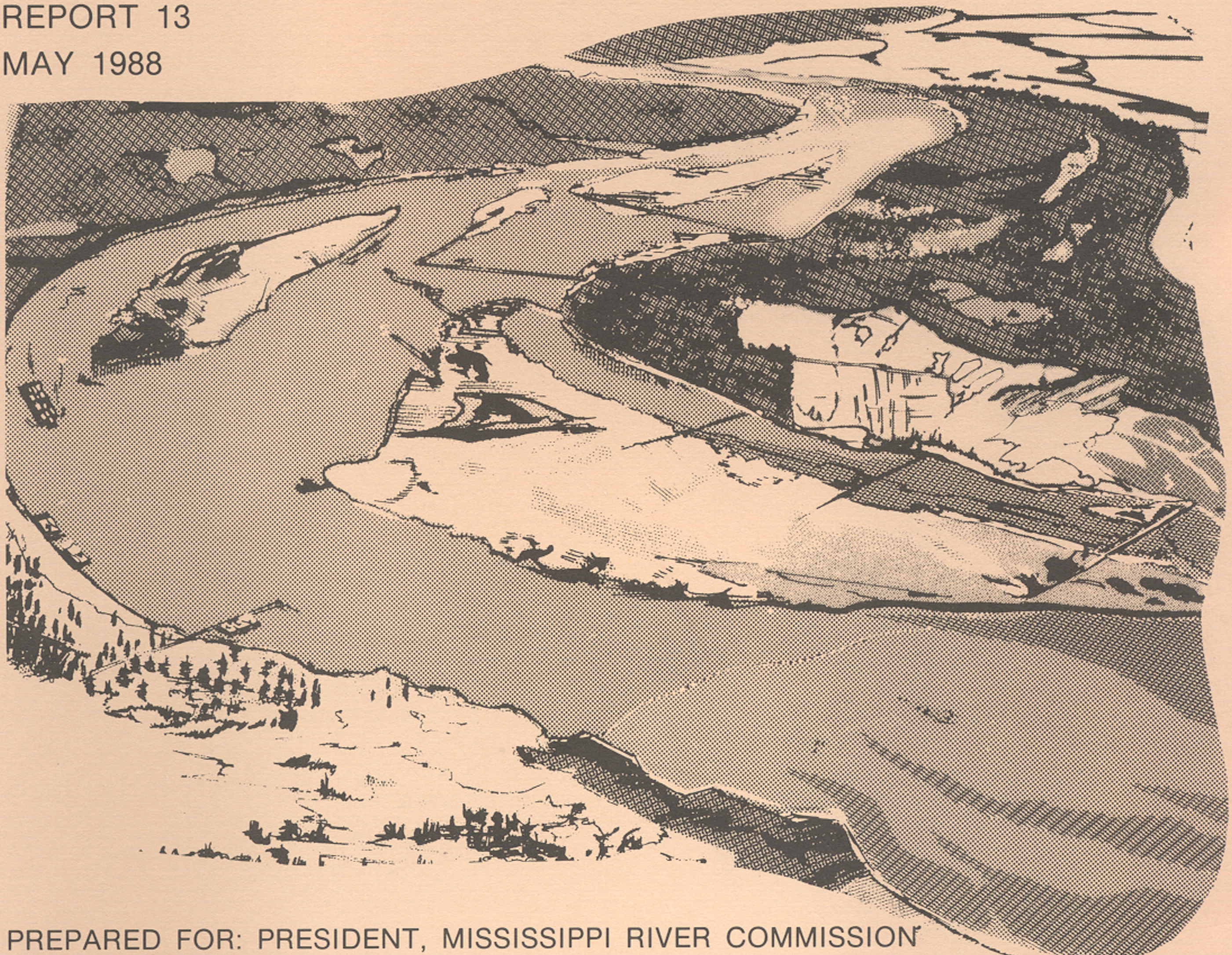
US Army Corps
of Engineers
Mississippi River
Commission

PRELIMINARY ENVIRONMENTAL DESIGN CONSIDERATIONS ASSOCIATED WITH ARTICULATED CONCRETE MATTRESS REVETMENTS ALONG THE LOWER MISSISSIPPI RIVER

LOWER MISSISSIPPI RIVER ENVIRONMENTAL PROGRAM
REPORT 13
MAY 1988



PREPARED FOR: PRESIDENT, MISSISSIPPI RIVER COMMISSION
PO BOX 80
VICKSBURG, MISSISSIPPI 39180-0080

Destroy this report when no longer needed. Do not return it to the originator.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) Lower Mississippi River Environmental Program; Report 13
6a. NAME OF PERFORMING ORGANIZATION Aquatic Ecosystem Analysts 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION President, Mississippi River Commission
6c. ADDRESS (City, State, and ZIP Code) PO Box 4188 Fayetteville, AR 72702	7b. ADDRESS (City, State, and ZIP Code) PO Box 80 Vicksburg, MS 39180-0080
8a. NAME OF FUNDING/SPONSORING ORGANIZATION President, Mississippi River Commission 8b. OFFICE SYMBOL (If applicable) MRC-PO-R	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. DACW38-87-C-0019
8c. ADDRESS (City, State, and ZIP Code) PO Box 80 Vicksburg, MS 39180-0080	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
See reverse.

12. PERSONAL AUTHOR(S)
Aggus, L. R.; Jenkins, R. M.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Report 13 of a series	FROM ______ TO ______	May 1988	70

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Fisheries	Mississippi River
			Wildlife	Revetments
			Macroinvertebrates	Design considerations

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

Preliminary environmental design considerations are described for Articulated Concrete Mattress (ACM) revetments along the Lower Mississippi River. These considerations were developed for the Mississippi River Commission for possible use and maintenance of ACM revetments within the Mississippi River and Tributaries Project. The environmental considerations are preliminary inasmuch as they would require additional field testing and engineering and cost evaluation prior to large-scale implementation. Environmental measures discussed include modification to the upper surfaces of ACM blocks, stone and wood habitat structures, creation or expansion of eddies, artificial spawning devices, and management of vegetation for fish, macroinvertebrates, and wildlife. A review of the literature relating to environmental values of ACM revetments is presented.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

11. TITLE (Continued):

Lower Mississippi River Environmental Program; Report 13, Preliminary Environmental Design Considerations Associated with Articulated Concrete Mattress Revetments Along the Lower Mississippi River

PREFACE

The Lower Mississippi River Environmental Program (LMREP) is being conducted by the Mississippi River Commission (MRC), US Army Corps of Engineers. It is a comprehensive program of environmental studies of the leveed floodplain of the Lower Mississippi River and navigation and flood-control features of the Mississippi River and Tributaries (MR&T) Project. Objectives of the program are to develop an environmental inventory of the Lower Mississippi River, to identify environmentally important parameters associated with navigation and flood-control features of the MR&T Project, and to provide these as preliminary design considerations.

One component of the LMREP is the revetment investigation. This report presents preliminary environmental design considerations for Articulated Concrete Mattress revetments along the Lower Mississippi River and is the final product of the investigation. Other components of the investigation addressed fish and fisheries, wildlife, and physical and hydrological aspects of revetments.

The report was prepared by Messrs. Larry R. Aggus and Robert M. Jenkins, Aquatic Ecosystem Analysts, PO Box 4188, Fayetteville, Ark. Mr. Stephen P. Cobb, MRC, Vicksburg, Miss., was the project officer and program manager for the LMREP. Mr. Charles Elliott (Engineering Division, MRC) provided guidance on river engineering aspects of the project. The work was sponsored by the Engineering Division, MRC, and was conducted by the Planning Division, MRC, under the direction of the President, Mississippi River Commission, BG Thomas A. Sands, CE.

CONTENTS

	Page
PREFACE	1
CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT	3
PART I: INTRODUCTION	4
Purpose and Scope	4
Background	5
PART II: OVERRIDING FACTORS AND CONSTRAINTS	13
Engineering	13
Physical	14
PART III: INTEGRATED PLANNING	16
PART IV: DESIGN CONSIDERATIONS FOR FISH AND WILDLIFE	18
Macroinvertebrates and Fish	19
Wildlife	33
REFERENCES	37
APPENDIX A: LITERATURE REVIEW OF ENVIRONMENTAL CONSIDERATIONS	A1
General Ecological Considerations	A1
Fluctuations in River Stage	A5
Substrate Relations	A7
Currents	A12
Cover and Structure	A16

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

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

Multiply	By	To Obtain
Acres	4,046.873	square meters
Farenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	meters
gallons	3.785412	cubic decimeters
inches	2.54	centimeters
miles (US statute)	1.609347	kilometeres

* To obtain Celsius (C) temperature readings from Farenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

PRELIMINARY ENVIRONMENTAL DESIGN CONSIDERATIONS ASSOCIATED WITH ARTICULATED CONCRETE MATTRESS REVETMENTS ALONG THE LOWER MISSISSIPPI RIVER

PART I: INTRODUCTION

Purpose and Scope

1. The purpose of this report is to identify preliminary environmental design considerations for the construction and maintenance of Articulated Concrete Mattress (ACM) revetments on the Lower Mississippi River (LMR). These considerations represent refinements in design or new structural features that could be incorporated into the revetment program to improve the environmental quality of the habitat associated with revetted banks. They are considered preliminary because most would require further field testing and evaluation prior to large-scale implementation. They are not intended to be a departure in policy with respect to the design and construction of ACM revetments. Environmental design considerations are subject to various engineering, legal, cost, regulatory, and project authority constraints.

2. Preliminary environmental design considerations for ACM revetments were developed as part of the Mississippi River Commission's (MRC) Lower Mississippi River Environmental Program (LMREP). Within this program, field investigations were made of fish and wildlife communities and important physical and hydrological features of major aquatic and terrestrial floodplain habitats in the LMR from southern Missouri and western Kentucky to southern Louisiana to provide data for the formulation of environmental design considerations. Historical data were also obtained from an extensive review of technical literature pertaining to fish and wildlife management in environments and situations relevant to ACM revetments. These environmental data were combined with engineering design and operational criteria to develop the environmental design considerations prescribed herein. The objectives of this report are as follows:

a. To describe environmental values of ACM revetments with an emphasis on fish and wildlife populations and habitat.

b. To identify preliminary environmental design considerations for ACM revetments that benefit fish and wildlife and may be feasible from engineering, project authority, and cost perspectives.

3. Optimal environmental characteristics for ACM revetments were developed using widely accepted ecological principles for riverbank habitats, and results from the LMREP field investigations (Table 1). The approach assumes that design features which create more diverse current patterns and substrate characteristics and increase the amount of cover and structure on revetted banks will benefit aquatic and riparian resources. These features are presented without consideration of cost, legal, and authority constraints; however, engineering constraints are discussed.

4. The following synopsis is presented to assist readers in finding specific information contained in this report. The remainder of Part I provides background information on the revetment construction and maintenance program and the LMREP. Part II describes engineering, project authority, and physical constraints that influence environmental design considerations for fish and wildlife. Part III outlines an integrated approach to assist workers in identifying and planning appropriate environmental considerations. Part IV is a summary of possible design considerations to enhance fish and wildlife, with discussions of rationale, engineering feasibility, and criteria for application. Appendix A summarizes a literature review concerning environmental effects of revetments on fish and wildlife.

Background

LMREP

5. The devastating Mississippi River flood of 1927 prompted Congress to pass the Flood Control Act of 1928, authorizing the US Army Corps of Engineers (CE) to undertake the Mississippi River and Tributaries (MR&T) Project, which included extensive construction for flood control and navigation. Primary features of the project on the LMR are levees, floodways, revetments, dikes, and dredging. Under the MR&T Project, the CE was authorized to construct

Table 1

Optimal Physical Characteristics of ACM Revetments for Benthic Macroinvertebrates, Fish and Fishing, and Wildlife

Characteristic	Benthic Macroinvertebrates	Fish and Fishing	Wildlife
Water quality	Similar to main channel.	Similar to main channel.	Similar to main channel.
Shoreline shape	Sinuous with many points and indentations; should maintain these features at a wide range of river stages.	Same as for benthic macroinvertebrates.	Not important.
Shoreline slope	Variable, ranging from 3H:1V to 10H:1V.	Same as for benthic macroinvertebrates.	3H:1V or flatter.
Bottom shape	Variable with many interstices.	Variable with many depressions large enough to protect adult fish from current.	Not important.
Substrates	Predominantly firm substrates with many small interstices and fine sedimentary materials; minimal sand substrates.	Same as for benthic macroinvertebrates but with large interstices in firm substrates.	Firm substrates.
Currents	Variable, but mostly less than 0.5 ft/sec or greater than 2.6 ft/sec to control sediment deposition.	Variable with much turbulence and areas with currents less than 1 ft/sec.	Currents slow near shoreline.

(Continued)

Table 1 (Concluded)

Characteristic	Benthic Macroinvertebrates	Fish and Fishing	Wildlife
Eddies	Permanent, extending over large vertical range of shoreline.	Permanent, extending over large vertical range of shoreline; large enough to encourage angler use (1-acre or larger).	Same as for benthic macroinvertebrates and fish.
Cover and structure	Cover unlimited below mean low-water elevation.	Large structures in areas of low current velocity, and below mean low-water elevation; should be large enough to provide escape cover for fish.	Unlimited along landward boundary; structures should be large enough to provide protection to large mammals.
Vegetation	Mixed woody and herbaceous plants, with large trees on upper bank.	Same as for benthic macroinvertebrates.	Mixed woody and herbaceous species with high food or cover value; should extend from top of ACM to landward boundary of revetment site.

968.2 miles* of ACM revetment on the LMR. By 1 January, 1987, 879.7 miles of structures had been placed. An additional 88.4 miles of revetment, mostly downstream from New Orleans, are planned for construction before the MR&T completion date of March 2010. With culmination of the currently authorized work, about 50 percent of the shoreline of the LMR will be revetted (MRC 1977).

6. The LMREP was initiated in fiscal year 1981 and is scheduled for completion in fiscal year 1988. Additional work is being considered for future years. The program has as objectives the development of baseline environmental resources data on the river and associated floodplain and the formulation of environmental design considerations for channel training works (dikes and revetments) and the main stem levee system. Fish and wildlife populations and habitat are the main focus of the LMREP. The program is made up of the following work units: habitat inventories including development of the Computerized Environmental Resources Data System (CERDS) (a geographic information system), levee borrow pit investigations, dike system investigations, and revetment investigations. This report is part of the revetment investigations work unit.

Revetments

7. Revetments protect and stabilize natural bluff bank habitat from the elevation on the upper bank where erosion is considered a problem to the thalweg. An effective revetment must be flexible enough to follow irregularities in the shoreline, hold the bank as settling occurs, be permeable while preventing soil erosion, and be relatively indestructible in air and water (MRC 1977). The design best suited for use in the LMR is a revetment made of ACM on the lower (subaqueous) bank and broken stone (riprap) on the upper bank. The general sequence of ACM revetment construction involves site preparation (clearing, snagging, grubbing) and bank grading, placing ACM on the subaqueous bank, and paving of the upper bank with riprap. In this procedure, the vegetation at a construction site is first cleared, and

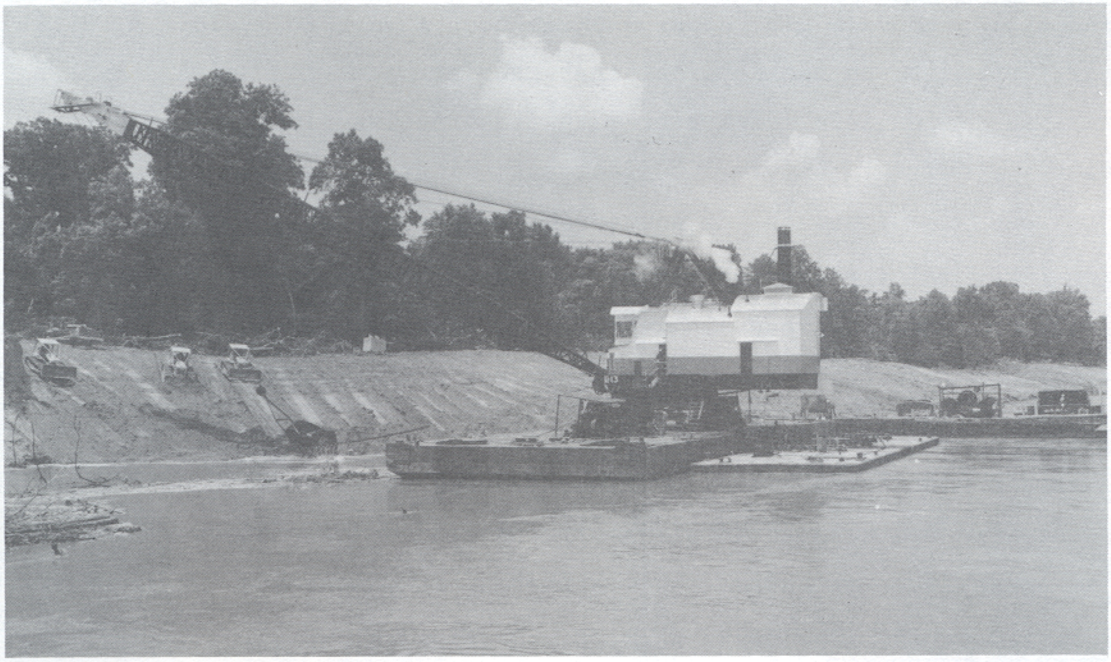
---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

