjacent reaches, related systems, or the watershed at large. Instead, streams should be viewed as one part of the fluvial system, which, in turn, strongly interacts with the biological system. When viewed in this systems context, many secondary effects that occur when flood channels are altered are predictable, at least in a qualitative sense. Such predictions are possible because the available knowledge about stream processes and the experience with modified channels are sufficient to establish functional relationships among some of the major components of the fluvial system. These relationships are expressed in Equations 5-21.

383. Many negative environmental impacts of flood channel modifications can be reduced or eliminated by incorporating environmental features into flood control channel designs. Environmental features are defined as any structures or actions employed in planning, designing, constructing, or maintaining flood control channels that improve the net environmental effect. Environmental features may include modifications

of standard techniques, such as selective clearing and snagging or single-bank construction; modified channel designs, such as low flow channels, pools and riffles, and meandering alignments; structures for erosion and sediment control, water level management, and instream habitat; design and maintenance of projects to improve aquatic and terrestrial habitat; inclusion of recreational facilities in project design; and special designs and treatments for aesthetic purposes.

Recommendations

384. Environmental objectives should be given equal consideration with economic objectives in the planning, design, construction, and maintenance of flood control channel projects. Environmental features discussed in Part IV of this report can be used to achieve environmental objectives. Experience with environmental features in flood control channels has been generally positive. However, not all features have performed as anticipated. Experience gained from both failures and successes is valuable in developing design guidance. The design considerations presented in Part IV are based largely on prior experience with the use of environmental features in modified channels. Some features have received little use; thus, there is little basis for evaluation and development of design guidance. In these cases, guidance is based largely on fluvial processes and natural stream geometry.

385. Specific recommendations for improving the environmental quality of flood control channels are as follows:

- a. Formulate general environmental objectives early in the planning process.
- b. Use Table 19 to select potential environmental features for accomplishing environmental objectives.
- c. Eliminate features unsuitable because of stream or watershed conditions (Table 20).
- d. Plan, design, construct, and maintain environmental features according to procedures presented in Part IV of this report. An interdisciplinary team approach that includes representatives from disciplines dealing with the major environmental resources affected by the project is highly recommended.

386. Development of sound design guidance requires feedback on project performance. Designers need to know the conditions under which features perform as expected and the conditions under which they fail. Inspection and maintenance procedures employed on most flood control channel projects are intended to maintain project components in proper functioning condition and to identify and repair deteriorated or failed components. Inspections are not intended to evaluate the overall performance of the project design or of specific components. Continued development and improvement of design guidance for environmental features will depend on the development of procedures for regular inspection and evaluation of environmental features used on CE flood control channel projects. Ideally, standard evaluation procedures should be developed for each type of feature, and evaluations should be incorporated into inspection visits on an annual basis. These evaluations could be made available to investigators charged with extending and modifying official CE guidance.

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Table 10

Experiences with Habitat Structures in Modified Channels

Stream	Design	Material	Dimensions, feet: Height Above Grade	Key-in Depth	Crest Width	Spacing	Bed Material	Effectiveness
Fisher River, Mont.	Sills with low flow notch off center	Stones weighing between 200 and 2000 lb with 50% heavier than 100 lb on 1-ft gravel bedding	2	2.5	2	125	Sandy silty gravel with cobbles and boulders	Several structures failed in high flows. Trout populations not enhanced because of increased sediment load and removal of riparian vegetation
Rapid Creek, S. D.	Triangular deflectors, revetments	Stones 1-3 ft in diam in a 6-ft-thick layer over stream gravel	1.5	1.5	N/A	Varies	Gravel, rubble.	Preliminary indications are favorable. Structures are providing good habitat and speeding trout reproduction in the modified reach
Weber River, Utah	Deflectors, sills, random rocks	Gabions, boul- weighing 1-4 tons	1.5-2	2.5-3	4	Varies	Gravel, rubble	Aquatic community in modified reaches similar to unchanged reaches 2-3 years after construction. Recovery aided by presence of several unaltered reaches. Some gabion baskets failed
Olentangy River, Ohio	Sills in low-flow channel. Crest 0.5 ft underwater at normal flow.	Rock mostly 1.5-ft diam or larger over earthen fill	3	0-5	20	840	Clay, silt, sand, and gravel	Reach with structures recovered fish and benthic populations much more quickly than modified reach without structure. Still inferior to unaltered conditions.
Rock Creek, Wyo.	Random rocks in a pattern. Groupings of two and four boulders on alternating sides of channel	Boulders about 5 ft in diam weighing 7-8 tons	4	1	N/A	50-90	Cobble	Trout population recovered from a very limited density to a density comparable to a control (unaltered) section within 2 years
Crow Creek, Ala.	Sills of various design	Riprap, sheet piling, timber. Some sills capped with reinforced concrete	Varies	Varies	Varies	Varies	Gravel, sand, some clay and silt	Some structures placed too high and too close together to create a physically diverse pool-riffle sequence. Structures that produced pools and riffles did provide good habitat
Prairie Creek, Tenn.	Sills with a central gap and preformed scour hole, lined with stone	Stones weighing between 25 and 150 lb with 25%-50% heavier than 100 lb	2	2	2	900	Silty clay, sandy clay, and gravelly sandy clay	Structures provide superior habitat to modified channel without structure
Chippewa Creek, Ohio	Sills similar to Prairie Creek structures	Stones weighing between 10 and 300 lb with 25%-70% heavier than 100 lb	2	1	2	Varies	Silt, sand, and gravel	Fish species diversity, density, and biomass much greater in reaches with structures
River Styx, Ohio	Two sill designs - one similar to Prairie Creek, another similar to Olentangy River. Deflectors	Stones such that 80% are larger than a 0.75-ft-square opening	2	1	2	220	Sand	Minimal effectiveness due to structural structural damage by ice. No pool-riffle sequence developed

Source: Shields, 1983.

Table 11
Costs of Water Control Structures on Corps of Engineers
Flood Control Channels

Project	Channel Capacity cfs	Dimensions, ft (Height × Crest Length × Base Width)	Type of Structure	Cost, $	Base Year
Flint River, Mich.	11,400	6 × 100 × 3	Fabridam	501,000*	1976
Threemile Creek, Ala.	12,500	10 × 190 (approximate)	Sheet pile drop structure	260,000**	1982
Red River, Ark.	22,000†	5 × 80 × 2	Concrete weir	24,000	1972
Roseau River, Minn. (not implemented)	7,950	7.3 × 139 × 21.9	Gabion	77,000	1980
		Variable	Unexcavated channel plugs	1,300**	1980
Souris River, N. D.	5,000	10 × 165 × 2	Concrete	200,000*	1975
		3 × 30 × 40	Gabion	50,000*	1975
Stanefer Creek, Miss.	1,750	5.7 × 150	Sheet pile	22,000	1968

* Bid costs. All other costs based on General Design Memorandum estimates.
** Average cost (total cost/number of structures).
† Capacity between levees.

Table 12

Space Requirements for Spawning Fish

Fish Species	Approx. Average Weight, lb	Average Area of Redd sq yd	Area Recommended per Spawning Pair, sq yd
Chinook			
a. summer and fall run	25	6.1	24.0
b. spring run	15	3.9	16.0
Coho	9	3.4	14.0
Chums	10	2.7	11.0
Sockeye	3	2.1	8.0
Chinook (spring run)		13.0	
Pinks	5	0.7	0.7
Trout	1(?)	0.3	2.0

Table 13
Fishways in Modified Channels

Project	Flood Channel Capacity, cfs	Obstacle	Fishway Type	Dimensions, ft (l × w × h)*	Operating Discharge, cfs	Cost	Base Year
Johnson Creek, Oreg.	4400	10-ft drop structure	Hell's Gate	72 × 6 × 12	--	44,000	1973
Corte Madera, Calif.**	6900	6-ft drop structure	Dual Denil	25.5 × 4.5 × 5.5 31.5 × 4.5 × 5.5	10-100 100-240	10,500	1978
Bull Creek, Pa.	Not available	870-ft-long culvert with 0.002 slope	Baffles with rock-lined pools	870 × 21.6 × 1.7	Not available	Not available	
Hayward Creek, Mass.	85	Drop inlet	Pool and weir	26 × 2 × 4.2	0.1-3	3,000	1978

* For Denil and vertical slot structures, H is the height of structure at the downstream end when fully submerged. For weir structures, H is the difference in elevation of highest weir and channel invert below structure.
** Not yet constructed.

Table 14

Corps of Engineers Projects Designed with Aquatic and Wetlands Habitat

Project	Concept	Cost	Year
Zumbro River, Minn.	Plugged meander loop for wildlife habitat. Upstream plug has a flap-gated culvert to allow filling at high flow	$53,000	1971
Souris River, N. D.	Flow maintenance in bendways. Low sills in lower end of bendway for ponding. Gabion and concrete water level structures in bypass channels for water diversion. Sluice-gated barriers at both ends of some oxbows	Less than $50,000 to more than $200,000, depending on type and size of structure	1976
Lower Rio Grande, Tex.	Diking of low swales. Water control structures for Laguna Madre marsh. Diversion ditch	$1,508,000	1982
Taylors Bayou, Tex.	Water ponded in 4 disposal areas for waterfowl. Water level maintained by adjustable weirs. Water control structure	$245,000*	1982

(Continued)

* In lieu of managing two of the disposal areas, local interests, at their own initiative and expense, acquired additional wetlands at an estimated cost of $1,771,000.

Table 14 (Concluded)

Project	Concept	Cost	Year
Little Blue River, Mo.	4 oxbow lakes; 15 flow-through oxbow fisheries	Not available	
West Tennessee Tributaries, Tenn.	21 bendway impoundments; 60 greentree reservoirs	Typical gated corrugated metal pipe $25,000; typical gated drop structure $50,000; typical nongated drop structure $37,000	1981

Table 15

Preservation and Development of Terrestrial Habitat on Flood Control Channel Projects

Project	Habitat Concepts	Cost ($)	Base Year
Byram River, Conn.-N. Y.	Trees and shrubs removed in construction will be replaced with same species or species of equivalent wildlife value	67,000	1976
Mamaroneck-Sheldrake Rivers, N. Y.	Trees and shrubs removed in construction will be replaced with same species or species of equivalent wildlife value	123,000*	1976
Swan Lake, Steele Bayou, Miss.	22 acres of plantings for wildlife food	1,000/acre	1979
	1,200 acres of reforestation	125/acre	1979
Park River, N. D. (proposed)	10 acres planted to trees for wildlife habitat	Not itemized	
South Fork Zumbro River, Minn.	Sharecropping of wildlife food plots; plant mast-producing trees; posting and fencing of wildlife management area	Not itemized	
	Acquisition of 145 acres for mitigation	215,000	1982
Hocking River, Ohio	Adjustments of channel alignment to save a vegetative buffer zone and quality trees and shrubs; wildlife plantings	Not available	
Lower Rio Grande Basin, Tex.	Development of 6057 acres (4088 on disposal areas) of brushland and grassland habitats; 200 miles fencing to protect wildlife management areas	4,395,000	1982

* Estimate does not include costs for Sheldrake River section.