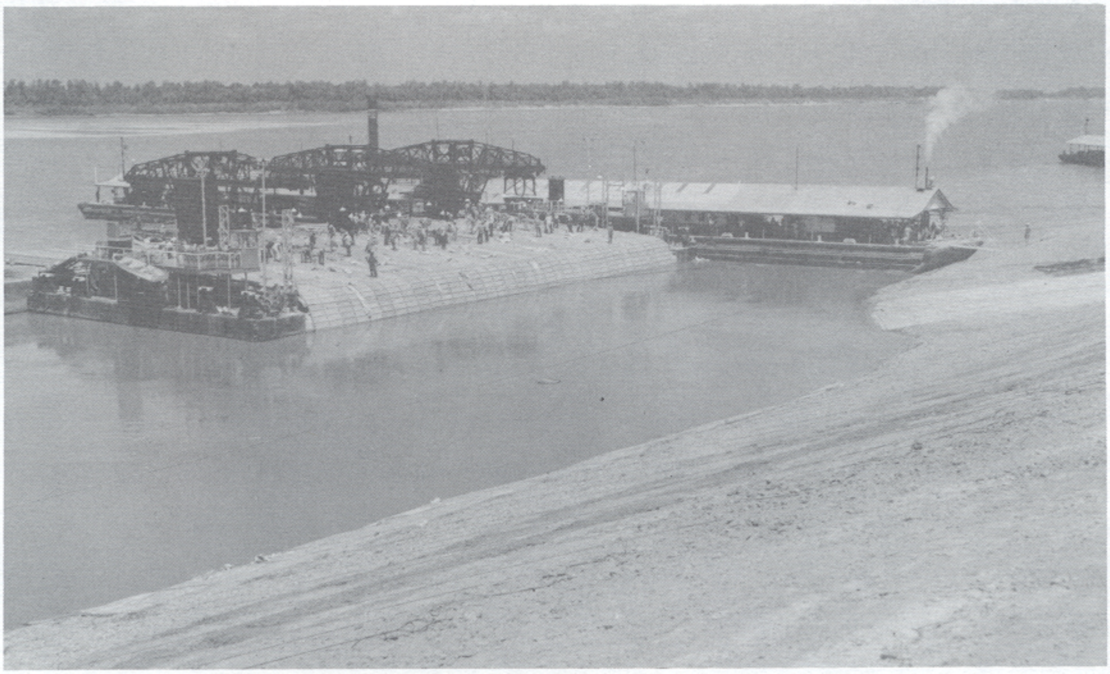
the snags are removed. The upper bank is then graded to a slope of 3V:1H or flatter, depending on the physical characteristics of the soils. Excess bank material is graded into deep water with floating draglines and is usually entrained by currents before ACM placement (Figure 1a).

8. ACM is placed on the subaqueous bank soon after grading to minimize erosion. The mattress is fabricated at the construction site by one of two specially designed mattress-sinking plants (Figure 1b). The mattress is made up of units 4 feet (ft) wide, 25 ft long, and 3 inches (in.) thick. Each unit is currently formed from 16 individual blocks 4 ft wide and 17 in. long (US Army Corps of Engineers 1986). Units are bound together with corrosion resistant wire and allowed to slide off the sloping deck of the mattress-sinking plant as it is moved slowly away from shore until a continuous mattress 140 or 157 ft wide is sunk on the graded riverbank. The plant is then moved upstream, and additional layers are added so that the sections overlap like shingles. Revetment construction and repair must be done during the low-water season, which usually lasts from July to November. However, budget constraints or unusually high water levels during this period can shorten the working season.

9. The upper bank is paved with riprap immediately after placement of the ACM to protect the mattress and bank from erosion during high river stages (Figures 1c and d). Several paving materials including monolithic concrete and uncompacted asphalt have been used to protect the upper banks of ACM revetments, and these substrates can be found at many older sites. Experience has shown that riprap affords superior protection to the upper bank, conforms well to irregularities in the shoreline, and permits regrowth of terrestrial vegetation that helps stabilize the upper bank. Riprap is now specified for all revetment construction and repair in the LMR. It is usually placed by machine to an average thickness of 10 in. A gravel, crushed stone, or shell blanket is laid along the waterline before the riprap is placed to protect the graded bank in the interim and to help prevent soil from leaching through the revetment interstices (Moore 1972).

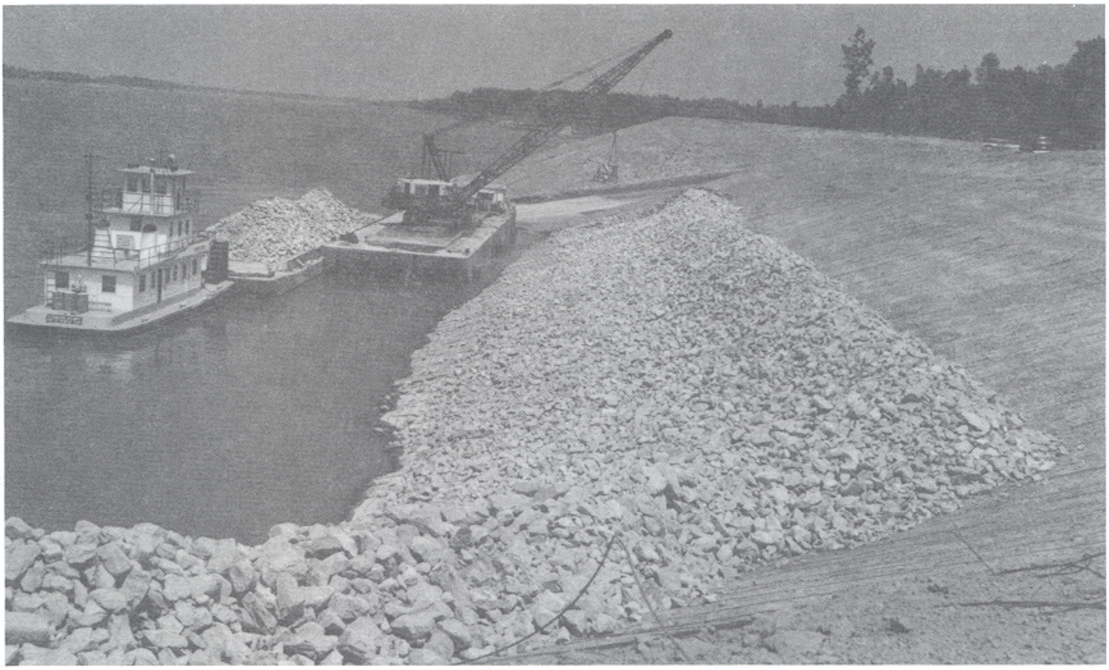


a. Bank grading



b. Mattress-laying plant in operation

Figure 1. Procedures for constructing ACM revetment (Continued)



c. Placing stone pavement on upper bank

d. Close-up of revetment in place

Figure 1. (Concluded)

10. Revetments make up a relatively small percentage of the aquatic habitat in the leveed floodplain of the LMR, but they are important ecologically because they comprise a substantial part of the total bank habitat of the main channel. At a bank-full stage, there were 34,044 acres of ACM revetment habitat as of the 1973-1974 period based on data from the CERDS geographic information system (Cobb and Williamson 1985). This amounted to about 7 percent of the total area of aquatic habitat in the main channel and 5.6 percent of the aquatic habitat within the leveed floodplain. At this river stage, the surface area of revetments was about 1.8 times greater than that of the remaining natural banks.* This ratio would be higher at present because significant amounts of revetment have been built in the last 14 years. The percentage of main channel habitat made up by revetments apparently remains constant at stages below bank-full. Habitat mapping of a 50-mile reach of the the river between river miles 480 and 530 revealed that revetments make up about 5 percent of the aquatic habitat at midbank and low river stages (Cobb and Clark 1981).

---

* Personal Communication, July 1987, Mr. Stephen P. Cobb, US Army Engineer Division, Lower Mississippi Valley, Vicksburg, Miss.

PART II: OVERRIDING FACTORS AND CONSTRAINTS

11. The development of environmental design considerations for fish and wildlife can be overridden or constrained by several engineering and physical factors. These conditions can affect construction activities at a particular site or the placement of revetments in general. When identified prior to construction, they can assist planners and engineers in determining what environmental considerations, if any, are appropriate for a particular revetment site. Streambank and hydrological features of the LMR are extremely variable. Although the factors that cause bank failure in the alluvial substrates of the LMR are well defined (Keown et al. 1977, Shields and Palermo 1982, Schnick et al. 1982, Henderson and Shields 1984), variations in the conditions of deposition and erosion make it virtually impossible to predict substrate characteristics over a large area (Keown et al. 1977).

Engineering

12. A major constraint for the development of environmental design considerations for revetments in the LMR is the large capital and technological investment in the existing revetment construction methodology, mat-sinking and bank-grading plants, and mat-casting facilities. The present engineering technology for revetment construction and maintenance has undergone extensive refinement since experimental testing began in 1914, and it has been used exclusively for revetment construction since 1945 (Keown et al. 1977). Although other types of revetment designs, materials, and construction methods might provide benefits for fish and wildlife resources, the large capital and technological investments in the current ACM revetment methodology and the proven effectiveness of the present design preclude radical changes in the existing program. Revetment construction and maintenance work with the present equipment must be done during the low-water season, which limits flexibility in construction schedules. Implementation of environmental design considerations must not appreciably slow work of the bank-grading or mat-

sinking plants because of the large per-unit time costs and the limited duration of the low-water working season.

13. Site-specific characteristics at a proposed construction site limit engineering design actions for fish and wildlife, and it is considered good engineering practice to approach revetment construction on a site-specific basis. The precise location, shoreline slope, and length of a revetment are determined by established engineering procedures. The structure must extend a sufficient distance along the bank to ensure that a stable shoreline is created and riverward to the thalweg to prevent undercutting of the subaqueous bank (US Army Corps of Engineers 1986). Shoreline slope is determined by the structure and cohesiveness of the soils comprising the bank and involves the use of established geotechnical engineering practices.

14. Environmental design considerations that could reduce the effectiveness of the revetments or significantly weaken the ACM structurally are not acceptable from an engineering, social, or economic perspective. The structures must be designed to have a long life with a very low risk of revetted bank failure. Bank failure can result in breaches of the levee system and disruptions of navigation channel alignment.

Physical

15. Physical factors identified as having an overriding influence on the development of environmental design considerations for fish and wildlife include: (a) large fluctuations in river stage, (b) current patterns and velocity, and (c) the dominant vegetation communities in the area adjacent to the construction site. These factors acting singly, or in combination, set limits on potential habitat improvement considerations for fish and wildlife that cannot be easily negated through design modifications.

16. Design considerations on ACM revetments for fish and wildlife must be effective across the wide range of river stages that occur in the LMR. This influences the size of structures for habitat improvement, the types of construction materials that can be used, and costs. River stages vary widely both seasonally and annually, and actions to create a desired ecological

effect can be modified or negated by changes in river stage. Habitat structures designed to benefit fish or wildlife during a particular season or life history stage may have to be placed across a range of elevations to provide some benefits at an expected range of river stages. This may necessitate larger and more costly improvements. Also, habitat structures must be designed to withstand the physical forces of high-flow events.

17. Currents adjacent to revetted banks can be among the strongest found in the LMR. Revetments located in areas with strong currents, such as the concave banks of sharp bends, afford few opportunities for habitat improvement. In contrast, relatively straight sections of revetment placed along an irregular bank offer a variety of possibilities for habitat improvement. An understanding of local variations in current direction and velocity is required to determine if the construction of a habitat improvement structure will scour or accrete sediments as well as to determine the types of structures and construction materials that should be used and the locations where habitat improvements may be effective.

18. Dominant plant communities in the area surrounding a revetment construction site influence the species of plants that will revegetate the upper bank following construction, the species of mammals and birds that will use the site, and the availability of woody materials for potential use in the construction of habitat improvement structures. A subjective examination of the plant communities surrounding a proposed revetment site enables engineers and environmental planners to assess probable wildlife use and appropriate habitat improvement features. For example, a revetment site located adjacent to an agricultural area may benefit from the planting of a wooded shelter belt along the landward margin to create a migration corridor for wildlife. A site adjacent to a mature bottomland hardwood stand may be allowed to revegetate naturally. A site with large amounts of trees can provide materials for brush shelters.

PART III: INTEGRATED PLANNING

19. An integrated approach to planning provides several advantages for identifying potential environmental considerations and incorporating these into the construction and maintenance of revetments. It allows engineering and environmental planning personnel to examine certain types of basic data to identify potentially valuable habitat features at a proposed construction site during early design stages and to determine the feasibility of implementing specific environmental actions. Construction and maintenance of revetments require large expenditures, and design considerations to improve habitat have a greater chance of receiving favorable funding consideration when they are identified early in the planning process.

20. Opportunities for habitat improvement during revetment construction and maintenance are strongly limited by the engineering, authority, and physical constraints identified in Part II. Actions to enhance fish and wildlife will depend on the ability of the engineer and planner to identify desirable environmental features at a proposed revetment project and integrate these into the complex construction process.

21. The basic procedure outlined in Figure 2 illustrates a practical series of steps that engineers and environmental planners may use to identify suitable environmental considerations for a particular revetment site. The users can then select the appropriate sections of this report to obtain more detailed guidance or background information.

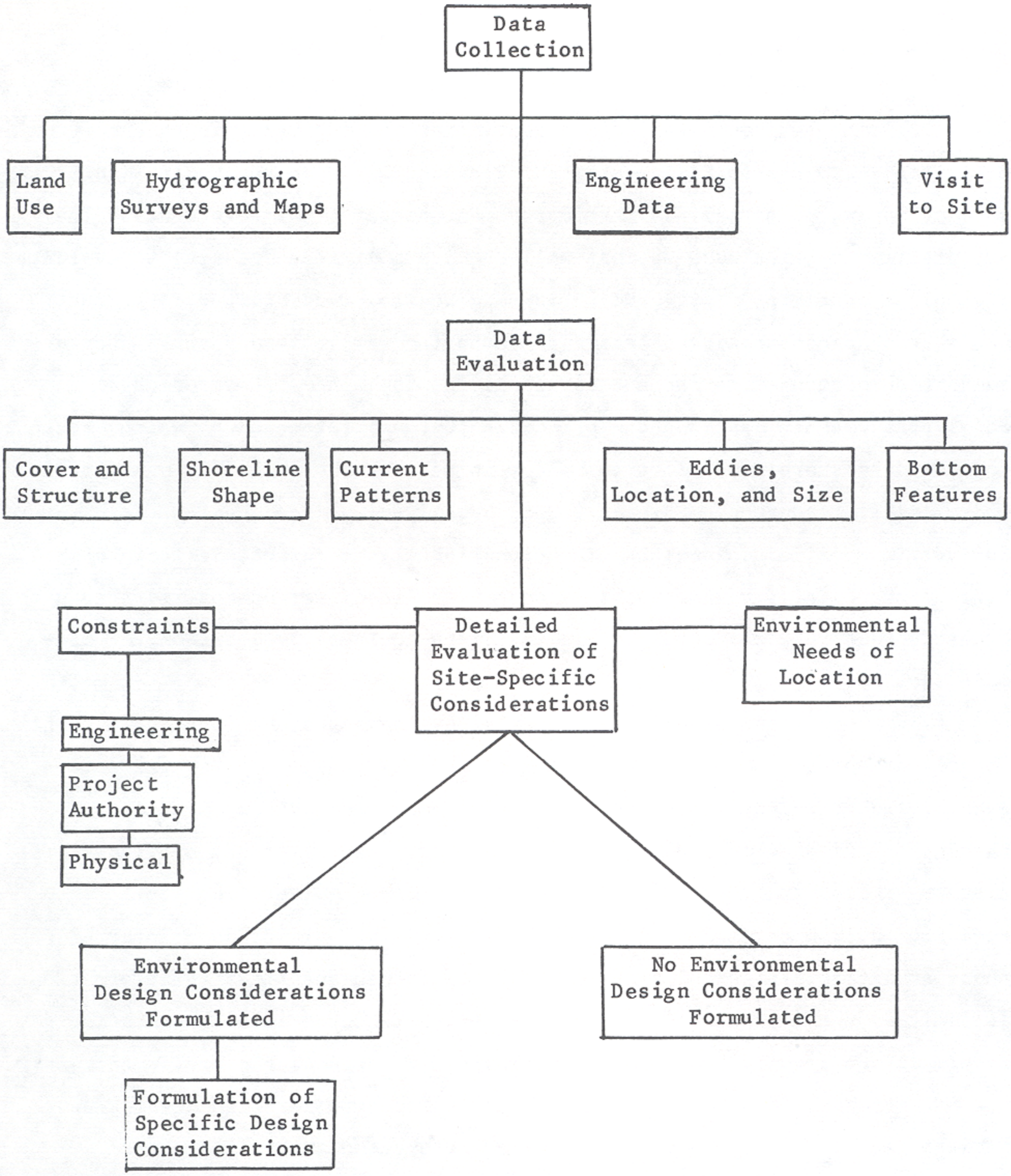


Figure 2. Flowchart for determining appropriate levels of environmental considerations for fish and wildlife during revetment construction or repair

PART IV: DESIGN CONSIDERATIONS FOR FISH AND WILDLIFE

22. The environmental design considerations described in this section are intended to assist Engineering and Planning Division staffs in identifying and developing potential habitat improvement features for revetments. They are preliminary, inasmuch as most will require additional testing to evaluate biological benefits, verify and refine engineering feasibility, determine costs, and assess impacts relative to authorized project purposes. They are subject to continued refinement as experience is gained. Environmental considerations are based on the principle that habitat features which create a more diverse shoreline and streambed or increase turbulence will benefit fish and wildlife resources. Shields (1983) broadly classified habitat structures for use in modified channel habitats functionally as current deflectors (including eddies), random rocks (stones piled in different configurations to create structure), and cover (including brush shelters, vegetation, or man-made features).