Table 16

Examples of Aesthetic Treatments on CE Flood Channel Projects

Type of Feature	Project	Dimensions	Total or Unit Cost ($)*	Base Year
Special treatments for flood channels and paved surfaces				
Brushed concrete with color	Indian Bend Wash, Ariz.	--	1.50/sq. ft	1977
Forms for molded concrete	Duck Creek, Tex.	**	3,200	1970
	Corte Madera, Calif.	48 in. 22 in.	10,000	1968
	Indian Bend Wash, Ariz.	**	2,500	1977
Exposed aggregate	Indian Bend Wash, Ariz.	--	1.30/sq ft	1977
Decomposed granite	Indian Bend Wash, Ariz.	--	20/sq ft	1977
Cobbles in grout	Indian Bend Wash, Ariz.	--	1.25/sq ft	1977
Cobble paving on granite	Indian Bend Wash, Ariz.	--	3.33/sq ft	1977
Cobblestone paving	Indian Bend Wash, Ariz.	--	1.50/sq ft	1977
Cobble channel bottom	Indian Bend Wash	--	2.90/sq ft	1977
Stone facing for concrete	San Antonio River, Tex.	**		
Seeding of riprap	Corte Madera Creek, Calif.			
Topsoil		--	10/sq yd	1978
Hydromulching		--	0.05/sq ft	1978
Landscaping planters				
Concrete walls	San Antonio River, Tex.	80 10 5	29,000 (B)	1981
Walls and curbing	Flint River, Mich.	2675 lin ft	72,225	1974
	Tujunga Wash, Calif.	25,000/sq ft	37,500	1975
Tree well	Corte Madera, Calif.	**	3,500	1978
Tree protection during construction (includes cost of shims and avoiding trees during construction)	San Antonio River, Tex.	**	1,700/tree (B)	1981
Fencing				
Vinyl-covered chainlink	River Rouge, Mich.	34,172 6 ft	6.50/ft (B)	1976
Wooden rail	Cucamonga, Calif.	13,000 ft	3.00/ft	1973
Redwood	Corte Madera, Calif.	4 ft high	**	
Columns (pilasters) for floodwails				
Stone faced	San Antonio River, Tex.			
Stone faced	Corte Madera, Calif.	--	40/sq ft	1978
Water displays				
Water cascade	Flint River, Mich.	**	**	
Water cascade	Indian Bend Wash, Ariz.	**	50,000	1977
Reflecting pools	Duck Creek, Tex.	**	1,000 ea	1970
Fountain	Indian Bend Wash, Ariz.	**	39,000	1977
Low Water Crossings				
Concrete sill with stepping stones	Apache Creek, Tex.	**	**	
Grouted sill with stepping stones	Duck Creek, Tex.	**	1,000 ea	1970
Grass and other planted ground covers				
Sodding, topsoil, and fertilizer	Flint River, Mich.	sq yd	2.50/sq yd	1976
Seeding, topsoil, and fertilizer	Flint River, Mich.	sq yd	1.00/sq yd	1976
Turf with auto irrigation	Indian Bend Wash, Ariz.	sq yd	1.50/sq yd	1974
Hydromulched multiseed mixture	South Platte, Colo.	sq yd	0.93/sq yd	1983
Seeding without irrigation	West Tennessee Tributaries	sq yd	0.05/sq yd	1981
Irrigation systems				
	South Platte, Colo.	sq ft	0.35-0.70/sq ft	1976
	Corte Madera, Calif.	sq ft	0.60/sq ft	1978
	Cucamonga, Calif.	sq ft	0.25/sq ft	1973

* Costs other than those denoted B (bid price) are estimates.
** Not available.

Table 17

Selected Recreation Features Incorporated in Flood Control Channel Projects

Project	Hike, bike trails	Picnic areas	Playgrounds, game fields	Nature study areas and trails	Lakes for fishing, boating	Swimming and wading pools	Equestrian trails	Overlooks	Fishing structures, access areas	Amphitheaters and bandstands	Campgrounds	Pavilions/plazas	Boat ramps	Canoeing/rafting
Fourmile Run, Md.	X													
Ellicott Creek, N.Y.	X	X	X					X						
Flint River, Mich.	X					X					X	X	X	X
Sabine River, Tex.	X													
San Antonio River & Tribs., Tex.	X	X			X									
Boggy Creek, Tex.	X	X		X										
Chillicothe, Ohio	X	X	X					X	X					
Hocking River, Ohio	X			X					X					
Tenmile Creek, Pa.	X													
Sandy Lick Creek, Pa.	X													
Indian Bend Wash, Ariz.	X	X	X	X	X	X	X				X	X		
Little Blue River, Mo.	X	X	X		X				X					
Ballona Creek, Calif.	X													
Cucamonga Creek, Calif.	X	X					X							
New River, Ariz.	X	X					X							
Tujunga Wash, Calif.	X													
Mill Creek, Ohio	X	X												
Miss. River State Park, Ark.	X	X						X	X	X				
Threemile Creek, Ala.	X	X	X											
South Platte, Colo.	X						X	X						X
Chartiers Creek, Pa.	X													
Souris River, N.D.	X	X	X	X		X		X						
South Fork Zumbro River, Minn.	X	X	X	X					X					
Walnut Creek, Calif.	X	X												