23. Documented experience with the development of habitat improvement considerations for ACM revetments is extremely limited, and this reflects a general lack of quantitative information for modified stream channels (Henderson and Shields 1984, Nunnally and Shields 1985). Most available case history studies are from small unaltered streams, and justification for specific environmental design actions must often be estimated or inferred from these studies (Shields and Palermo 1982). Although quantitative information is limited, the incorporation of environmental features into the existing revetment construction program is desirable. Construction of revetments in the LMR is about 90 percent complete, and few opportunities to develop new habitat improvement techniques will exist before the authorized river alignment program ends (Shields 1983). Maintenance will continue indefinitely, as about 1 percent of existing revetments will need repair each year (MRC 1977). Environmental features incorporated into selected sections of new ACM on an experimental basis, and carefully evaluated, can serve as models for environmental design improvements during future maintenance work.

Macroinvertebrates and Fish

Grooved upper surfaces of ACM blocks for macroinvertebrates

24. The upper surfaces of ACM blocks can be modified with shallow grooves during casting to increase surface area and to provide protection from the current for benthic macroinvertebrates. Modified blocks should include the following environmental considerations: (a) grooves should substantially increase the upper surface area of the block while providing sheltered areas large enough to protect common species of benthic macroinvertebrates from exposure to direct current, (b) grooves should not increase sediment accretion on the upper surface of blocks at moderate or high current velocities, (c) the design modification should not cause the upper surfaces of blocks to erode at a more rapid rate than occurs with unmodified blocks, and (d) modifications should not significantly reduce the strength of the blocks or cause excessive breakage during construction operations.

25. Rationale. Benthic macroinvertebrates play an important role in the conversion of particulate organic matter to fish tissue in large alluvial rivers. The production of these organisms is highest in areas of fine sediments and firm substrates. Irregularly shaped, firm substrates similar to those found on dikes and riprap banks are colonized by a diverse and abundant assemblage of benthic macroinvertebrates. Mathis, Bingham, and Sanders (1982) implanted stone-filled baskets in dike structures and found that large numbers of benthic macroinvertebrates colonized samplers implanted on the upstream side or top of dikes where currents were strongest.

26. The ACM provides a firm substrate for benthic organisms when the upper surfaces of blocks remain free of sediments, but the surface is relatively smooth and affords only limited protection from the current. Experiments conducted under the LMREP demonstrated that macroinvertebrate abundance on the ACM increased substantially when the blocks were modified to increase the surface area for attachment and to provide small interstices where organisms could escape the current. In these experiments, blocks with shallow parallel grooves in the upper surface were colonized by larger numbers

of organisms than blocks with small circular depressions in the surface or ones with artificial substrate materials (Fish-Hab) attached to the surface (Baker et al., in preparation). Macroinvertebrates were approximately twice as abundant on the grooved blocks as on unmodified controls, an increase about equal to the increase in upper surface area of the blocks.

27. Engineering feasibility. Large-scale use of grooved ACM blocks to enhance macroinvertebrates will require the development of an efficient procedure for incorporating modifications into the existing casting procedure to produce blocks at a minimal cost increase while maintaining the strength of the blocks. Because of logistic constraints, the grooved blocks will have to be engineeringly suitable for placement in any location. In preliminary tests to evaluate the effectiveness of a modified ACM for enhancing benthic colonization, blocks were modified with parallel grooves 0.25 in. in both width and depth and spaced at 0.125-in. intervals (Baker et al., in preparation). Grooves were formed across the short axis of blocks so as to be oriented at approximately right angles to the current when the blocks were in place as they would be during normal use (Figure 3). This configuration increased the area of the upper surface by 2.3 times. No measurable erosion of the grooved surfaces was reported after the blocks had been in the river for approximately 1 year. Effects of this design on strength and performance of blocks were not evaluated.

28. Criteria for application. Grooved ACM blocks will be desirable for all future revetment construction and maintenance if appropriate methods can be developed to form blocks with no significantly increased costs or loss of performance. However, the greatest potential for environmental enhancement can be realized at locations with strong currents where the upper surfaces of blocks remain free of sediments. The concave banks of sharp bends or other areas of high current velocities are suitable locations for this type of habitat improvement feature. It is one of the few environmental actions that can be used at sites with very strong currents.

Tree shelters

29. Hardwood trees and brush obtained during construction or repair of revetments can be anchored, separately or in bundles, along the subaqueous

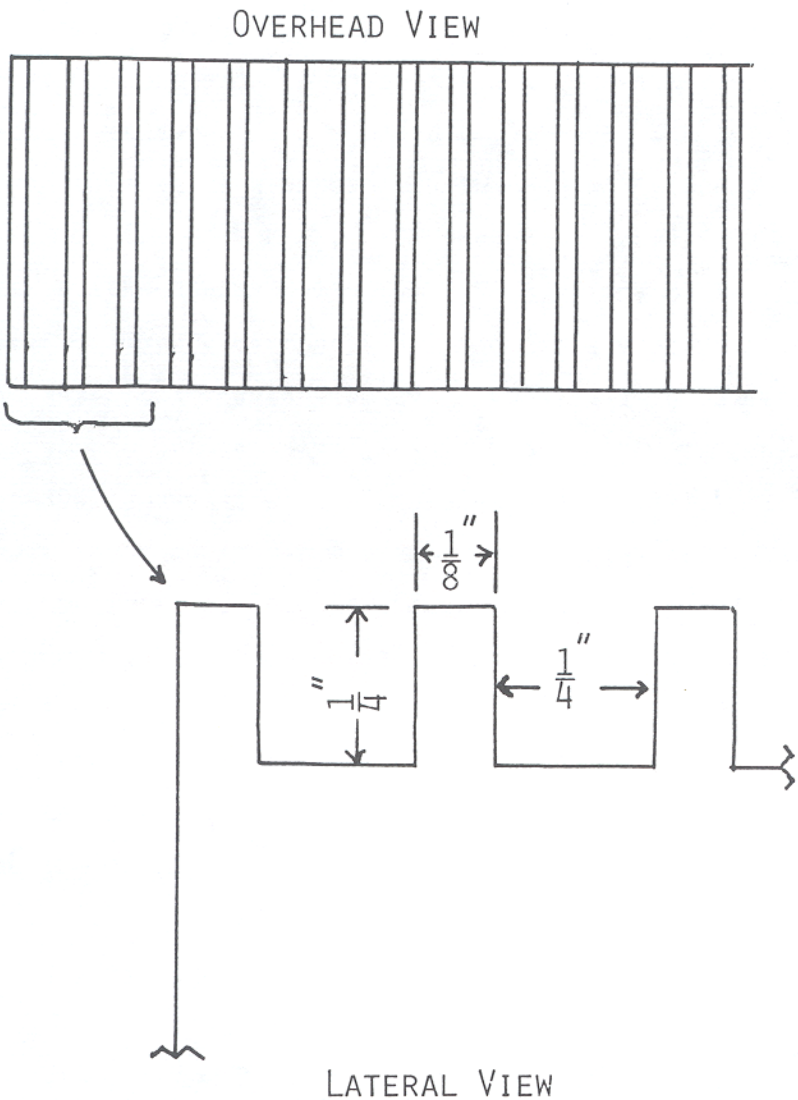


Figure 3. Modified ACM block illustrating grooves across short axis of upper surface (overhead view) and detail of possible configuration for grooves (lateral view)

bank in areas of low current to provide cover for fish and a firm substrate for benthic macroinvertebrate attachment (Figure 4). The structures should be placed below the low-water level to slow the rate of decomposition of the structures and reduce potential hazards to boats. Shelters can be of variable size and shape, depending on the quantity of woody material accumulated during construction and the amount of habitat suitable for placing structures. At a minimum, a shelter should consist of a single tree large enough to provide escape cover for adult fish. However, brush shelters covering approximately 1 acre were also very effective in concentrating some species of sport fish in Lake Barkley, Kentucky (Pierce and Hooper 1979).

30. Rationale. Tree shelters are a relatively inexpensive method of increasing shoreline structure where physical conditions permit. Tree shelters create a more complex physical environment that increases carrying capacity for some fish, provides niches for a larger number of species, and provides areas of firm substrate for epibenthic invertebrates that are a food source for some fish. This type of cover is abundant along most steep unstable banks of the LMR. Revetment construction often results in a loss of cover and habitat structure when compared with natural caving banks because small recesses in the shoreline, woody vegetation, and snags are eliminated. Sites for the placement of tree shelters on revetted banks should afford some shelter from currents, such as in scalloped recesses along irregular bank lines. Using trees or woody debris felled during revetment construction or maintenance to increase habitat diversity is environmentally preferable to disposing of these materials by burning, burying, chipping, random windrowing, or removal from the construction site.

31. Engineering feasibility. From an engineering perspective, localized structurally induced scour limits the use of brush shelters to areas with reduced current. The structures are subject to damage or dislodging during high flows and should be placed only in locations where they will be afforded protection from the current. The structures pose a potential threat to navigation and pleasure boats. However, this risk can be greatly reduced if shelters are placed and securely anchored below the mean low river stage along straight sections of revetment where the navigation channel is not

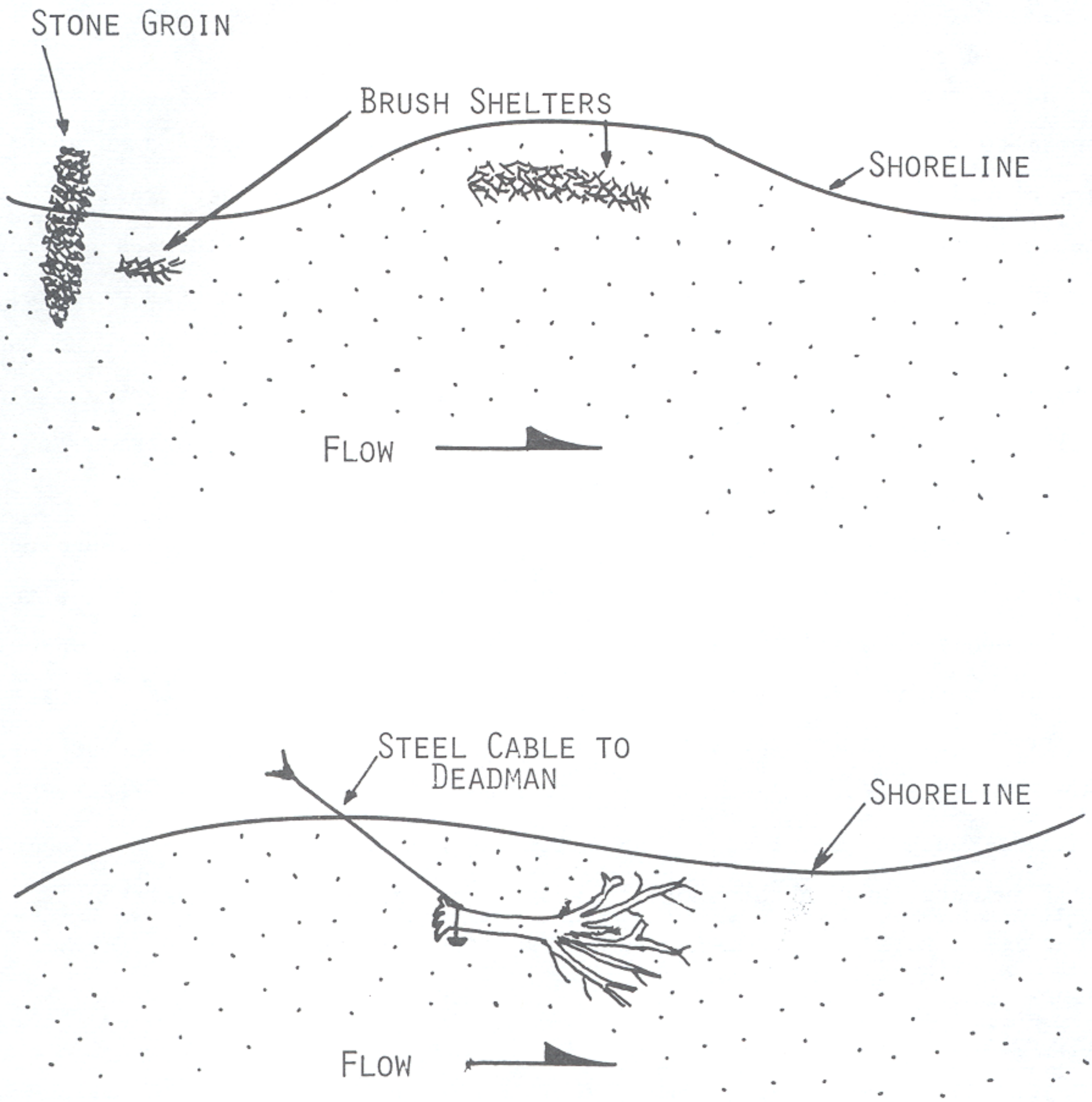


Figure 4. Brush shelters placed in protected areas of revetted shoreline (top), and tree cabled and anchored near shoreline

adjacent to the revetted bank. Brush shelters must be constructed soon after the ACM is placed so that the materials do not dry out. Tree shelters can be put in place during revetment construction and maintenance or by a separate work effort.

32. Tree structures should be secured with noncorrosive cable and anchored to withstand currents expected during flood flows. Trees anchored singly should be cabled near the base of the trunk so that they trail downstream with minimal resistance to the current. Large shelters should be elliptical or rectangular in shape and oriented with the long axis parallel to the current to minimize friction during high flows (Figure 4). Henderson and Shields (1984) have described procedures for placing and anchoring trees along shorelines as bank protection devices on small streams. These methods are appropriate for use on the LMR.

33. Criteria for application. Tree shelters can be used to improve habitat for fish at most revetments. However, use is limited to areas with suitable woody materials at a construction site or at locations where uprooted trees can be found along the banks close to a revetment, and areas that are partially sheltered from currents. Structures should not be placed where they pose a threat to navigation. Relatively straight sections of revetment where maximum currents adjacent to the shoreline do not exceed 5 feet per second, natural indentations in the shoreline, or areas immediately downstream of current deflectors or flow-retarding structures are suitable sites for brush shelters.

Stone groins

34. Stone groins of variable size and shape can be used to create localized areas of reduced current along revetted banks and to provide structure and attachment substrate for fish and benthic organisms. Large groins (approximately 10 ft in height, 30 ft wide at the base, and variable in length) can be placed along smooth reaches of ACM revetment to create eddies or immediately upstream of existing eddies to increase their size and stability. A structure of the size described above extending from the top of a revetted bank to a point below the mean low-water elevation will create a relatively permanent eddy across a range of river stages (Figure 5). In main

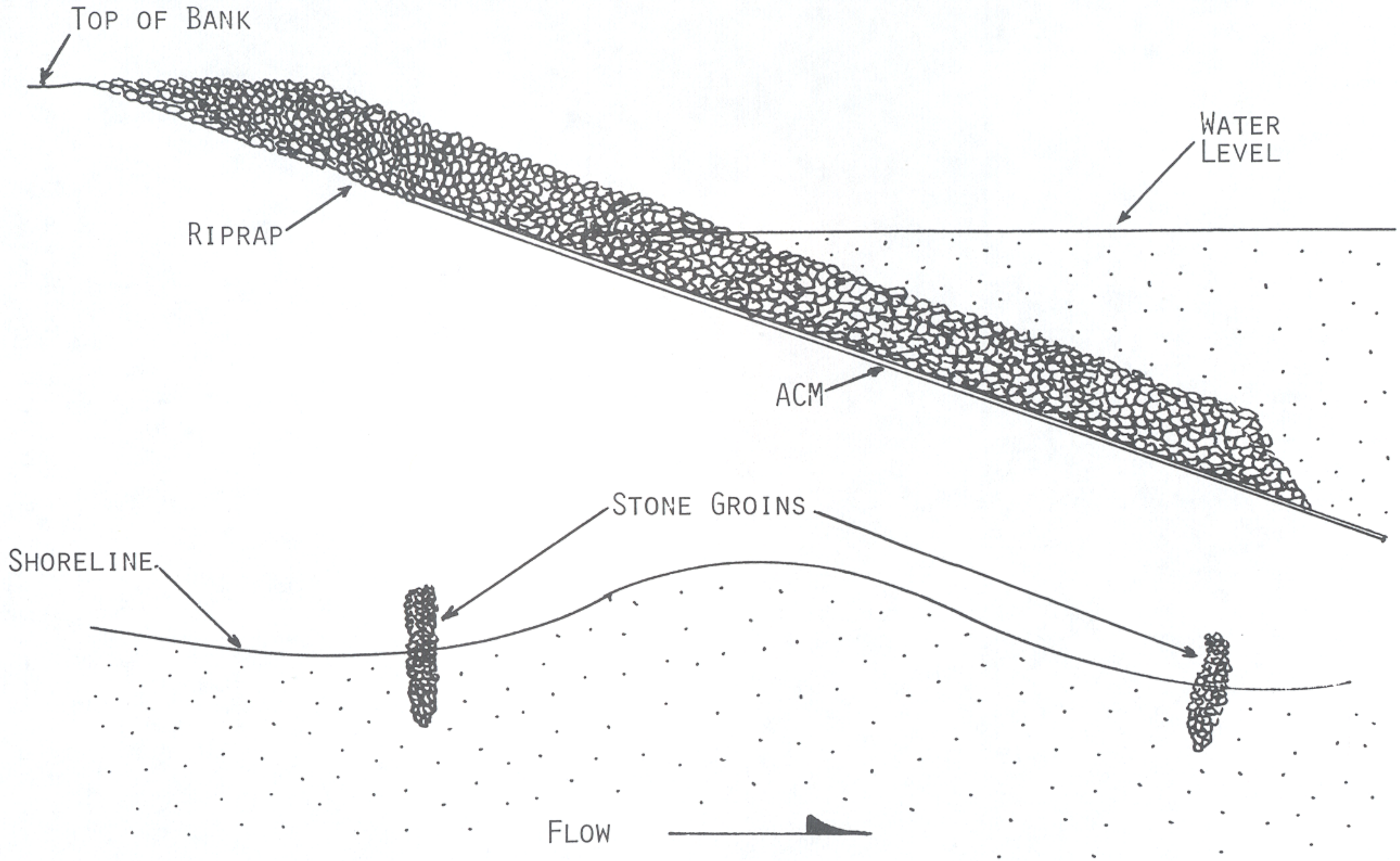
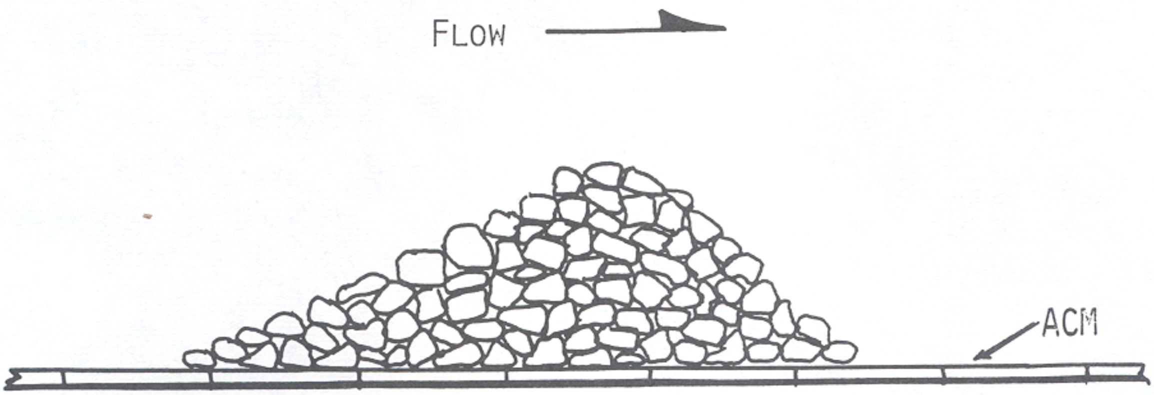
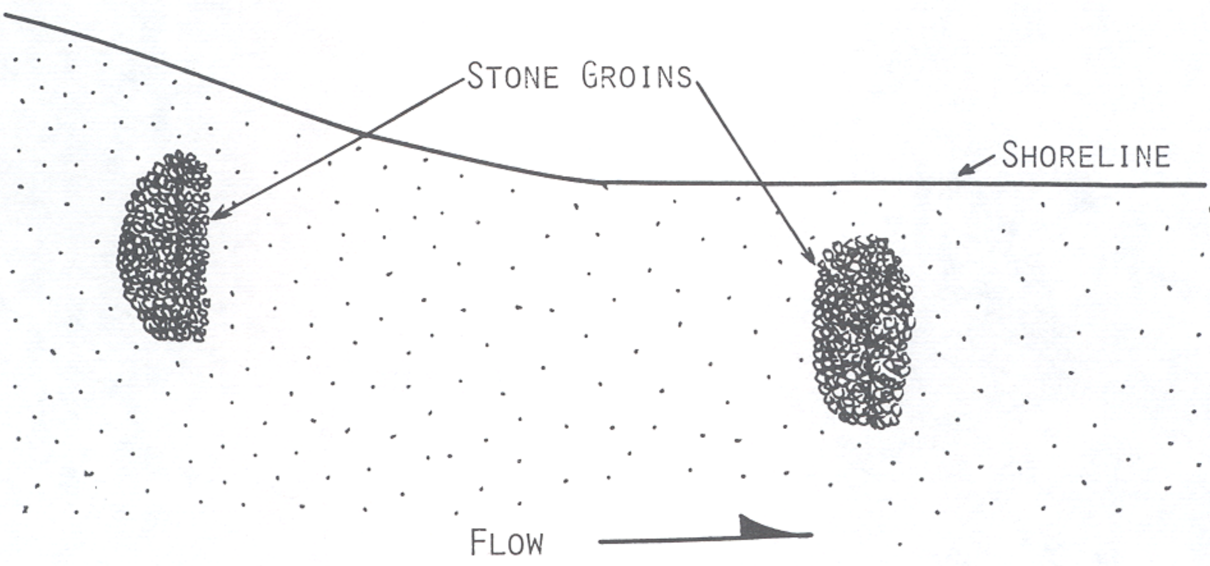


Figure 5. Stone groins used as habitat improvement features in lateral view (top) and overhead view (bottom) in different scales



a. Lateral view



b. Overhead view

Figure 6. Small stone groins used as habitat improvement features for fish and macroinvertebrates in lateral view (a) and overhead view (b) in different scales

channel habitats, the region of turbulence created by the structures can be 4 to 5 times longer than wide (Schnick et al. 1982). Assuming average shoreline slopes between 3H:1V and 4H:1V, a stone groin of the above dimensions should create an area of turbulence 50 to 60 ft wide and 250 to 300 ft long.

35. Small groins (approximately 6 ft in height, 15 ft wide at the base, and variable in length) can be placed on the ACM to provide localized areas of reduced current for fish and substrate for epibenthic organisms. These structures can be constructed perpendicular to the shoreline from a point near the top of the bank riverward on the subaqueous bank to the point where placement becomes impractical because of currents or depth. The upstream side of the structures should have a flatter slope (approximately 2H:1V) to increase the area of substrate for benthic macroinvertebrates, with a steeper slope (1V:1H) on the downstream side to create an area of reduced current for fish (Figure 6a).

36. Elliptical or rectangular piles of riprap 5 ft in height and 15 by 30 ft at the base can also be placed on the subaqueous bank to increase habitat for fish (Figure 6b). Structures of this configuration would increase roughness of the riverbed from the upper part of the subaqueous bank riverward to a point where the placement of stone becomes uncertain because of depth or strong currents or to the depth where the accretion of bed-load materials becomes great enough to cover the structures. They should be placed with the long axis perpendicular to the current to increase turbulence (Figure 6b). One or two structures for each acre of revetment would provide protection from the current for bottom-dwelling fish and would increase the amount of epibenthic invertebrate habitat.

37. Rationale. Revetment often creates a smoother shoreline and riverbank and reduces habitat complexity compared with natural banks. Stone groins placed at intervals along a revetted shoreline can be used to create local areas of turbulence and reduced current velocities downstream of the structures that provide shelter for fish and benthic macroinvertebrates in areas where cover or structure is limited. The structures can also serve as current deflectors to create or enlarge eddies. Unlike many coldwater fishes that are territorial, large numbers of warmwater fish will concentrate in the

localized areas near structures. Revetments are stable, and it is feasible to increase habitat diversity for fish in selected locations by placing inert materials on the ACM. Placing riprap groins on the ACM creates environmental effects similar to mattress buckling.

38. Engineering feasibility. Engineering studies are needed to determine scour and deposition caused by stone groins on revetments and to evaluate the effects of groins on revetment stability. Excessive sediment accretion downstream of a stone groin reduces its effectiveness as habitat for fish. Structure-induced scour destroys the integrity of the revetment surrounding the structure, although areas around the base of a groin can be armored with an extra thickness of stone to control scour. The weight of a groin can decrease bank stability in some cases.

39. Stone groins represent permanent physical modifications to the revetment surface. The structures must not be placed in critical navigation reaches, such as the concave sides of sharp bends where the thalweg is near the bank. They should not be of such a configuration or size as to impede repair of a failed ACM.

40. Criteria for application. Stone groins are best suited for use along straight sections of a revetted bank where the navigation channel is not adjacent to the bank, existing shoreline cover and structure are limited, and bank slopes are moderate. Groins can be used in a much wider range of currents than tree structures. Large groins can be placed upstream of natural or man-made indentations in the shoreline to enlarge eddies or create areas of reduced current. A stone groin placed upstream of an existing eddy can increase the size or permanency of the habitat feature. Smaller stone groins are suitable for areas where the shoreline and riverbed are smooth and there is a lack of nearby structure.

Creation of eddies

41. Eddies can be created along revetted banks by indentations or inflections in the shoreline or by placing structures on the ACM to deflect current. The size and permanency of existing eddies can also be altered by excavating and contouring the shoreline to a desired shape and slope. The Corps' current revetment construction policy generally retains the existing

bank alignment, but reshaping of the bank to accommodate mat-laying equipment often reduces the abruptness of natural shoreline irregularities.

42. Eddies on natural banks vary greatly in size and shape, and an optimum size or shape for revetment eddies probably does not exist. Currents along revetted shorelines are strong, and eddies will generally be several times longer than wide. Zimpfer et al. (1988) considered large eddies to have greater value for fish and invertebrates and suggested that they be as large as practical to form an area of reduced current over a wide range of river stages. The size of an eddy is probably of less concern than creating a feature that persists over a wide range of river stages. Periodic bank failures create indentations of variable size and shape along revetted shorelines. These features should be retained during revetment repair to create eddies.

43. Rationale. Natural caving banks contain many irregularities that form eddies and increase habitat diversity. Although these features are inherently unstable because of frequent bank caving, they increase shoreline habitat diversity by creating areas of reduced current and upstream flow. These sinuous shorelines with many localized areas of turbulence and upstream currents provide a more diverse physical habitat for fish and benthic macroinvertebrates than many revetted banks with more laminar flow. Creating areas of reduced current by retaining natural indentations or inflections in the shoreline or by maintaining the shape of failed sections of an ACM provides an effective method of increasing habitat diversity on revetted banks.

44. Engineering feasibility. From an engineering perspective, creation of eddies on revetments is constrained by requirements to accommodate the floating plant, navigation considerations, and the cost of excavating and shaping the features. These requirements limit the general shape and size of a particular eddy. Creating eddies on revetted banks does not usually pose a hazard to navigation or flood control when current CE criteria for bank preparation are followed. Placing stone groins upstream of eddies to enlarge or stabilize existing features (see previous section) can present significant hazards to navigation in locations where the channel is adjacent to the revetment.

45. Data on the number and spatial distribution of eddies are unknown. Additional studies are needed to describe the amount of eddy habitat presently available on revetted banks and to determine the appropriate sizes, shapes, and locations for revetment eddies.

46. Criteria for application. Eddies have potential environmental value at most locations, and bank line irregularities should be retained during revetment construction and maintenance whenever possible. Potential environmental benefits for eddy construction are greatest on straight sections of revetment with few shoreline irregularities. Most sites where existing revetments have failed also create shoreline features conducive to eddy formation. Optimum shapes, sizes, numbers, and locations for revetment eddies have not been defined. A planning strategy that encourages construction or maintenance actions to maximize both the area and depth of existing eddies should be used until additional information is obtained.

Artificial nesting cavities

47. Short lengths of pipe made of concrete, polyvinyl chloride (PVC), or other inert materials can be buried in the riprap upper bank or securely attached to the ACM to provide spawning and resting cavities for catfish, minnows, or other solitary fishes. Sections of pipe 3.5 ft long, 12 to 14 in. in diameter, and capped on one end provide suitable spawning and resting sites for all but the largest individuals.

48. Catfish spawn in cavities at depths less than 15 ft when water temperatures exceed 70° F in the spring (late April to June in the LMR), and minnows continue to spawn throughout the summer (Carlander 1969, Pflieger 1975). The LMR experiences large and unpredictable variations in elevation during this period, and nesting cavities will need to be spaced vertically across the upper revetted banks to ensure the availability of some structures at different river stages. This will require that structures be buried in the riprap upper bank and attached to the ACM on the upper part of the subaqueous bank. Nesting structures placed on the upper bank should be buried in a horizontal position with the open end oriented slightly downstream and covered with riprap as shown in Figure 7a. Structures placed on the ACM should be cabled or strapped directly to the mattress during placement (Figure 7b) with

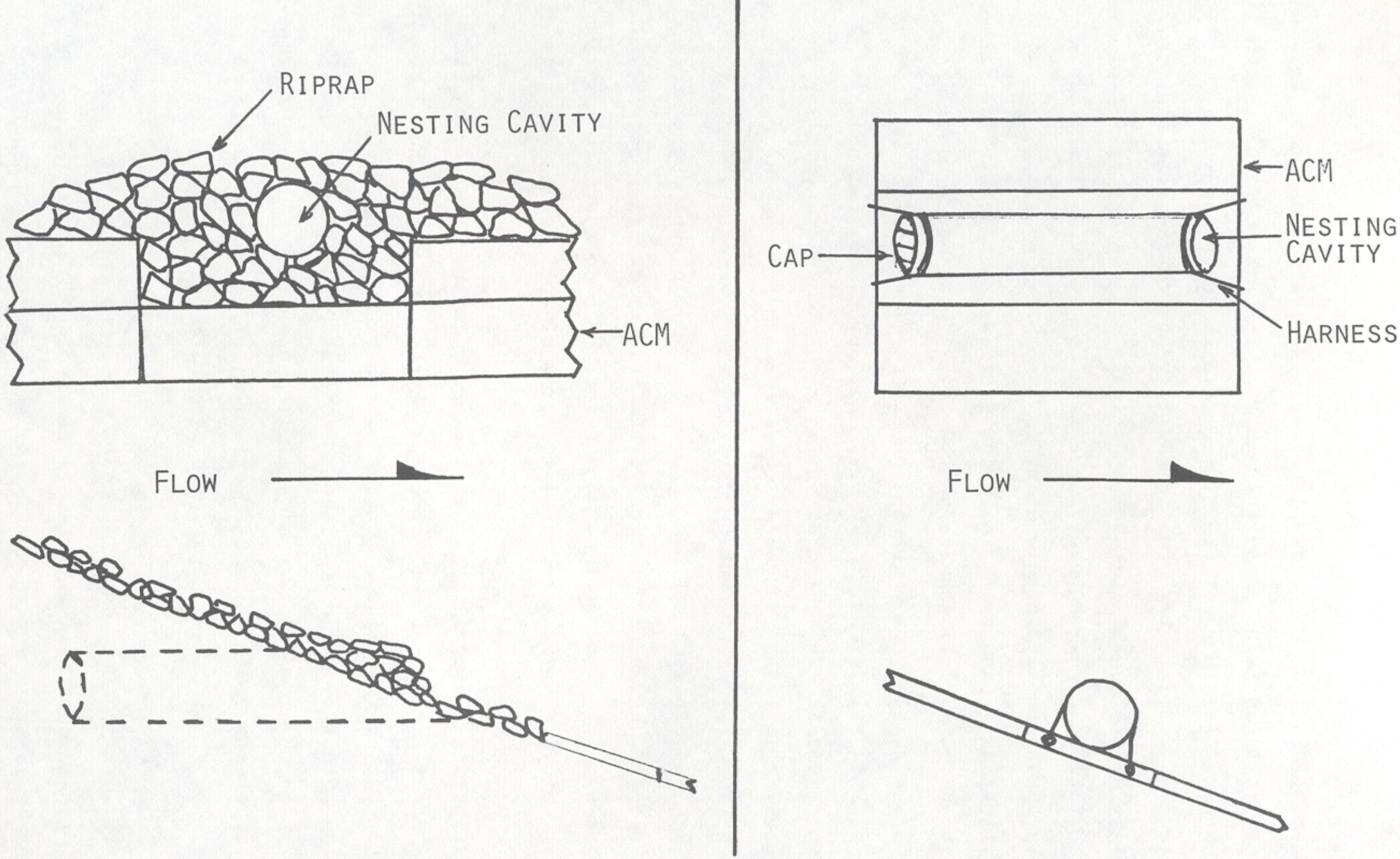
the open end oriented downstream to minimize resistance to current and reduce the risk of the structure becoming filled with sediments.