Table 18

Trails Incorporated in Flood Control Channel Projects

Project	District	Type of Surface	Cost ($ per sq yd)*	Base Year
		Hike and Bike Trails		
Chartiers Creek, Pa.	Pittsburgh	Bituminous	9.50 (B)	1975
Fourmile Run, Md.	Baltimore	Concrete	12.00	1972
		Bituminous	5.97 (B)	1980
Ellicott Creek, N. Y.	New York	Asphalt/concrete	11.20	1982
South Platte River, Colo.	Omaha	Regular concrete, 8 ft × 4 in.	10.00	1983
Flint River, Mich.	Detroit	Scored concrete	45.00	1976
Flint River, Mich.	Detroit	Regular concrete	22.50	1976
		Equestrian Trails		
Cucamonga Creek, Calif.	Los Angeles	Graded soil	1.80	1973
South Platte River, Colo.	Omaha	Graded soil	0.70	1976

* Costs other than those denoted B (bid price) are estimates from project General Design Memorandums.

Table 19

Selecting Features to Achieve Environmental Objectives

ENVIRONMENTAL FEATURE	LIMIT BED AND BANK EROSION	AVOID BED AGGRADATON	PREVENT GROUND-WATER LOWERING	IMPROVE LOW-FLOW CONDITIONS	IMPROVE WATER QUALITY	PRESERVE FISH HABITAT	IMPROVE AQUATIC HABITAT DIVERSITY	REDUCE LOSS OF RIPARIAN VEGETATION	IMPROVE TERRESTRIAL HABITAT DIVERSITY	MITIGATE WETLANDS	IMPROVE INSTREAM AESTHETICS	IMPROVE STREAMSIDE AESTHETICS	IMPROVE INSTREAM RECREATION	IMPROVE STREAMSIDE RECREATION
SELECTIVE CLEARING AND SNAGGING		O	O	O	O			O	O		O		O	O
TRADITIONAL CLEARING AND SNAGGING		O												
LOW- AND NORMAL-FLOW CHANNELS		O		O	O		O				O		O	
FLOODWAYS AND IMPASS CHANNELS				O										
MEANDERING ALIGNMENTS	O						O				O			
POOL AND RIFFLE GRADES				O	O	O	O				O		O	
SINGLE BANK MODIFICATION	O				O	O	O	O	O		O	O		O
GRADE CONTROL STRUCTURES	O													
ARMOR	O					O	O				O			
RIGID LININGS	O													
BANK PROTECTION	O	O												
INSTREAM HABITAT STRUCTURES				O	O	O	O				O		O	
WATER LEVEL CONTROL STRUCTURES			O	O	O	O	O				O		O	
FISHWAYS						O								
SUBSTRATE CONSTRUCTION	O					O	O							
OXBOW AND BENDWAY MAINTENANCE			O		O	O	O			O	O		O	
GREENTREE AREAS			O					O	O	O		O		O
VEGETATIVE PLANTINGS	O							O	O			O		
PLACEMENT AND SHAPING OF SPOIL									O	O		O		
PRESERVATION OF CUTOFF ISLANDS								O	O			O		O
SEDIMENT TRAPS		O		O							O			
SCHEDULING WORK FOR ENVIRONMENTAL REASONS						O							O	
VEGETATIVE BUFFER STRIPS	O	O			O	O		O	O			O		O
REVEGETATION OF DISTURBED AREAS	O	O						O	O			O		
SPECIAL ARCHITECTURAL DESIGNS											O	O		
SPECIAL MATERIALS AND FINISHES											O	O		
WATER DISPLAYS											O	O		
SPECIAL STRUCTURES FOR STREAM-BASED RECREATION													O	
TRAILS														O
PICNIC AREAS, CAMPGROUNDS, ETC.														O
PLAYGROUNDS, SPORT FIELDS, ETC.														O
"PASSIVE" RECREATIONAL AREAS														O

NOTE: "O" INDICATES THAT THE ENVIRONMENTAL FEATURE HAS BEEN OR CAN BE USED TO ACHIEVE THE ENVIRONMENTAL GOAL.

Table 20

Suitability of Features for Various Preproject Stream and Watershed Characteristics