49. Nesting cavities could be placed at relatively close intervals (one structure every 15 to 30 ft of shoreline) in reaches where natural nesting sites are limited. Catfish are extremely aggressive during spawning, but territoriality is limited to the area immediately surrounding the nest cavity. They are solitary nesters, and only one individual will occupy a nesting cavity at a particular time. However, more than one individual may use a nesting cavity during the spawning season.

50. Rationale. Channel catfish, blue catfish, and flathead catfish are valuable sport and commercial species in the LMR. These bottom-dwelling species are well adapted to main channel habitats. They utilize hollow submerged trees and cavities formed by brush and caved areas along natural banks as spawning sites. Revetment of caving natural banks may reduce the number of shoreline cavities on reaches where the ACM does not become buckled or folded. Placing artificial nesting cavities on revetments where natural cavities are limited can increase habitat for these important sport and commercial species. Catfish are secretive and utilize cavities as resting sites. Several species of minnows common to the LMR also spawn in cavities, although their specific habitat requirements are not well documented (Pflieger 1975).

51. Engineering feasibility. Catfish spawn during late spring and early summer when the river stages are high. Nesting cavities should be placed on both the upper portion of the ACM and buried in the riprap upper bank to provide potential spawning sites at depths up to 15 ft across the range of river stages expected from mid-April through early June. Maintenance of spawning structures would be impractical, and they should be designed to withstand frequent flooding and dewatering with a low risk of loss to vandalism.

52. Artificial nesting cavities could be placed during revetment construction or maintenance if a procedure is developed for attaching the structures to the mattress during mat laying at minimal cost. Additional engineering studies would be needed to develop a standard design for the



a. Buried in riprap upper bank

b. Attached to ACM

Figure 7. Artificial nesting cavities buried in riprap upper bank of revetment (a) and attached to ACM (b)

structures and cost-effective procedures for securely attaching artificial nesting cavities to an ACM block during mat placement.

53. Placing nesting cavities on the upper riprap bank would require substantially more labor than attaching structures to the ACM. However, structures buried in the upper riprap bank should have little risk of vandalism and a longer period of service. Riprap should be carefully laid in the area immediately surrounding the nesting cavity to prevent damage to the structure and to ensure that the opening remains unobstructed.

54. Criteria for application. Artificial nesting cavities could be placed in selected locations where natural cavities are limited. They should be placed during construction or repair at a predetermined number of units per unit of shoreline.

Wildlife

55. Environmental design considerations for wildlife are limited compared with those available for macroinvertebrates and fish. Revetment construction is confined to a narrow margin along the bank of the main channel, and much of this area is subsequently covered with riprap and ACM. Opportunities for wildlife enhancement are limited to the narrow strip of land along the landward boundary of the construction site. The quantities and types of cover in this area, such as brush or living plants, can provide habitat for many species of wildlife. Cover can also help stabilize the upper revetted bank and control scour and sediment accretion.

Brush shelters

56. Brush, trees, snags, and root balls obtained during revetment construction or repair can be stacked along the landward boundary of the site to provide cover for game and nongame wildlife species. These materials can also provide limited protection against scouring and floodplain sediment accretion during overbank flooding. Current CE policy permits the windrowing of brush and other woody materials along the landward boundary of a revetment construction site. These windrows are fairly compact to minimize the amount of clearing necessary for construction access.

57. The availability of materials should determine which sites receive brush structures, as well as the number and size of structures to be placed. Structures can be circular or rectangular and of variable height to provide cover for a variety of small mammals and birds (Yoakum et al. 1980). Windrowed brush placed along the landward margin of a construction site provides migration corridors for larger mammals. Rectangular brush piles should be oriented with the long axis parallel to the shoreline to offer minimal resistance to currents during overbank flooding. Windrowed brush and trees placed along the landward boundary should have an opening (5 to 10 ft wide) for each 200 to 300 ft to facilitate movement of wildlife to and from the river. Brush piles should be placed at equally spaced intervals along the upper boundary of the construction site, cabled, and anchored to withstand periodic flooding.

58. Rationale. The construction of brush piles to provide cover and protection from the elements for birds and mammals is a widely used wildlife management technique (Yoakum et al. 1980). Trees and shrubs felled during site preparation must be disposed of when construction is complete. They can be stacked and anchored in various configurations along the landward margin of a construction site to provide escape cover, shelter during inclement weather, and travel lanes for a variety of game and nongame wildlife species. Brush structures can also prevent scouring, enhance localized sediment accretion under certain current patterns, and reduce floodplain deposition. Using woody materials obtained during revetment construction or repair to create habitat for wildlife is a desirable environmental alternative to disposal by burning, burying, mulching, or removal from the construction site.

59. Engineering feasibility. Each application of brush shelters should be reviewed by engineering and environmental planning staffs to determine if site-specific characteristics limit their use. Land use patterns limit the employment of these materials at some locations. Trees dislodged during high flow also present potential hazards to navigation vessels, bridges, or other man-made structures placed along the shore.

60. Criteria for application. Wildlife benefits can be derived from brush piles at most revetment sites, but the greatest potential for wildlife

enhancement occurs in areas where cover in the surrounding batture is limited. Unfortunately, these are often areas that have been cleared for agricultural use, and woody material at the construction site may be limited.

61. The construction of brush piles should be viewed as an interim bank protection and wildlife enhancement feature until woody vegetation becomes established on the upper bank. Brush piles constructed for wildlife decompose in 5 to 10 years because of frequent wetting and drying (Henderson and Shields 1984). Large trees should be used for fish shelters, and the smaller trees and shrubs for wildlife structures where large amounts of woody materials are present.

Selective seeding and planting

62. Seeding or planting selected plant species can be used to create a variety of habitat effects following revetment construction or repair. Selective seeding or planting can be used to speed the rate of revegetation, reduce erosion, and encourage the development of plants with high food and cover value for wildlife (Aggus and Ploskey 1986). Rows of young trees planted along the landward margin of a construction site can create migration corridors for wildlife in areas where cover in surrounding floodplain is limited. Shelter belts of trees provide erosion control along revetted banks that are subject to excessive erosion and provide cover for wildlife during periods of inclement weather. Selective planting can also be used to create a more natural appearance to the upper riprap portion of the bank and a visual transition to the surrounding floodplain in areas of high human use (Henderson and Shields 1984).

63. Rationale. The types and quantities of vegetation present on the upper bank of a revetment determine its value for wildlife. Although natural regrowth of woody and herbaceous vegetation usually begins within weeks after revetment construction is completed, the rate of natural revegetation is influenced by site-specific soil and hydrological conditions and by the composition of the plant communities in the surrounding batture. Seeding or planting selected plant species offers a viable means of improving habitat for wildlife and controlling erosion.

64. _Engineering feasibility._ Selective seeding or planting is done following revetment construction or repair and therefore has minimal impact on construction activities. The use of selective seeding or planting has application under certain environmental conditions where natural revegetation is expected to be slow or severe erosion problems are anticipated. Selection of woody or herbaceous species should be limited to plants known to be adapted to the habitat. Obtaining suitable nursery stock or seed can be difficult because many plants suited to shoreline habitats are not commonly grown by nurseries. Several workers have developed guidelines to match plants with flood tolerance or habitat preferences and they have also developed appropriate methods of seeding or planting (see Appendix A).

65. _Criteria for application._ Selective planting or seeding must be approached on a site-by-site basis. Planting small trees for bank protection would be appropriate when woody vegetation and cover adjacent to the construction site is limited or where erosion poses a serious threat to the surrounding floodplain (e.g., floodplain land that is being farmed to the edge of the upper bank). Stands of bottomland hardwood adjacent to a revetment usually provide both an effective barrier to erosion and deposition and excellent habitat for wildlife. Natural revegetation of these areas would be appropriate in most instances. However, selective seeding of plants with excellent food or cover value for wildlife could further enhance the worth of the site.

REFERENCES

Aggus, L. R., and Ploskey, G. R. 1986. "Environmental Design Considerations for Main Stem Levee Borrow Areas Along the Lower Mississippi River," Lower Mississippi River Environmental Program Report 4, US Army Corps of Engineers, Mississippi River Commission, Vicksburg, Miss.

Allen, H. H., and Klimas, C. V. 1986. "Reservoir Shoreline Revegetation Guidelines," Technical Report E-86-13, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Atchison, G. J., et al. 1986. "Aquatic Biota Associated with Channel Stabilization Structures and Abandoned Channels in the Middle Missouri River," Technical Report E-86-6, prepared by Iowa State University, Ames, Iowa, for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Baker, J. A., et al. "Lower Mississippi River Environmental Program. Revetted and Natural Bank Surveys," Technical Report in preparation, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Barnickol, P. G., and Starrett, W. C. 1951. "Commercial and Sport Fishes of the Mississippi River Between Caruthersville, Missouri and Dubuque, Iowa," Illinois Natural History Survey Bulletin, Vol 25, No. 5, pp 267-350.

Beckett, D. C., Bingham, C. R., Sanders, L. G., Mathis, D. B., and McLemore, E. M. 1983. "Benthic Macroinvertebrates of Selected Habitats of the Lower Mississippi River," Technical Report E-83-10, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Beckett, D. C., and Pennington, C. H. 1986. "Water Quality, Macroinvertebrates, Larval Fishes, and Fishes of the Lower Mississippi River - A Synthesis," Technical Report E-86-12, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Benke, A. C., Henry, R. L., III, Gillespie, D. M., and Hunter, R. J. 1985. "Importance of Snag Habitat for Animal Production in Southeastern Streams," Fisheries, Vol 10, No. 5, pp 8-13.

Benke, A. C., and Wallace, J. B. 1980. "Trophic Basis of Production Among Net-spinning Caddisflies in a Southern Appalachian Stream," Ecology, Vol 61, pp 108-118.

Benson, N. G. 1980. "Effects of Post-Impoundment Shore Modification on Fish Populations in Missouri River Reservoirs," Research Report 80, US Fish and Wildlife Service, Washington, DC.

Berner, L. M. 1951. "Limnology of the Lower Missouri River," Ecology, Vol 32, No. 1, pp 1-12.

Bingham, C. R., Cobb, S. P., and Magoun, A. D. 1980. "Aquatic Habitat Studies on the Lower Mississippi River, River Mile 480 to 530; Report 4, Diel Periodicity of Benthic Macroinvertebrate Drift," Miscellaneous Paper E-80-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Blaxter, J. H. S. 1969. "Swimming Speeds of Fish," Food and Agriculture Organization of the United Nations, Fisheries Report 62, pp 69-100.

Bosley, T. R., Pennington, C. H., and Potter, M. E. 1984. "Distribution of Larval Fishes in a Lower Mississippi River Dike Field," Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies. Vol 38, pp 615-621.

Brown, C. J. D. 1975. "Fish," in River Ecology. B. A. Whitton, ed., University of California Press, Berkley.

Bryant, C. F., and Conner, J. V. 1980. "Use of Bottomland Hardwood Forests by Fishes in the Southeastern US," Wetlands and Bottomland Hardwood Forests. J. R. Clark and J. Benforado, eds., Elsevier Scientific Publishing Company, New York.

Burke, T. D., and Robinson, J. W. 1979. "River Structure Modifications to Provide Habitat Diversity," The Mitigation Symposium: A National Workshop on Mitigating Losses of Fish and Wildlife Habitats. Fort Collins, Colo.

Burress, R. M., Krieger, D. A., and Pennington, C. W. 1982. "Aquatic Biota of Bank Stabilization Structures on the Missouri River, North Dakota," Technical Report E-82-6, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Carlander, K. D. 1969. Handbook of Freshwater Fishery Biology. Iowa State University Press, Ames, Iowa.

Carter, S. R., Bazata, K. R., and Andersen, D. L. 1982. "Macroinvertebrate Communities of the Channelized Missouri River near Two Nuclear Power Stations," The Middle Missouri River, a Collection of Papers on the Biology with Special Reference to Power Station Effects. L. W. Hesse, G. L. Hergenrader, H. S. Lewis, S. D. Reetz, and A. B. Schlesinger, eds., Missouri River Study Group, PO Box 934, Norfolk, Nebr., pp 147-184.

Cleary, R. E., and Greenbank, J. 1954. "An Analysis of Techniques Used in Estimating Fish Populations in Streams, with Particular Reference to Large Non-Trout Streams," Journal of Wildlife Management. Vol 18, No. 4, pp 461-476.

Cobb, S. P., and Clark, J. R. 1981. "Aquatic Habitat Studies on the Lower Mississippi River, River Mile 480 to 530; Report 2, Aquatic Habitat Mapping," Miscellaneous Paper E-80-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Cobb, S. P., and Williamson, A. N. 1985. "The Computerized Environmental Resources Data System (CERDS): A Geographic Information System for Environmental Data on the Leveed Floodplain of the Lower Mississippi River," Proceedings of the US Army Corps of Engineers Fifth Remote Sensing Symposium: Remote Sensing Applications for Water Resources Management. US Army Engineer Water Resources Support Center, Fort Belvoir, Va.

Conner, J. W., Pennington, C. H., and Bosley, T. R. 1983. "Larval Fish of Selected Aquatic Habitats on the Lower Mississippi River," Technical Report E-83-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Crowder, L. B., and Cooper, W. E. 1982. "Habitat Structural Complexity and the Interaction Between Bluegills and Their Prey," Ecology, Vol 63, No. 6, pp 1802-1813.

Cummins, K. W. 1973. "Trophic Relations of Aquatic Insects," Annual Review of Entomology, Vol 18, pp 183-206.

Cummins, K. W. 1975. "Invertebrates," in River Ecology, B. A. Whitton, ed., University of California Press, Berkley, Calif., pp 170-198.

Environmental Laboratory. 1985. "Lower Mississippi River Environmental Program; Report 3: Bird and Mammal Use of Main Stem Levee Borrow Pits Along the Lower Mississippi River," Mississippi River Commission, Vicksburg, Miss.

Farabee, G. B. 1986. "Fish Species Associated with Revetted and Natural Main Channel Border Habitats in Pool 24 of the Upper Mississippi River," North American Journal of Fisheries Management, Vol 6, pp 504-508.

Farlinger, S., and Beamish, F. W. H. 1977. "Effects of Time and Velocity Increments on the Critical Swimming Speed of Largemouth Bass (*Micropterus salmoides*)," Transactions of the American Fisheries Society, Vol 106, pp 436-439.

Fraser, J. C. 1972. "Regulated Discharge and the Stream Environment," River Ecology and Man, R. T. Oglesby et al., eds., Academic Press, New York.

Fredrickson, L. H., and Taylor, T. S. 1982. "Management of Seasonally Flooded Impoundments for Wildlife," Resource Publication 148, US Fish and Wildlife Service, Washington, DC.

Funk, J. L., and Robinson, J. W. 1974. "Changes in the Channel of the Lower Missouri River and Effects on Fish and Wildlife," Aquatic Series No. 11, Missouri Department of Conservation, Jefferson City, Mo.

Gallagher, R. P., and Conner, J. V. 1980. "Spacio-Temporal Distribution of Ichthyoplankton in the Lower Mississippi River, Louisiana," Proceedings of the 4th Annual Larval Fish Conference, L. A. Fuiman, ed., US Fish and Wildlife Service, Ann Arbor, Mich., pp 101-115.

Gorman, O. T., and Karr, J. R. 1978. "Habitat Structure and Stream Fish Communities," Ecology, Vol 59, No. 3, pp 507-515.

Groen, C. L., and Schmulbach, J. C. 1978. "The Sport Fishery of the Channelized and Unchannelized Missouri River," Transactions of the American Fisheries Society, Vol 107, No. 3, pp 412-418.

Guillory, V. 1979. "Utilization of the Inundated Floodplain by Mississippi River Fishes," Florida Scientist, Vol 42, No. 4, pp 222-228.

Gunter, G. 1956. "Wildlife and Flood Control in the Mississippi Valley," Transactions of the 22nd North American Wildlife Conference, pp 189-196.

Henderson, J. E., and Shields, F. D., Jr. 1984. "Environmental Features for Streambank Protection Projects," Technical Report E-84-11, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Hergenrader, G. L., Harrow, L. G., King, R. G., Cada, G. F., and Schlesinger, A. B. 1982. "Larval Fishes in the Missouri River and the Effects of Entrainment," The Middle Missouri River, A Collection of Papers on the Biology with Special Reference to Power Station Effects. L. W. Hesse, G. L. Hergenrader, H. S. Lewis, S. D. Reetz, and A. B. Schlesinger, eds., Missouri River Study Group, PO Box 934, Norfolk, Nebr., pp 185-223.

Hesse, L. W., and Newcomb, B. A. 1982. "On Estimating the Abundance of Fish in the Upper Channelized Missouri River," North American Journal of Fisheries Management. Vol 2, pp 80-83.

Hjort, R. C., et al. 1984. "Fish and Invertebrates of Revetments and Other Habitats in the Williamette River, Oregon," Technical Report E-84-9, prepared by Oregon State University for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Hocutt, C. H. 1973. "Swimming Performance of Three Warmwater Fishes," Chesapeake Science. Vol 14, No. 1, pp 11-16.

Holland, L. E. 1986. "Distribution of Early Life History Stages of Fishes in Selected Pools of the Upper Mississippi River," Hydrobiologia. Vol 136, pp 121-130.

Holland, L., Huff, D., Littlejohn, S., and Jacobson, R. 1984. "Analysis of Existing Information on Adult Fish Movements Through Dams on the Upper Mississippi River," prepared by the US Fish and Wildlife Service for the US Army Engineer District, St. Paul, St. Paul, Minn.

Hynes, H. B. N. 1970. The Ecology of Running Waters. University of Toronto Press, Toronto, Ontario, Canada.

Hynson, J. R., et al. 1985. "Environmental Features for Streamside Levee Projects," Technical Report E-85-7, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Johnson, J. H., Solomon, R. C., Bingham, C. R., Colbert, B. K., and Enge, W. P. 1974. "Environmental Analysis and Assessment of the Mississippi River 9-Ft Channel Project Between St. Louis, Missouri, and Cairo, Illinois," Technical Report Y-74-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Johnson, R. L., and Burkhardt, E. C. 1976. "Natural Cottonwood Stands - Past Management and Implications for Plantations," Proceedings: Symposium on Eastern Cottonwood and Related Species. B. A. Thielges and S. B. Land, Jr., eds., Louisiana State University, Baton Rouge, La., pp 20-29.

Kallemeyn, L. W., and Novotny, J. F. 1977. "Fish and Fish Food Organisms in Various Habitats of the Missouri River in South Dakota, Nebraska, and Iowa," FWS/OBS-77/25, US Fish and Wildlife Service, Washington, DC.

Keown, M. P., Dardeau, E. A., Jr., and Causey, E. M. 1986. "Historic Trends in the Sediment Flow Regime of the Mississippi River," Water Resources Research, Vol 22, No. 11, pp 1555-1564.

Keown, M. P., Oswalt, N. R., Perry, E. B., and Dardeau, E. A., Jr. 1977. "Literature Survey and Preliminary Evaluation of Streambank Protection Methods," Technical Report H-77-9, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Klimas, C. V., Martin, C. O., and Teaford, J. W. 1981. "Impacts of Flooding Regime Modification on Wildlife Habitats of Bottomland Hardwood Forests of the Lower Mississippi Valley," Technical Report EL-81-13, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Kozel, D. J., and Schmulbach, J. C. 1976. "Utilization of Marsh and Sandbar Habitats by Fishes in the Unchannelized Missouri River," Proceedings of the South Dakota Academy of Science, Vol 55, p 177.

Krinitzsky, E. L. 1965. "Geological Influences on Bank Erosion Along Meanders of the Lower Mississippi River," Potamology Investigations Report 12-15, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Marzolf, R. C. 1957. "The Reproduction of Channel Catfish in Missouri Ponds," Journal of Wildlife Management, Vol 21, pp 22-28.

Mathis, D. B., Bingham, C. R., and Sanders, L. G. 1982. "Assessment of Implanted Substrate Samplers for Macroinvertebrates Inhabiting Stone Dikes of the Lower Mississippi River," Miscellaneous Paper E-82-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Mathis, D. B., Cobb, S. P., Sanders, L. G., Magoun, A. D., and Bingham, C. R. 1981. "Aquatic Habitat Studies on the Lower Mississippi River, River Mile 480 to 530; Report 3, Benthic Macroinvertebrate Studies - Pilot Report," Miscellaneous Paper E-80-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Miller, A. C. 1981. "Aquatic Habitat Studies on the Lower Mississippi River, River Mile 480 to 530; Report 1, Introduction," Miscellaneous Paper E-80-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Miller, E. E. 1966. "Channel Catfish," in Inland Fisheries Management, A. Calhoun, ed., California Department of Fish and Game, Sacramento, Calif., pp 440-463.

Mississippi River Commission. 1977. "Channel Improvement Features, Flood Control, Mississippi River and Tributaries Project," Office of the President, Mississippi River Commission, Vicksburg, Miss.

Moore, N. R. 1972. Improvement of the Lower Mississippi River and Tributaries, 1931-1972, Mississippi River Commission, Vicksburg, Miss.

Morris, L. A., Langemeier, R. N., Russell, T. R., and Witt, A., Jr. 1968. "Effects of Main Stem Impoundments upon the Limnology of the Missouri River, Nebraska," Transactions of the American Fisheries Society, Vol 97, No. 4, pp 380-388.

Nelson, R. W., Horak, G. C., and Olson, J. E. 1978. "Western Reservoir and Stream Habitat Improvements Handbook," Report No. FWS/OBS-78/56, Office of Biological Services, Fish and Wildlife Service, US Department of the Interior, Washington, DC.

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

Pardue, G. B. 1973. "Production Response of the Bluegill Sunfish, Lepomis macrochirus Rafinesque, to Added Attachment Surface for Fish-food Organisms," Transactions of the American Fisheries Society, Vol 102, pp 622-626.

Pennington, C. H., Baker, J. A., and Bond, C. L. 1983. "Fishes of Selected Aquatic Habitats on the Lower Mississippi River," Technical Report E-82-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Pennington, C. H., Baker, J. A., and Potter, M. E. 1983. "Fish Populations Along Natural and Revetted Banks on the Lower Mississippi River," North American Journal of Fisheries Management, Vol 3, pp 204-211.

Pennington, C. H., et al. 1980. "Aquatic Habitat Studies on the Lower Mississippi River, River Mile 480 to 530; Report 5, Fish Studies - Pilot Report," Miscellaneous Paper E-80-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Pflieger, W. L. 1975. The Fishes of Missouri, Missouri Department of Conservation, Columbia, Mo.

Pierce, B. E., and Hooper, G. R. 1979. "Fish Standing Crop Comparisons of Tire and Brush Attractors in Barkley Lake, Kentucky," Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies, Vol 33, pp 688-691.

Ploskey, G. R. 1985. "Impacts of Terrestrial Vegetation and Preimpoundment Clearing on Reservoir Ecology and Fisheries in the USA and Canada," Fisheries Technical Paper 258, Food and Agriculture Organization, United Nations, Rome, Italy.

Polovino, H. N., Farrell, M. P., and Pennington, C. H. 1983. "Evaluating Changes in Dike Field Fishes with Community Indices," Technical Report E-83-14, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Rasmussen, J. L., et al. 1979. "A Compendium of Fishery Information on the Upper Mississippi River," Second Edition, Upper Mississippi River Conservation Committee, Rock Island, Ill.

Sandheinrich, M. B., and Atchison, G. J. 1986. "Environmental Effects of Dikes and Revetments on Large Riverine Systems," Technical Report E-86-5, prepared by US Fish and Wildlife Service, Iowa Cooperative Fishery Research Unit and Department of Animal Ecology, Iowa State University for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Savino, J. F., and Stein, R. A. 1982. "Predator Prey Interactions Between Largemouth Bass and Bluegills as Influenced by Simulated, Submerged Vegetation," Transactions of the American Fisheries Society, Vol 111, No. 3, pp 255-266.

Schmulbach, J. C., Gould, G., and Groen, C. L. 1975. "Relative Abundance and Distribution of Fishes in the Missouri River, Gavins Point Dam to Rulo, Nebraska," Proceedings of the South Dakota Academy of Science, Vol 54, pp 194-221.

Schnick, R. A., Morton, J. M., Mochalski, J. C., and Beall, J. T. 1982. "Mitigation and Enhancement Techniques for the Upper Mississippi River System and Other Large River Systems," Resource Publication 149, Fish and Wildlife Service, US Department of the Interior, Washington, DC.

Schramm, H. L., Jr., and Pennington, C. H. 1981. "Aquatic Habitat Studies on the Lower Mississippi River, River Mile 480 to 530; Report 6, Larval Fish Studies - Pilot Report," Miscellaneous Paper E-80-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Shields, F. D., Jr. 1982. "Environmental Features of Flood Control Channels," Technical Report E-82-7, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

_______. 1983. "Design of Habitat Structures for Open Channels," Journal of Water Resource Planning and Management, Vol 109, No. 4, pp 331-343.

Shields, F. D., Jr., and Palermo, M. R. 1982. "Assessment of Environmental Considerations in the Design and Construction of Waterway Projects," Technical Report E-82-8, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Sims, K. R. 1982. "The Development and Effect of Fish Attractors on the Tennessee-Tombigbee Waterway," Canadian Water Resources Journal, Vol 7, No. 2, pp 161-171.

Snow, J. R. 1959. "Notes on the Propagation of the Flathead Catfish Pylodictis olivaris (Rafinesque)," Progressive Fish-Culturist, Vol 21, pp 71-75.

Swales, S., and O'Hara, K. 1980. "Instream Habitat Improvement Devices and Their Use in Freshwater Fisheries Management," Journal of Environmental Management, Vol 10, pp 167-179.

Tennessee Valley Authority. 1987. "Improving Reservoir Releases," Office of Natural Resources and Economic Development, Division of Air and Water Resources, Tennessee Valley Authority, Knoxville, Tenn.

Thomas, P. M., Legault, R. O., and Carpenter, G. E. 1968. "Durability and Efficiency of Brush Shelters Installed in 1937 in Douglas Lake, Michigan," Journal of Wildlife Management, Vol 32, No. 3, pp 515-520.

Trautman, M. B. 1957. The Fishes of Ohio, Ohio State University Press, Columbus, Ohio.

Tuttle, J. R., and Pinner, W. 1982. "Analysis of Major Parameters Affecting the Behavior of the Mississippi River," Potamology Program (P-1), Report 4, Mississippi River Commission, Vicksburg, Miss.

US Army Corps of Engineers. 1986. "Bank Protection Master Specifications for Revetment Work," Mississippi River Commission, Vicksburg, Miss.

Viosca, P. J. 1927. "Flood Control in the Mississippi Valley in Its Relation to Louisiana Fisheries," Transactions of the American Fisheries Society, Vol 57, pp 49-64.

Waters, T. F. 1972. "The Drift of Stream Insects," Scientific Journal Series, Minnesota Agricultural Experiment Station, Paper No. 7630, pp 253-272.

Webb, J. S. "Vegetation Development on Revetments Along the Lower Mississippi River," Technical Report in preparation, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wells, F. C., and Demas, C. R. 1979. "Benthic Invertebrates of the Lower Mississippi River," Water Resources Bulletin, Vol 15, pp 1565-1577.

White, R. J., and Brynildson, O. M. 1967. "Guidelines for Management of Trout Stream Habitat in Wisconsin," Technical Bulletin 39, Department of Natural Resources, Madison, Wis.

Whitlow, T. H., and Harris, R. W. 1979. "Flood Tolerance in Plants: A State-of-the-Art Review," Technical Report E-79-2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Wilbur, R. L. 1978. "Two Types of Fish Attractors Compared in Lake Tohopekaliga, Florida," Transactions of the American Fisheries Society, Vol 107, No. 5, pp 689-695.

Yoakum, J., et al. 1980. "Habitat Improvement Techniques," pp 329-403 in S. D. Schemnitz, ed., Wildlife Techniques Manual, Fourth Edition, The Wildlife Society, Washington, DC.

Zimpfer, S. P., Kelso, W. E., Bryan, C. E., and Pennington, C. H. 1988. "Ecological Features of Eddies Associated with Revetments in the Lower Mississippi River," Lower Mississippi River Environmental Program Report No. 8, Mississippi River Commission, Vicksburg, Miss.

APPENDIX A: LITERATURE REVIEW OF ENVIRONMENTAL CONSIDERATIONS

General Ecological Considerations

1. Revetments are constructed on natural caving banks, and thus natural bank habitat is replaced by revetted bank habitat. The environmental value of revetments must be evaluated relative to the ecological characteristics of preconstruction bank habitat. However, each major type of habitat also has value in sustaining the existing aquatic community of the Lower Mississippi River (LMR). Actions that significantly alter the relative proportions of the various habitat types influence the species composition and relative abundance of aquatic organisms throughout the region (Kallemeyn and Novotny 1977; Pennington, Baker, and Bond 1983*).

2. Ecological values of revetments for fish must be estimated from comparisons of species composition and relative numerical or biomass catch rates of fish in different habitats of the LMR and the extrapolation of findings from other river systems. Accurate assessments of the size, distribution, and composition of riverine fish communities have been difficult because of a lack of quantitative sampling methods for rivers (Cleary and Greenbank 1954). The problem of developing quantitative comparisons between specific habitats in large rivers has been made especially difficult by fluctuating river stages, random movement of fish between habitats, and selectivity of sampling gears for certain species and sizes of fish (Burke and Robinson 1979, Pennington et al. 1980, Hesse and Newcomb 1982).

3. Fish assemblages on both natural and revetted banks of the LMR are dominated by adults of several important sport, commercial, and forage species adapted to strong currents. Gizzard shad, common carp, shovelnose sturgeon, blue sucker, smallmouth buffalo, blue catfish, channel catfish, flathead catfish, and freshwater drum are numerically dominant forms on both natural and revetted bank habitats. The shovelnose sturgeon, goldeye, mooneye, and spotted sucker are considered rather unique to these bank habitats. Blue

---

* See References at the end of the main text.

sucker and shovelnose sturgeon exhibit a preference for revetted banks (Pennington et al. 1980; Pennington, Baker, and Bond 1983; Pennington, Baker, and Potter 1983; Beckett and Pennington 1986). Pennington et al. (1980) reported that the two habitat types supported similar total numbers of fish and that the same species were generally present. Natural bank habitats yielded a larger number of species than revetted banks when data were adjusted to compensate for differences in sampling effort between the two habitat types (Pennington, Baker, and Bond 1983; Pennington, Baker, and Potter 1983). The additional species collected on natural banks were uncommon forms, and no species of even moderate abundance was unique to either habitat.

4. Studies comparing relative abundance, biomass composition, and presence or absence of fish species on natural and revetted banks are limited. However, revetted banks appear to be a more variable habitat for fish. Pennington, Baker, and Bond (1983) and Pennington, Baker, and Potter (1983) calculated percentage similarity coefficients (an index of relative abundance) for fish communities from two revetments and two natural banks, and they found that the natural banks exhibited a higher degree of similarity than revetted banks. The percentage composition by weight of several important sport and commercial species also differed substantially between the two habitats. Carp, smallmouth buffalo, blue sucker, channel catfish, and river carpsucker made up more than 50 percent of the biomass on revetted banks, but only about 10 percent of the biomass on natural banks. Conversely, longnose gar, bigmouth buffalo, flathead catfish, and freshwater drum made up more than 50 percent of the biomass on natural banks, but only 25 percent of the biomass on revetted banks. A greater portion of the biomass of fish on revetted banks included forms with sport or commercial value. The authors also calculated coefficient of community indexes (a measure of species presence or absence) for natural banks and revetted banks which revealed that species composition of fish was more similar on natural banks across a range of river stages. Differences between the two habitats were most pronounced when river stages were low.

5. Total abundance and biomass of fish assemblages on revetted banks have not been quantified relative to other main channel aquatic habitats.

Pennington, Baker, and Bond (1983) reported that natural and revetted banks contained fewer species of fish than did dike fields or abandoned channel lakes. Fish were generally larger on natural and revetted banks, but the authors were unable to determine if apparent size differences reflected sampling bias or true community differences. The authors suggested that each major habitat had a value in maintaining the existing river ichthyiofauna, although data were considered inadequate for making definitive comparisons between habitat types. Sandheinrich and Atchison (1986) summarized fishery data from previous large river studies and found no clear-cut relationships between revetments and other main channel aquatic habitats with respect to abundance, species composition, and biomass of fish.

6. Quantitative data are not available to compare commercial and sport fish yields on Articulated Concrete Mattress (ACM) revetted banks with other main channel aquatic habitats. Revetments are inhabited by adults of several fish species with high commercial and sport value (Pennington et al. 1980; Pennington, Baker, and Bond 1983; Beckett and Pennington 1986). However, several factors influence angler use on revetments. Strong currents and navigation traffic limit angling opportunities at some revetment sites. Limited access poses a more serious constraint at most locations. Currents in the main channel restrict the types of gear that can be fished. Angler use may be concentrated in eddies and irregularities in revetted shorelines that provide suitable sites for both commercial and sport fishing gears. Yield statistics from other parts of the Mississippi River drainage suggest that sport and commercial harvests are highest in areas of reduced current (Barnickol and Starrett 1951, Groen and Schmulbach 1978, Rasmussen et al. 1979).