	SELECTIVE CLEARING AND SNAGGING	LOW AND NORMAL FLOW CHANNELS	FLOODWAYS AND BYPASS CHANNELS	MEANDERING ALIGNMENTS	POOL AND RIFFLE GRADES	SINGLE BANK MODIFICATION	GRADE CONTROL STRUCTURES	ARMOR	RIGID LININGS	BANK PROTECTION	INSTREAM HABITAT STRUCTURES	WATER LEVEL CONTROL STRUCTURES	FISHWAYS	SUBSTRATE CONSTRUCTION	OXBOW AND BENDWAY MAINTENANCE	GREENTREE AREAS	VEGETATIVE PLANTINGS	PLACEMENT AND SHAPING OF SPOIL	PRESERVATION OF CUTOFF ISLANDS	SEDIMENT TRAPS	SCHEDULING WORK FOR ENV. REASONS	VEGETATIVE BUFFER STRIPS	REVEGETATION OF DISTURBED AREAS	SPECIAL ARCHITECTURAL DESIGNS	SPECIAL MATERIALS AND FINISHES	WATER DISPLAYS	SPECIAL STRUCTURES FOR STREAM-BASED RECREATION	TRAILS	PICNIC AREAS, CAMPGROUNDS, ETC.	PLAYGROUNDS, SPORT FIELDS, ETC.	"PASSIVE" RECREATIONAL AREAS	CAMPGROUNDS
STREAM REACH CHARACTERISTICS																															
CHANNEL PATTERN																															
BRAIDED		□		□	□			□			□	□		□	□					△											
MEANDERING			○	○																											
STRAIGHT TO SINUOUS				△																											
POOL-RIFFLE SEQUENCE																															
WELL DEVELOPED					○																										
NOT WELL DEVELOPED					△																										
SEDIMENT TRANSPORT																				○											
HIGH BEDLOAD		□		△	△			△			□	□		□	△					○											
HIGH SUSPENDED LOAD											△				△																
MODERATE TO LOW		○									○				○																
CHANNEL STABILITY																															
STABLE								○																							
UNSTABLE		△		△	△			△				△		□											□						
SUBSTRATE																															
BEDROCK			△					□			△																				
GRAVEL								○			○																				
SAND		△			□			□			△	△		□						○											
SILT-CLAY-ORGANIC								△						□																	
BANK COHESIVENESS																															
HIGH																															
LOW				△	△		△																								
SLOPE																															
HIGH (>0.04)											□	□				□															
MODERATE (0.002-0.04)											○																				
HIGH (<0.002)				△							△																				
SETTING																															
URBAN																□															
RURAL																									□						
DISCHARGE (BANKFULL)																															
LOW <1,000 CFS											○																△				
MED. 1,000-10,000 CFS											△																				
HIGH >10,000 CFS								△			□																				
ANNUAL FLOW REGIME																															
EPHEMERAL		□			□						□	□	△	□	△	□									△						
EXTREME VARIATION											△																				
NORMAL															○																
WATER QUALITY, CHEMICAL																															
POOR		□									□	△	□	□	△										△	□					
FAIR																															
GOOD																															
FISHERY																															
LITTLE OR NONE											□		□	□																	
COLD WATER											○																				
WARM WATER											△																				
WATERSHED CHARACTERISTICS																															
LAND USE																															
URBAN											△					□															
AGRICULTURAL											△											○									
RANGELAND																															
FORESTED																○															
PRECIPITATION																															
ARID												△		△		□	△						□								
SEMIARID											△					△	△														
HUMID																○	○														
WINTER TEMPERATURE																															
COLD (STREAMS FREEZE OVER)											△	△																			
MODERATE TO WARM																															
TERRAIN																															
MOUNTAINOUS			□	△												□		△													
HILLY											○																				
FLAT																○															
WATERSHED EQUILIBRIUM																															
RELATIVELY UNDISTURBED											○																				
HIGHLY DISTURBED		△			△			△			△		△																		

NOTE: □ — HAS PROVEN UNSUCCESSFUL IN MOST CASES; LIKELY TO BE UNSUCCESSFUL DUE TO PHYSICAL CONSTRAINTS, OR INAPPROPRIATE.

△ — POTENTIAL PROBLEMS LIKELY TO BE ENCOUNTERED; SUCCESSFUL APPLICATIONS MAY REQUIRE SPECIAL DESIGNS OR CONSIDERABLE MAINTENANCE.

○ — HAS OFTEN PROVEN SUCCESSFUL.

BLANK — LITTLE OR NO INFORMATION; OR CONDITIONS NOT A CONSIDERATION.

APPENDIX A: GLOSSARY

aggradation Deposition of sediment in a channel, on a floodplain, or other surface in sufficient quantity to increase local elevation.

annual series The discharge record consisting of the greatest discharge each year during the period of record.

armor A coarse layer of gravel or cobble that develops on a streambed through winnowing away of fines.

baffle A plate, wall, screen, or other device to deflect or impede flow.

bedforms Ripples, waves, dunes, and related forms that develop under various flow conditions on the beds of alluvial streams with significant bedload transport.

bedload Sediment, usually sand size or larger, that is transported along the bed by rolling, skipping, dragging, or saltation.

benthic Of, pertaining to, or related to the bottom of a stream or other body of water.

berm A terrace or ledge formed within a channel at base of the streambank. Also a terrace or ledge cut on a slope or embankment to divert water or intercept sliding earth.

bollards Heavy post and chain fixtures used to exclude wheeled vehicles from protected areas.

braided channel A channel pattern characterized by numerous intertwined channelways, steep gradient, and coarse bed material.

bypass channel A short flood diversion channel constructed to bypass a tortuous reach of natural stream or features of special interest such as wetlands. Bypass channels may be constructed to convey all flows or flood discharges only.

check dam A low dam constructed of logs, loose rock, or other material to control water flow and check erosion.

cobble Gravel and stones that have been rounded by abrasive action of flowing water or waves.

coldwater stream Headwater stream located at an elevation or latitude sufficient to produce water temperatures low enough to support salmonid fishes.

cross-sectional area The area of a section of a channel at right angles to the direction of flow.

cutoff island An island created in a bend or meander by excavating a bypass or diversion channel across the meander neck.

debris basin A basin constructed, usually at the mouth of a canyon or steep mountain stream, to trap sediment or debris that would clog or damage a flood channel.

Denil fishway A fishway design that uses side and bottom vanes inside a steep trough to create countercurrents that slow velocities.

drop structure A grade control structure which provides for a vertical drop in the channel invert between the upstream and downstream sides.

ephemeral stream A stream that flows only during or immediately after periods of rainfall or snowmelt.

equilibrium A condition of fluvial systems in which slope, discharge, channel pattern, channel morphology, and sediment supply are balanced.

evapotranspiration The combined moisture loss from evaporation and transpiration.

fabridam A dam constructed of fabric and rubber that can be inflated with air or water.

fish ladder A fishway that provides passage over or around a vertical obstruction.

fishway A structure designed to allow fish passage around, over, or through obstacles.

flap gate A gate hinged at the top and allowing flow in only one direction.

flood channel Any partially or completely excavated channel intended to convey flows above normal discharges. Flood channels may be sized to convey any return interval discharge above the 2-year or other normal bankfull discharge.

flood diversion channel (See floodway).

floodway A natural or constructed channel which conveys flood flows.

flume An open channel constructed of wood, steel, or reinforced concrete and used to convey water for various purposes, including grade control.

form liner A liner for concrete forms designed to produce a special finish.

gabions Rock-filled wire cages used on streams for erosion protection and construction of dams and other structures.

grade control structure Any of several types of structures used to control erosion on channels with steep grades (see stabilizer, drop structure, and flume).

greenbelt A linear park, usually located along a stream corridor or other right-of-way.

greentree reservoir A shallow reservoir in which water levels are manipulated for wildlife and timber production.

headcut A point of abrupt change in the longitudinal profile of a stream. Headcuts typically migrate upstream through time.

Hells Gate fishway A fishway design which combines principles of the Denil fishway with a vertical slot design.

high flow channel A channel design employing a subchannel for normal and low flows and high flow berms that are flooded on an infrequent basis. When the existing natural channel is used for the subchannel, excavation may take place from one or both sides, but the existing channel is disturbed as little as possible.

hydraulic radius Equal to A/P, where A is cross-sectional area and P is wetted perimeter. Roughly comparable to average depth in wide, shallow streams.

intermittent stream A stream which flows most of the time, but ceases to flow seasonally or occasionally because bed seepage and evaporation exceed the supply of water.

invert The bed of a channel or culvert.

knickpoint (Same as headcut).

low flow channel A subchannel designed to concentrate low flows for biologic, recreation, or aesthetic reasons.

macroinvertebrates Large invertebrates found in streams and consisting largely of larval insects, worms, and related organisms.

Manning's n A resistance coefficient used in the Manning equation for uniform steady flow, $V = \frac{1.49}{n} R^{2/3} S^{1/2}$ where V is mean velocity, R is hydraulic radius, and S is slope, all expressed in English units.

meander A broad, looping bend in a stream channel.

meander amplitude Meander width, usually expressed as a multiple of stream width (see Figure 20).

meander wavelength The average distance from crest to crest, or trough to trough, in a series of meander waves (see Figure 20).

natural stream channel A channel whose alignment, dimensions, cross-sectional shape, and grade have not been intentionally modified by humans.

oxbow lake A lake formed in a former stream meander that has been abandoned naturally or cut off during channel construction for navigation or flood control purposes.

paddleway A reach of a low gradient stream developed for canoeing.

point bar A crescent shaped bar of coarse sediment built out from the convex bank of a meander.

pool Topographically low area produced by scour and which generally contains fine-grained sediments. Pools are usually associated with point bars on meandering streams.

pool and orifice fishway A fishway designed with a series of baffles or weirs with openings or orifices in them, through which fish pass.

pool and weir fishway A fishway consisting of low weirs in series. Fish ascend by jumping from pool to pool.

propagule Seed, cutting, tuber, bulb, rhizome, or other vegetative component used to propagate plants.

regime theory Theory that channel morphology can be related quantitatively to discharge for streams that are stable or in equilibrium.

resistance coefficient An empirically derived coefficient used in uniform flow equations to account for flow resistance.

riffle A topographically high area in a channel created by the accumulation of relatively coarse-grained sediments.

riparian vegetation Vegetation along the bank of a watercourse.

salmonid or salminoid Collective term referring to salmon, trout, grayling, or white fish, all of which prefer coldwater environments.

saltation Movement of sediment along a channel bed by intermittent bouncing.

SCS curve number Values ranging between 1 and 100 that are used in calculating runoff rates by the SCS method. The more impervious a surface is, the higher the curve number.

sediment basin A basin constructed to trap sediment eroded from a slope or being transported by a stream.

selective clearing and snagging A modified version of clearing and snagging which limits the types and amount of snags and vegetation removed and uses construction methods that create minimal disturbance.

shear stress Stress imposed on the streambed and banks by flowing water.

sill A low dam designed to prevent erosion or create pools for fish habitat.

sinuosity A measure of meandering calculated as a ratio of stream length to valley length.

stable channel A channel which neither erodes nor deposits over a period of several years; a graded stream.

stabilizer A low sill across a channel, used to prevent bed erosion (see Figure 15a).

stilling basin An enlarged area in a channel that is deep enough to reduce flow velocity.

stream power The product of a stream's discharge rate (Q) and slope (S).

subchannel A channel inside a larger flood control channel that is used to convey low and/or normal flows (see low flow channel).

substrate Surface to which stream biota adhere or within which they live.

suspended load That portion of a stream's sediment load that is carried in suspension.

thalweg A line connecting the deepest points along a channel.

through flow That part of storm runoff that moves through the soil (same as interflow).

threshold A point or value which, if exceeded, creates either positive or negative feedback. Positive feedback destroys equilibrium conditions in fluvial systems, whereas negative feedback tends to restore them.

toe slope The lowest portion of a bank slope where it merges with the channel invert.

tractive force (See shear stress).

turbidity Reduction in transparency caused by suspended solids or colloidal liquid droplets.

unit discharge Discharge rate per unit width (Q/W).