7. The effect of revetment on macroinvertebrate communities is important because these organisms serve a primary function in the conversion of reduced carbon compounds (fine particulate organic matter) derived from the watershed into temporary storage in their tissues (Hynes 1970, Cummins 1975). In a highly turbid river such as the LMR, this represents a primary energy pathway wherein particulate organic matter is converted to fish biomass and higher trophic levels. Most riverine macroinvertebrates are trophic

generalists within the range of particle sizes that they are physically capable of ingesting (Cummins 1973). The abundance and distribution of these organisms in rivers are determined primarily by the availability of food, nature of sediments, and current patterns (Cummins 1975). Both natural and revetted banks contain a wide range of substrate types and support diverse macroinvertebrate assemblages.

8. Revetment construction has both positive and negative effects on the wildlife community when compared with natural banks. There is an immediate loss of plant cover in the construction zone, and this may include the loss of plants with relatively high wildlife value.* Shaping and contouring of natural caving banks during construction improve access to the river for wildlife species, as the natural banks are often steep and highly unstable. However, some species (such as muskrat) that live in cavities along natural caving banks experience a loss of habitat (Henderson and Shields 1984).

9. Maintaining satisfactory water quality is usually not an important consideration in developing environmental design features for revetments. Water quality near revetments is similar to that of natural banks and the main channel. Baker et al. (in preparation) reported only minor differences in water temperature, dissolved oxygen concentration, pH, conductivity, turbidity, oxygen-reduction potential, total organic carbon, and dissolved and suspended solids at two natural banks and three revetted banks during 1985. Water quality in the LMR is strongly influenced by the presence or absence of current (Beckett and Pennington 1986). Main channel habitats are well mixed, and water quality is similar from one location to another. Revetted banks and other main channel aquatic habitats are characterized by high turbidity, suspended solids, and nutrient concentrations and by low transparency and algal biomass. Localized variations in water quality and sediment concentrations occur in eddies (Zimpfer et al. 1988), but these do not pose a serious problem to the development of environmental considerations. In

---

* Personal Communication, March 1987, Dr. Charles V. Klimas, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

contrast, backwater and floodplain aquatic habitats can vary substantially with respect to productivity, turbidity, and concentrations of important ions (Beckett and Pennington 1986).

10. Revetment construction modifies the morphology of the channel and sediment patterns. Localized, short-term increases in turbidity and suspended sediment concentrations occur when substrate materials are graded into the river. However, the portion of the sediment load resulting from bank erosion is reduced substantially following construction by the creation of a stable shoreline (Henderson and Shields 1984). The total suspended sediment load in the LMR has decreased substantially since 1953 (Tuttle and Pinner 1982), and this has accompanied the construction of revetments, reservoirs, and related channel improvement features throughout the basin. Keown, Dardeau, and Causey (1986) attributed this reduction in suspended sediment to the combination of flood-control and channel-improvement structures, rapidly changing land uses, and improved land management practices. Coarse materials of the bed load have apparently changed little with revetment. There is evidence that revetments have caused the thalweg to deepen to a greater extent than if shorelines were not stabilized (Tuttle and Pinner 1982).

Fluctuations in River Stage

11. Natural fluctuations in river stage have an overriding influence on the development of environmental design considerations for revetments. The ecological value of revetments for fish and wildlife differs greatly with changing river stages. Plant and animal communities of the leveed floodplain of the LMR are adapted to the large seasonal and annual fluctuations of the river. Reproductive and behavioral strategies of many riverine fish are linked to the annual cycle of springtime inundation of the floodplain and low water in the late summer and autumn (Viosca 1927, Gunter 1956). Many forms use several habitats as part of their life history. Environmental design features must, therefore, be viewed relative to potential effects on aquatic organisms across a wide range of river stages.

12. Revetments have limited environmental value for fish and wildlife when extensive overbank flooding occurs. Species of wildlife move to higher areas in the batture or to habitats outside the mainstem levees until floodwaters recede (Environmental Laboratory 1985). Fish move from the main channel into the inundated floodplain to find food, cover, and protection from strong currents (Guillory 1979, Bryant and Conner 1980). The inundated floodplain provides important spawning, nursery, and feeding habitat for many riverine fish (Gallagher and Conner 1980, Holland 1986). Benthic macroinvertebrates may continue to colonize revetments during these times, convert particulate organic matter into tissue, and accumulate biomass that provides food for bottom-feeding fish when the river recedes.

13. Revetted banks provide important habitat for aquatic organisms when river elevations are bank-full or lower. However, habitat value changes as levels recede from bank-full to the average dike crown elevation and below average dike crown elevations. Inundated floodplain areas are dewatered when the river recedes below bank-full. The crowns of dikes are below the surface, and the structures provide only limited protection from the current (Polovino, Farrell, and Pennington 1983). Currents in the main channel remain strong, and shoreline features that create turbulence or reduced current needed by many species of fish as nursery and resting sites become important. Relations between aquatic communities and specific habitat types become most distinct when river stages are below average dike crown elevations in a given reach (Pennington, Baker, and Bond 1983). Total surface area and volume of main channel aquatic habitat can be reduced by as much as two-thirds (Cobb and Clark 1981), and many floodplain lakes become cutoff from the main channel at low river stages. Pools in dike systems form slack-water habitat, and revetted banks make up an important part of the shoreline habitat for rheophilic fish. The reduced volume of main channel aquatic habitat intensifies competition for food and space among aquatic organisms. Environmental considerations that create localized areas of turbulence or reduced current or that increase cover and structure on revetments increase habitat diversity.

Substrate Relations

Physical-chemical

14. Substrate materials on natural and revetted banks include a wide range of particle sizes and textures. The composition and texture of these materials are determined by current patterns that can change rapidly in response to changing river stages (Baker et al., in preparation). They have been broadly classified as sediments and firm substrates relatively free of sediments (Baker et al., in preparation). Sediments comprising natural banks consist of a variety of clays, silts, and sands. Sediments overlying ACM revetments are highly variable in texture, but they are usually composed of unconsolidated fine sands and fines of variable thickness. Current velocities adjacent to revetted and natural banks approach those of the main channel a short distance from shore. Coarse sands and fine gravels of the bed load accrete near the foot of these bank habitats and extend riverward to the thalweg (Mathis et al. 1981). Firm substrates on natural banks consist mostly of fallen trees and lodged woody debris. Riprap, ACM, and vegetation on the upper bank comprise the solid substrates on revetments.

15. Quantitative data comparing the relative amounts of sediments and firm substrates on revetments and natural banks have been limited. Baker et al. (in preparation) measured sediments on two sections of revetted bank and estimated that 50 percent or less of the ACM was covered with sediments at any given river stage. The authors hypothesized that the total amount of firm substrate on revetments was much greater than on natural banks, although the total surface area of woody material on natural banks was not measured.

16. Johnson et al. (1974) suggested that revetments create a superior habitat to that of natural banks because shorelines are stabilized. The mechanisms of bank failure do not change when natural banks are covered with ACM revetment, but the magnitude and frequency of these failures are changed (Krinitzsky 1965). Substrate characteristics of natural banks can change rapidly because of frequent bank slumping (Mathis et al. 1981), whereas the ACM creates a stable shoreline substrate that can accrete sediments or scour depending on current variations.

Macroinvertebrates

17. The species composition, abundance, and distribution of benthic communities in rivers are determined by current velocity and direction, substrate composition and texture, and concentrations of dissolved materials (Hynes 1970, Wells and Demas 1979, Beckett et al. 1983). Interactions between highly erodible alluvial soils, variable currents, and rapidly fluctuating water levels create a wide range of substrate conditions. Benthic assemblages are physically linked to substrate particle size and texture and respond quickly to changes in substrate characteristics (Beckett and Pennington 1986). They can occur on the surface of firm substrates (epibenthic) or within sediments (embenthic). Functional relations between benthic macroinvertebrates and substrates are similar for all aquatic habitats in the LMR (Baker et al., in preparation). Environmental design considerations to enhance benthic organisms on revetments therefore involve actions to create certain textures of substrates that subsequently determine the species composition and abundance of benthic organisms.

18. Environmental design features for revetments that create areas of very low current velocity including eddies, indentations in the bank, and irregularities in the bottom on ACM revetments will accrete silt and fine sands (Zimpfer et al. 1988). These sedimentary substrates are colonized by a diverse assemblage of embenthic macroinvertebrates, including burrowing chironomids, mayflies, and tubificid worms. When the substrates remain stable, they support benthic assemblages similar to backwater habitats that are characterized by fine sediments, low current velocities, and high macroinvertebrate production (Atchison et al. 1986, Beckett and Pennington 1986). Depositional substrates on revetted banks are frequently unstable because of constantly changing river stages and current patterns. Colonization by drifting organisms is rapid, and macroinvertebrate assemblages may form and disappear within short time intervals as habitat conditions change (Bingham, Cobb, and Magoun 1980).

19. Habitat features that produce currents of intermediate velocity accrete sands of variable texture. These are usually less productive for benthic organisms than fine sediments or firm substrates. Relatively firm

sandy substrates can support populations of the asiatic clam (Corbicula sp.), while less stable substrates support distinct assemblages of chironomids (Wells and Demas 1979, Beckett and Pennington 1986).

20. Coarse sands and fine gravels comprising the bed load support a diverse assemblage of benthic macroinvertebrates, but at very low densities (Wells and Demas 1979, Mathis et al. 1981, Beckett and Pennington 1986). These substrates are widespread in the main channel of the LMR. Similar habitat conditions have been reported in the Middle and Lower Missouri River where Berner (1951) and Morris et al. (1968) identified areas with high current velocities and coarse, unstable substrates as poor habitat for benthic organisms. The point at which bed-load materials accrete on the lower bank of revetments limits the area of bank habitat that can be modified to benefit benthic organisms.

21. Habitat features that create firm substrates in areas of strong current can enhance epibenthic macroinvertebrates. Firm substrates support a productive assemblage of epibenthic macroinvertebrates. This community is dominated throughout the Mississippi River basin by net-spinning caddisflies (Hydropsyche sp.), tube-building chironomids (Rheotanytarsus sp.), isopods, and clinging mayflies (Baetis sp. and Stenonema sp.) (Mathis, Bingham, and Sanders 1982; Burress, Krieger, and Pennington 1982; Atchison et al. 1986; Beckett and Pennington 1986). Lodged trees and woody debris provide habitat for epibenthic macroinvertebrates on natural banks, and stone riprap and ACM provide physically similar substrates on revetments.

22. Riprap used to form the upper banks of revetments, dikes, and other channel improvement structures is a productive substrate for benthic macroinvertebrates (Kallemeyn and Novotny 1977; Burress, Krieger, and Pennington 1982; Mathis, Bingham, and Sanders 1982; Hjort et al. 1984; Atchison et al. 1986). The riprap paving on the upper banks of ACM revetments provides only limited benefit to macroinvertebrates because areas where this material is used are above water much of the year. The material can be productive for benthic organisms when placed on the lower bank as habitat structure. It is generally considered the material of choice for habitat improvement structures (Keown et al. 1977, Schnick et al. 1982).

23. The upper surface of the ACM is colonized by epibenthic organisms when it remains free of sediments. Initial attempts to collect macroinvertebrates on the ACM were unsuccessful because benthic grabs did not effectively sample the exposed mattress (Mathis et al. 1981). However, later experiments in which ACM blocks were used as samplers showed that the upper surfaces of blocks were colonized by several epibenthic species and that the abundance of these organisms increased substantially when the upper surfaces were grooved to increase surface area. Baker et al. (in preparation) reported macroinvertebrate densities in excess of 5,200 per square meter (m^2) on ACM blocks that had shallow grooves formed in the upper surface. Densities of benthic organisms on unmodified blocks used as controls ranged from 1,100 to 2,300 organisms/m^2. The surface area of the modified ACM blocks was about two times that of unmodified controls, indicating that macroinvertebrate abundance increased roughly proportional to the increase in surface area.

24. Revetments reduce habitat for two large species of burrowing mayflies. *Tortopus incertus* and *Pentagenia vittagara* are important biomass components of the macroinvertebrate fauna on natural banks. These forms are widely distributed in the LMR in cohesive clay substrates found primarily on natural banks (Mathis et al. 1981, Beckett and Pennington 1986). Covering cohesive clay substrates with an ACM apparently reduces habitat for both species. Tunnels constructed by burrowing mayflies have been observed on revetted banks in areas where the ACM has buckled to expose the underlying clay substrate (Henderson and Shields 1984). However, the organisms are not able to colonize the clays when the ACM is in direct contact with the substrate except at the openings between the blocks. Fine-textured substrates which accrete on the upper surfaces of the ACM are not suitable habitat for either species (Baker et al., in preparation). The loss in biomass of these large burrowing mayflies is offset to an unknown extent by net-spinning caddisflies and other epibenthic forms that colonize the exposed upper surfaces of ACM blocks or stone riprap.

Fish and fisheries

25. Little evidence suggests that adults of most common riverine fish are as dependent on specific types of substrate as benthic macroinvertebrates.

Fish are often associated with specific substrates in rivers, but these apparent habitat preferences frequently involve responses to currents or other physical features. Fish select certain types of substrates for feeding, for protection, or as spawning sites (Trautman 1957, Hynes 1970, Pflieger 1975).

26. Revetments provide limited spawning habitat for some fish when the river is less than bank-full during the spawning season. Gizzard shad, threadfin shad, carp, bigmouth buffalo, smallmouth buffalo, white bass, gars, and other abundant riverine species deposit eggs that adhere to vegetation or other firm substrates; these fish may utilize revetments as spawning sites when the floodplain is not inundated. However, the leveed floodplain and associated backwater habitats are the primary spawning and nursery habitats for these species in years of average or above average runoff (Bryant and Conner 1980, Holland 1986).

27. Revetment can reduce the amount of spawning habitat for catfish if most cavities large enough to provide shelter for spawning adults are eliminated. Catfish spawn in submerged hollow trees and cavities formed by brush lodged along caving shorelines (Carlander 1969, Pflieger 1975, Benson 1980). Revetment substrates may contain few cavities suitable as catfish spawning sites unless the ACM buckles.

28. It is feasible to create spawning habitat for catfish by providing spawning cavities. Artificial nesting structures have been widely used to enhance catfish spawning in ponds that lack natural cavities. Many types of nesting structures including 10- or 15-gallon milk cans, sections of pipe or tile, and wooden nail kegs and boxes have been used (Marzolf 1957, Snow 1959, Miller 1966, and others). The major prerequisite appears to be providing a secluded cavity where fish can enter and deposit eggs.

29. Revetments provide potential nursery habitat for young fish that remain near the shoreline or seek protection in small interstices (Rasmussen et al. 1979). Studies of the distribution and abundance of larval fish in the Mississippi River have generally yielded about one-half the number of species present as adults (Gallagher and Conner 1980, Hergenrader et al. 1982, Holland 1986). Forms that live near the river bottom or in sheltered areas to escape predation and strong currents are not sampled with standard larval fish

sampling gears. Revetted banks may provide potential nursery habitat for these forms near vegetation on the upper bank, in interstices of the riprap (Hjort et al. 1984), and in areas where the ACM has buckled. However, the amount of revetment habitat available to young fish is limited relative to backwater and sandbar habitats.

Currents

Physical-chemical

30. Currents adjacent to revetted banks can vary greatly depending on the physical characteristics of the shoreline and its location relative to the thalweg. Cobb and Clark (1981) and Pennington, Baker, and Bond (1983) reported that currents adjacent to ACM revetments were usually stronger than those near natural banks. However, Baker et al. (in preparation) compared current patterns on three natural and two revetted banks and found differences in current velocities between the two habitat types to be small. The authors hypothesized that current speed and direction nearshore were determined by local features of the bank that were independent of habitat type (revetment or natural bank).

Macroinvertebrates

31. An understanding of current patterns at a proposed revetment construction or maintenance site can provide planning and engineering staffs with baseline data concerning the types of substrates that will be present. The direction and velocity of currents determine if a revetment surface will become covered with sediments, the types of sediments that will accrete, and therefore the kinds and quantities of benthic macroinvertebrates that will colonize these substrates (Keown et al. 1977, Beckett et al. 1983). Clay, silt, and fine sand are generally deposited in areas where current velocities are less than 0.5 ft/sec. Sands of increasing size are deposited as current velocities increase from 0.5 and 2.1 ft/sec (White and Brynildson 1967). Surfaces of ACM revetments tend to remain free of sediments at higher current velocities. Carter, Bazata, and Andersen (1982) found that substrate materials in the Missouri River were unstable at current velocities greater

than 2.6 ft/sec. Habitat features that produce current velocities less than 0.5 ft/sec or greater than 2.6 ft/sec would be desirable for benthic macroinvertebrates because fine sediments and firm substrates generally support more productive benthic assemblages than sand.