Universal Soil Loss Equation (USLE) An equation used to calculate average annual sheet and rill erosion from a land surface area.

warmwater stream A stream with water too warm to support salmonid fishes.

water control structure A device, such as a weir or gated structure, used primarily to control water level.

wing deflector A low structure used to create scour holes for fish habitat purposes (see Figure 38).

APPENDIX B: GENERAL PROCEDURE FOR THE DESIGN OF CONTROL CHANNEL PROJECTS

I. Establish Project Objectives

A. Flood damage reduction--level of protection desired

B. Environmental

1. Water quality
2. Recreation
3. Fish and wildlife

II. Choose Alternatives for Achieving Project Objectives

A. Nonstructural

B. Structural

1. Reservoirs
2. Levees
3. Flood control channels

III. Evaluate Alternatives and Select General Plan

IV. Detailed Project Design for Flood Control Channels

A. Data collection and analysis, existing conditions

1. Watershed conditions

a) Climate
b) Topography
c) Soils/geology
d) Sediment yield
e) Land use/cover (existing and recent changes)
f) Hydrology

2. Stream and floodplain (each reach)

a) Hydrology

i. Generate flood frequency series
ii. Determine corresponding stage data
iii. Calculate flow duration curves (hydrographs)

b) Hydraulics

i. Identify resistance components and determine existing n values at various discharges
ii. Determine amount and size distribution of bedload and suspended load

c) Geomorphology

i. Survey cross section and existing channel grade
ii. Establish relationship of cross-section geometry to discharge using Equations 22 and 23
iii. Measure pool-riffle spacing and meander geometry and relate to discharge and channel width (using formulas tabulated in paragraph 60)
iv. Evaluate stability of bed and banks
v. Measure size distribution of bed and bank material
vi. Measure cohesiveness of banks
vii. Identify and map locations of "hardpoints" in bed or bank

d) Stratigraphy (from test borings, exposed sections)

i. Determine stratigraphic sequence
ii. Describe stratigraphic units in detail
iii. Establish average depth to seasonal water tables

e) Existing structures

i. Types
ii. Locations
iii. Design
iv. Scour and deposition patterns

f) Ice

i. Recorded thickness
ii. Average dates of freeze and breakup
iii. Damage
iv. Flow patterns and blockages

g) Ecology

i. Map riparian vegetation and locate and identify unique or valuable trees
ii. Describe terrestrial ecology
iii. Describe aquatic ecology

h) Water quality

i. Turbidity
ii. Chemical
iii. Temperature

i) Aesthetic resources - identify, describe, and photograph major components

j) Cultural and recreational resources - identify and describe major resources, with particular attention to historical and archeological components

B. Flood control channel design

1. Fix exact location and alignment geometry of channels (for meandering alignments, follow procedure in paragraphs 165-169)

2. Hydraulic design

   a. Rapid flow channels - use lined channels; choice of environmental features severely limited (for design guidance see OCE (1970) or SCS (1977)

   b. Tranquil flow channels

      i. Select best combination of channel cross-section alignments and construction techniques to meet flood control and environmental objectives (use selection process described in Part V)

      ii. Select additional features to meet environmental objectives (use matrices in Part V)

      iii. Establish downstream water surface elevation and the water surface control line, including freeboard

      iv. Select n values for each reach

      v. Size channel

      vi. Check channel stability (if unstable, stabilize by one or more of the following: adjust cross section; adjust grade, line, or armor channel; provide grade control; provide bank protection)

3. Review design for maintenance consideration; adjust if necessary

4. Review design for aesthetics; adjust if needed

C. Design environmental features of project that are not part of the flood channel proper

D. Develop detailed cost estimates; if cost too high, modify project design beginning at Step IVB

APPENDIX C: CHECKLIST OF DATA SOURCES

Type of Data	Sources
1. Watershed conditions	
a. Climate	National Weather Service climatic summaries; U. S. Weather Bureau Technical Paper 40, "Rainfall Frequency, Atlas of the United States"
b. Topography	USGS topographic maps; city and county topographic surveys; aerial photos
c. Soils/geology	County soil surveys, state geologic survey sheets; aerial photos
d. Sediment yield	Local SCS office; state natural resource surveys
e. Land use/cover	Local planning agencies, USGS 1:250,000 land use quadrangles (LUDA sheets); aerial photos
f. Hydrology	(See sources under climate); USGS National Water Data Exchange (NAWDEX) file; drainage district maps
2. Stream and Flood Plain	
a. Stream morphology	Large-scale topographic maps; aerial photos; field measurements; close-range photography; drainage district records
b. Streambank stratigraphy	Exposed sections; construction test borings; soil maps; drainage district records
3. Historic data on land use, floods, prior modifications	Drainage districts, courthouse records, old surveys, longtime residents, archives, newspaper files
4. Unique resources	
a) Historical sites, including prehistoric	National Register of Historical Places; local historians and historical societies
b) Trees	National and state tree registers
c) Rare and endangered species	List of Rare and Endangered Species; Audubon Society; Sierra Club; Soil Conservation Society of America

APPENDIX D: SPECIFICATIONS FOR CONSTRUCTION OF CLAY BLANKET*

Fills

1. Embankment for the channel blocks and fills other than channel fill shall be constructed to the plan grade and cross section shown on the design drawings without additional allowance for shrinkage of the fill. Materials shall be obtained from required excavation. The classification of any material, rather than the origin, will determine where it may be used. Material shall be classified in accordance with the procedures specified hereinafter and shall be placed at the proper locations as approved by the Contracting Officer.

Materials

2. Impervious material shall be fine-grained materials of low permeability, consisting of clays (CH), clays (CL), or silts (ML), and shall be free of plant growth, roots, and humus. The particle size of impervious material shall be such that a minimum of 50 percent of the soil particles shall pass a U. S. Standard No. 200 screen, and where available, shall be material classified as CL or CH on the plasticity chart of the Unified Soil Classification Chart, Revised 1960, and published in Waterways Experiment Station Technical Memorandum 3-357.

3. Clay blanket material shall be impervious material as defined above, but restricted to clays (CH) and clays (CL) with a minimum liquid limit of 40.

Placement and Compaction

4. Clay blanket shall consist of clay blanket materials placed to the lines and grades shown, at the locations indicated as determined by the Contracting Officer. Material shall be placed in one lift so that

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* Source: U. S. Army Engineer District, Kansas City, 1972.

the final compacted thickness is a minimum of 12 in. Material shall be compacted with two passes of a crawler tractor.

Quality Control

Sampling, testing, and approval of materials

5. Tests, except as otherwise specified herein, shall be performed by the Contractor as a part of the quality control program. The Contractor shall obtain representative samples of the materials required for the tests. In addition, and upon request, samples shall be submitted to the Contracting Officer for Government testing. Tests performed on materials which do not meet specifications will not be counted as part of the required tests. Tests shall be performed in accordance with the following requirements.

a. Atterberg limits shall be determined in accordance with the Engineer Manual (EM) 1110-2-1906, Appendix III.

b. The maximum dry density and the optimum moisture content of the impervious material shall be determined in accordance with EM 1110-2-1906, Appendix VI, paragraph 2. A minimum of four points shall be run for each curve. Additional points shall be added to fully develop the curve in the range of specified moisture content.

c. Density tests on compacted materials shall be taken in the field in accordance with ASTM Standard D 1556.

d. Water content tests based on oven-dry specimens shall be in accordance with EM 1110-2-1906, Appendix I.

Initial tests

6. The Contractor shall test all material from required excavations that he plans to utilize as impervious fill. The location and elevation sampled shall be carefully selected to truly represent the material to be utilized and to show the range in properties of these materials. The Contractor shall perform the following minimum initial tests prior to the actual placement of material. Additional tests shall be run whenever a variation in material occurs.

Type of Test	Material	Number of Tests
Compaction test	Impervious	As required to develop a full family of compaction curves for each material source
Atterberg limits	Impervious	One per compaction test and as required to delineate acceptability of material prior to placement in the embankment and fill
Atterberg limits	Clay blanket material	One per 1000 cu yd of material in loose lift
Moisture content	Impervious	As required for control

APPENDIX E: PROPOSED LANDSCAPING MAINTENANCE REQUIREMENTS FOR WALNUT CREEK FLOOD CONTROL PROJECT*

Description

1. Trees and shrubs have been planted and irrigation systems installed at various sites along Walnut Creek and its tributaries. Aesthetic and functional considerations were requisites in the design and planting of these sites and should be the guiding criteria in their continuing maintenance.

Maintenance

2. Landscaped areas should be maintained as originally designed unless experience indicates that changes are required. After the expiration of maintenance required under the landscaping contract, it is the responsibility of the Superintendent to maintain landscaped and planted areas on a continuing basis. Some specific requirements are:

a. From May through October, watering is required in an amount sufficient to ensure moisture in the root zone of trees and shrubs to maintain good growing conditions. Sidewalls of water basins at the base of trees and large shrubs should be maintained to a height between 4 to 6 in.

b. Grass and weeds should be hoed out or trimmed to a 5-ft radius around trees and large shrubs as a fire guard. In lieu thereof, grass and weeds may be controlled by use of herbicides as authorized by local ordinance and appropriate regulatory agencies. Herbicides must be applied carefully to prevent damage to plantings.

c. Plantings should be fertilized to the extent necessary to maintain vigorous growth.

d. Trees and shrubs should be pruned and trimmed to preserve aesthetic value and promote healthy growth.

e. Tree stakes and ties should be checked at intervals to prevent girdling. Ties should be loosened as trees grow and replaced as old ties break. Ties should be loose

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* Source: U. S. Army Engineer District, San Francisco 1979.

enough to permit movement and growth. Stakes and ties should be removed when a tree no longer needs support.

f. Dead trees, shrubs, and other plantings should be replaced as necessary to preserve the aesthetic and functional value of the landscaping.

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