32. Habitat improvement structures that provide a firm surface in areas exposed to currents can enhance production of epibenthic macroinvertebrates. Most epibenthic forms either filter or scrape the fine particulate organic matter. Their abundance is positively related to current speed within the normal range of currents found adjacent to revetted banks, apparently because of increased food availability. Mathis, Bingham, and Sanders (1982) implanted stone-filled baskets at different locations on selected dikes in the LMR and observed that both the total densities and numbers of macroinvertebrate species were greater in samplers placed where currents were strongest. Samplers implanted on the upstream sides of dikes collected more than twice as many organisms as samplers placed on the more protected downstream surfaces. Macroinvertebrate densities in samplers placed on the tops of dikes where currents were strongest were about four times those on the downstream sides. Species assemblages were similar at all locations, although more species were usually present in samplers placed on the upstream sides or tops of dikes.

33. Positive relations between epibenthic macroinvertebrate abundance and current patterns have been reported throughout the Mississippi River basin. Atchison et al. (1986) found that riprap in areas of high current velocities were productive for attached macroinvertebrates and that sediments trapped in interstices between stones were also productive for burrowing forms in the Middle Missouri River. Burress, Krieger, and Pennington (1982) reported that the abundance of benthic invertebrates on stone revetments in the Missouri River in North Dakota increased with current velocity up to 2.3 ft/sec.

34. Increasing the amount of firm substrate on revetments may significantly enhance invertebrate drift and their availability as food for fish. Epibenthic macroinvertebrates experience higher rates of drift than organisms that burrow in the sediment and therefore become more vulnerable to

predation by fish. Benke et al. (1985) measured macroinvertebrate biomass and production on snag habitat in the Satilla River, Georgia, and found that snags (firm substrate) were comparatively productive for benthic organisms that experienced higher rates of drift than sediment-inhabiting forms. The authors postulated that a larger portion of the biomass of the snag fauna was available for the production of fish. Kallemeyn and Novotny (1977) reported similar high rates of drift by benthic invertebrates in channelized areas of the Missouri River where shoreline substrates included large amounts of riprap. Drifting invertebrates increase the amount of food available to fish living downstream as they are displaced rapidly to other habitats that may be more favorable to fish (Waters 1972).

Fish and fisheries

35. The abundance, distribution, and species composition of fish communities in rivers are determined to a large degree by their adaptations to currents (Hynes 1970, Fraser 1972). Three distinct fish communities have been identified in the LMR. A flowing-water community occupies the main channel habitats (revetments, natural banks, dike fields, and secondary channels); a standing-water community occurs in abandoned channels, borrow pits, and oxbow lakes; and an inshore community (made up mostly of minnows and young fish) inhabits the shoreline (Pennington et al. 1980). The authors hypothesized that the presence or absence of currents had a greater influence on the abundance and distribution of fish than other physical environmental factors in determining these communities.

36. Environmental design features that create areas of reduced current along revetted banks provide habitat for many species of fish. Currents adjacent to revetments are usually strong, and fish assemblages in these habitats are dominated by large rheophilic species. Even forms adapted to strong currents spend most of the time in sheltered areas (Hynes 1970, Brown 1975). Limited hydroacoustic assessments of fish assemblages from selected revetments and natural banks of the LMR indicate that fish indeed tend to concentrate near the bottom in these habitats and that they can be distributed from the shoreline to the thalweg. Estimates of abundance from hydroacoustic sampling ranged from 8.5 to 312 individuals per acre, which suggests that the

value of revetment habitats for fish is quite variable (Baker et al., in preparation). Fish living on revetted banks can escape currents in eddies, near depressions in the riverbed, or near shoreline cover or structure. The movement of fish in large rivers is considered random (Hesse and Newcomb 1982), and they can quickly locate desirable habitat by moving across the channel or along the shoreline.

37. Information on desirable current ranges for fish is limited, and planners and engineers must rely on general guidance to establish appropriate habitat conditions. The ability of fish to withstand currents is dependent on temperature of the water, concentrations of dissolved substances, and the size and physiological condition of the fish (Hocutt 1973, Farlinger and Beamish 1977). Unfortunately, a lack of standardization in assessing swimming speeds of fish (Blaxter 1969) and measures of habitat preferences with respect to current speed (Brown 1975) have precluded the development of precise habitat preferences for fish. Blaxter (1969) suggested that a sustained swimming speed of about two times the total length of a fish per second was reasonable for most species. Holland et al. (1984) used this relationship to estimate sustained swimming speeds for several fish common to the Mississippi River. Based on the above criteria, habitat features that create areas with current velocities less than 1 ft/sec would benefit adults and juveniles of most common species. However, much slower currents are needed by young fish.

38. Currents strongly influence the distribution of larval and juvenile fish near revetments. Studies of larval fish conducted throughout the Mississippi River indicate a distinct dichotomy in habitat preference among larval fishes based primarily on responses to current. Conner, Pennington, and Bosley (1983) and Schramm and Pennington (1981) recognized main channel and quiet backwater habitats as extremes for larval fish distribution in the LMR. Main channel habitats are dominated by shad, freshwater drum, carpsuckers, and minnows. Backwater habitats are dominated by shad, sunfish, and silversides. The inundated floodplain, backwater habitats, or areas of low current velocity are generally considered better spawning and nursery sites than main channel habitats (Kozel and Schmulbach 1976; Kallemeyn and Novotny 1977; Burress, Krieger, and Pennington 1982; Hergenrader et al. 1982; Conner,

Pennington, and Bosley 1983; Bosley, Pennington, and Potter 1984; Beckett and Pennington 1986; and Holland 1986).

39. Revetted banks provide limited habitat for young fish in areas adjacent to cover, irregularities in the riverbed formed by natural features or buckled ACMs, interstices in the revetment surface, and eddies formed by shoreline irregularities (Schramm and Pennington 1981). Young fish that become entrained in the main channel are transported rapidly downstream unless they find refuge from the current. Schramm and Pennington (1981) found that density and diversity of larval fishes were variable on revetted banks, and they postulated that sites with highly turbulent flows and upstream currents concentrated larval fish. Zimpfer et al. (1988) considered eddies to be very important habitat features for larval fish and suggested that permanent eddies be constructed on ACM revetments when feasible to create microhabitat for riverine fish. The authors proposed incorporating a large vertical expanse of bank into the features to maintain similar current patterns across the large normal range of river stages.

Cover and Structure

40. The structural complexity of aquatic and terrestrial habitats strongly influences the species composition, distribution, and abundance of fish and wildlife communities. Schnick et al. (1982) defined structure as "irregularities of substrate or relief, either artificial or natural, living or nonliving, which are concave or convex." Cover generally refers to natural or artificial habitat features that provide shelter and protection for aquatic and terrestrial organisms.

Physical-chemical

41. Revetment construction often reduces the structural complexity of the shoreline and the amount of cover present when compared with the pre-construction natural bank habitat. Natural caving banks are steep (slopes greater than 30 percent), irregular, and composed of erodible alluvial soils. Substrates at these sites are physically diverse and inherently unstable. Variable current patterns are typical. Caving banks often have large

quantities of downed trees and woody debris (Beckett and Pennington 1986). Turbulence created by fallen trees, bank friction, and irregularities in the eroding shoreline produce turbulence and create eddies (Cobb and Clark 1981). Revetted banks usually are smoother, with flatter slopes. Consequently, flows may be more streamlined (Cobb and Clark 1981). The amount of turbulence and structural complexity of the shoreline can also be reduced when fallen trees, lodged woody debris, and many small indentations in the shoreline are eliminated (Miller 1981; Pennington, Baker, and Bond 1983).

Macroinvertebrates

42. Benthic macroinvertebrates benefit from habitat structures that increase surface area for attachment and form interstices that provide protection from predation. The addition of habitat features to increase cover or structure is usually justified for fish enhancement. However, epibenthic organisms often colonize these firm substrates in proportion to the increase in surface area (Pardue 1973; Benke and Wallace 1980; Baker et al., in preparation). Habitat structures also alter predation on invertebrates by fish when they provide interstices large enough for benthic organisms to use as shelter.

Fish and fisheries

43. Habitat improvement features that make a revetted bank more irregular or modify current patterns and depths will benefit fish populations. The addition of cover or structure to increase habitat diversity has been widely used in the development of fishery management strategies for small streams (White and Brynildson 1967). Gorman and Karr (1978) related increased complexity of bottom type, depth, and current in small streams to increased species diversity of the fish communities. Assessing the effects of increasing shoreline cover and structure has been difficult in large rivers because of the inability to adequately assess fish populations in different habitats. Fishery studies on the Upper Missouri River have shown that species diversity, abundance, and yields of fish are higher in unchannelized reaches where more diverse microhabitats, shelter, and a greater proportion of backwater contribute to the apparent differences in fish production (Funk and

Robinson 1974; Schmulbach, Gould, and Groen 1975; Kallemeyn and Novotny 1977; Groen and Schmulbach 1978).

44. Placing cover on revetted banks can also increase both carrying capacity and yield of fish. Cover concentrates some species of sport and commercial fish. The technique has been used extensively in lakes and reservoirs and has been recommended to enhance fisheries in levee borrow pits of the LMR (Aggus and Ploskey 1986). Cover also enhances survival, growth, and reproduction of fish (Swales and O'Hara 1980). The value of cover for concentrating fish depends on species-specific preferences for cover, the amount of cover available, and its distribution (Ploskey 1985). Main channel habitats are exposed to navigation hazards and strong currents. Sport or commercial fishing near cover on revetted banks can vary locally, depending on access, navigation hazards, and placement relative to population centers or markets. Shelters placed on revetted banks may therefore enhance survival of fish harvested in other habitats.

45. Adding cover to a smooth revetted shoreline provides resting habitat for fish and increases carrying capacity by modifying predator-prey interactions. Fish concentrate in areas near cover to escape strong currents (Brown 1975). Small fish seek cover to escape predation, whereas certain predators use cover effectively as ambush sites. Crowder and Cooper (1982) and Savino and Stein (1982) found that the efficiency of predator-prey interactions was optimized with the addition of cover, but that extreme increases in structural complexity reduced the efficiency of predator-prey interactions. Predators generally consumed more prey and grew faster when intermediate amounts of structure or cover were present, thereby optimizing trophic efficiency and increasing fish production.

46. Habitat structure can be created by placing relatively dense materials directly on the revetted bank. Riprap is generally considered to be superior to most man-made materials for this construction from an environmental perspective. It is relatively inert, dense enough to withstand strong current, and comparatively inexpensive; it can be formed in many shapes and is generally considered more pleasing aesthetically than concrete or other man-made materials. When properly sized and graded with respect to maximum

hydraulic flow conditions, riprap can be used to create stable habitat structures that are utilized by a variety of aquatic organisms (Keown et al. 1977, Schnick et al. 1982). Structures made from riprap have been used effectively to create sanctuaries for fish in tailwaters where strong currents and a scoured channel produce physical habitats similar to those found near revetments (Tennessee Valley Authority 1987).

47. Stone used to create structure should be of such a size as to be stable under a wide range of currents and should be attractive to fish and invertebrates (Shields 1982). Stones of the size and grade used in dike construction provide a more desirable habitat for fish and benthic macro-invertebrates than smaller stones. Mathis, Bingham, and Sanders (1982) reported that benthic organisms were abundant in dike structures of the LMR. Kallemeyn and Novotny (1977) found that large stones provided habitat of high quality for benthic macroinvertebrates on the Upper Missouri River. Farabee (1986) reported that shoreline structures made of stones 2 ft in diameter or larger were utilized more heavily by fish than ones in which smaller stones were used during a study of Upper Mississippi River fish assemblages.

48. The amount of cover or structure needed to provide optimum habitat for fish has not been evaluated for the LMR. A relatively small amount of cover (less than 1 percent of the surface area) is effective in concentrating fish in lakes and reservoirs where structures can be selectively placed (Wilbur 1978, Pierce and Hooper 1979, Sims 1982). Strong currents adjacent to most revetted shorelines coupled with an uncertain supply of suitable construction materials strongly limit the areas on revetments where fish shelters can be placed. Shorelines make up only a small percentage of the aquatic habitat in the main channel. From this perspective, placing large structures at locations judged suitable on the basis of reduced current patterns and availability of suitable construction materials would be appropriate. For example, brush shelters approximately 1 acre in size were highly effective in concentrating fish in Lake Barkley, Kentucky (Pierce and Hooper 1979).

49. The types of materials used to create cover or structure influence the effectiveness in concentrating fish. Woody materials (trees and brush)

appear to be more effective than artificial materials for concentrating fish. Pierce and Hooper (1979) reported that brush shelters concentrated larger numbers and weights of sport fish in Lake Barkley, Kentucky, than structures made from used tires. Wilbur (1978) also reported that fish shelters made of brush afforded significantly higher fishing success than structures constructed of pipe in Lake Tohopekaliga, Florida.

50. The durability of brush shelters is determined by the kinds of woody materials used in construction, how often they are exposed to wetting and drying, and how securely they can be anchored to withstand currents. The rate of decomposition of woody materials is influenced by many factors, including water temperature, the availability of oxygen, disturbance by physical factors, plant tissue type, and the area to volume ratio of the wood used to form the structure (Ploskey 1985). Shelters last much longer if they are not exposed to frequent wetting and drying, and they should be placed well below the mean annual low stage to ensure that structures remain submerged as much of the time as possible. Shelters should include the largest limbs available because they will decompose more slowly than small limbs. Hardwoods should be used to construct shelters where a choice of woods is available. These materials decompose at a much slower rate than softer woods such as willow. Green oak is a preferred material because of its density, but other hardwoods are satisfactory. Dead or dry wood should be avoided because the greater buoyancy makes anchoring much more difficult (Schnick et al. 1982).

51. Brush shelters decompose at variable rates, depending on the types of materials used in construction and the frequency of wetting and drying. In rivers, there is an increased risk that the structures will dislodge during high flows. Shelters have value as fish attractors as long as they remain in place. Thomas, Legault, and Carpenter (1968) found that brush shelters placed in Douglas Lake, Michigan, in 1937 continued to concentrate fish after 30 years, although the effectiveness decreased as the structures became less dense with age. Nelson, Horak, and Olson (1978) reported that brush shelters and windrowed brush placed in Fort Gibson Reservoir prior to its filling remained functional as fish attractors 20 years after impoundment.

Wildlife

52. The use of revetments by wildlife is directly linked to the quantity of vegetation (living or dead) available as food and cover. The floodplain of the LMR supports a diverse assemblage of wildlife (Klimas, Martin, and Teaford 1981; Environmental Laboratory 1985). Woody and herbaceous plant cover and brush determine the kinds and abundance of wildlife species that will occur at a particular location. Although opportunities for wildlife management are limited to a narrow strip along the upper edge of the revetted bank, this habitat can be important because it comprises the margin or "edge" between floodplain terrestrial communities and the river (Yoakum et al. 1980). Opportunities to benefit wildlife are tied to the planting or seeding of species with high food or cover value and to the construction of shelters to provide escape cover and protection from the elements along the upper bank of a revetment site.

53. A substantial amount of effort has gone into the development of criteria for establishing desirable plant species in habitats similar to the upper banks of revetments. Plants inhabiting the floodplain are often adapted to a specific set of environmental conditions, and some understanding of these requirements increases the probability of a plant becoming established. It is important to match plants with the appropriate climatic, soil, and topographic characteristics (Hynson et al. 1985). The kinds and relative abundance of plants occurring as a result of natural recolonization of revetments have been described by Webb (in preparation). Flood tolerances of many plant species common to the LMR have been summarized by Whitlow and Harris (1979); Klimas, Martin, and Teaford (1981); and Fredrickson and Taylor (1982). Detailed guidance for seeding and planting has been developed for reservoir fluctuation zones (Allen and Klimas 1986). Many of these procedures are applicable to revetment shorelines in the LMR.

54. Planting fast-growing trees can provide protection from scouring currents and a migration corridor for wildlife. Revetments with limited natural cover may warrant the planting of a shelter belt of cottonwood trees along the upper margin. Cottonwood is well adapted to the floodplain of the

LMR and commonly grows 4 to 5 ft annually during the first 15 years of life (Johnson and Burkhardt 1976). If flood conditions are severe, there is some risk that trees planted to protect the bank will be killed before the trees become large enough to withstand prolonged flooding and strong currents, but replanting limited areas is relatively inexpensive and represents a viable risk under these conditions.

55. Shelters fabricated from trees and brush obtained during revetment construction afford cover for small mammals and birds. When placed along the landward edge of the construction site, they provide concealment from predators, nesting and rearing sites, and protection for small animals during inclement weather (Yoakum et al. 1980). Brush structures have the greatest ecological value in areas where natural cover is sparse (Aggus and Ploskey 1986). Unfortunately, these are often areas where the availability of suitable materials for constructing shelters are limited. Yoakum et al. (1980) reported guidelines for the construction of brush shelters and recommended that structures designed to benefit wildlife should be placed at wide intervals throughout the area.