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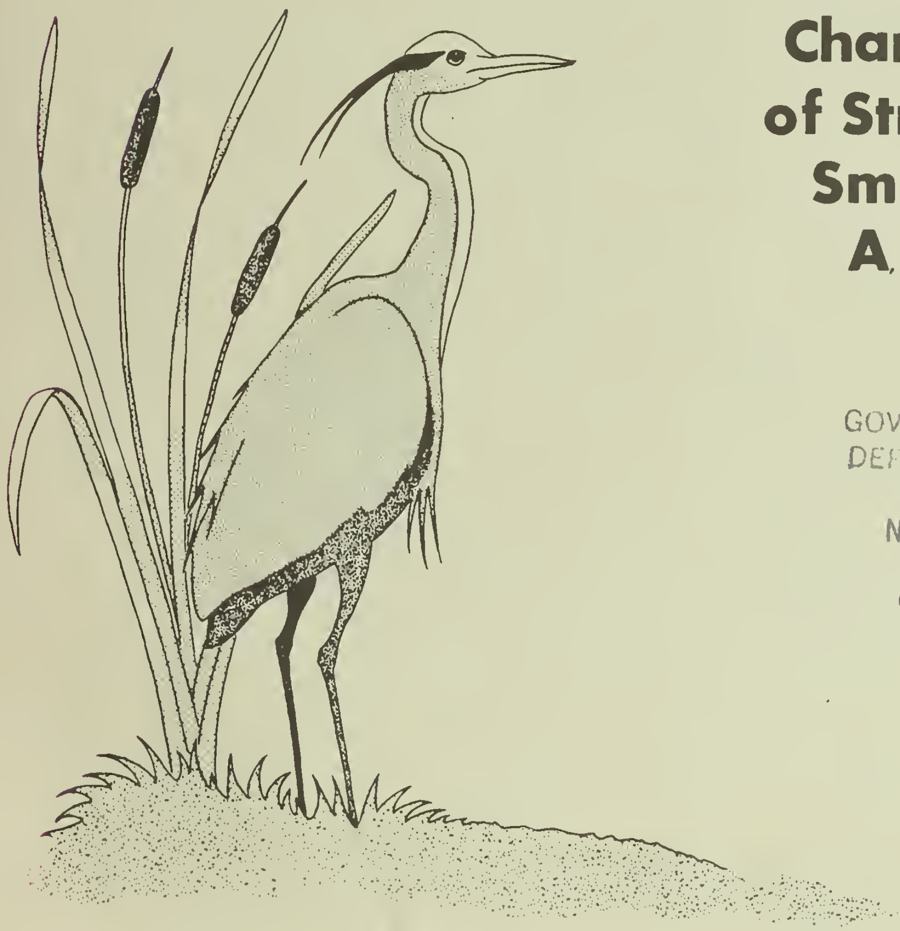
July 1980

Effects of Bank Stabilization on the Physical and Chemical Characteristics of Streams and Small Rivers: A Synthesis



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FWS/OBS-80/11
July 1980

EFFECTS OF BANK STABILIZATION ON THE PHYSICAL AND CHEMICAL CHARACTERISTICS OF STREAMS AND SMALL RIVERS: A SYNTHESIS

by

Daniel H. Stern and Michele S. Stern
Department of Biology
University of Missouri - Kansas City
Kansas City, Missouri 64110

and

Missouri Institute of River Studies
302 Engineering Research Building
University of Missouri - Rolla
Rolla, Missouri 65401

U.S. Fish and Wildlife Service Contract No. USDI 14-16-0009-78-035

Project Officer

Charles A. Segelquist
Eastern Energy and Land Use Team
National Water Resources Analysis Group
Kearneysville, West Virginia 25430

Performed for
Eastern Energy and Land Use Team
Office of Biological Services
Fish and Wildlife Service
U.S. Department of the Interior

For sale by the Superintendent of Documents, U.S. Government Printing Office Washington, D.C. 20402

Library of Congress Cataloging in Publication Data

Stern, Daniel H 1834-
Effects of bank stabilization on the physical and chemical characteristics of streams and small rivers.

Vol. 1: "FWS/OBS-80/11."
Vol. 2: "FWS/OBS-80/12."
"Contract no. USDI 14-16-0009-78-035."
Includes index.
CONTENTS: v. (1) A synthesis.--v. (2) An annotated bibliography.
Supt. of Docs. no.: I 49.2:B22
1. Stream channelization. 2. Rivers. 3. Streambank planting. 4. Erosion. 5. Turbidity. I. Stern, Michele S., joint author. II. Eastern Energy and Land Use Team. III. Title.
TC529.S73 627'.12 80-607768

PREFACE

This report was prepared in response to numerous requests from field personnel for information on the impact of bank stabilization on streams and small rivers. Information is organized to show changes that occur in depth, velocity, temperature and other stream parameters. Strategies for dealing with some bank stabilization problems are also discussed briefly.

A companion document entitled "Effects of Bank Stabilization on the Physical and Chemical Characteristics of Streams and Small Rivers: An Annotated Bibliography" (FWS/OBS-80/12) references the literature which formed the basis for this synthesis, and contains additional information that may be useful to the reader interested in streambank stabilization. The bibliography and synthesis are intended for use by individuals concerned with the biology, chemistry, engineering, geology and hydrology of streams that have been, or are to be, altered by man.

This report and the annotated bibliography are available from the:

Information Transfer Specialist
Eastern Energy and Land Use Team
U.S. Fish and Wildlife Service
Route 3, Box 44
Kearneysville, WV 25430
(304) 725-2061

EXECUTIVE SUMMARY

This synthesis of available literature relates the effects of bank stabilization to the physical and chemical characteristics of streams. This review has developed some points of universal importance with respect to this topic; these are summarized below.

1. Bank stabilization is one of four widely used techniques for channel modification, the others being: a) widening, deepening and straightening; b) clearing and snagging; and c) diking. Bank stabilization generally entails some combination of the following: a) sloping of the bank by building up of the toe of the slope and pulling back on its top; b) berm construction and planting of bank vegetation; and c) placement of materials, often as structures, to reduce or prevent bank erosion.

2. It is necessary to consider the impact of bank stabilization on stream hydraulics, and how this affects the flow and channel characteristics in adjacent reaches of the stream. The sequential effects of channel modification may be summarized as follows:

Cutoff of meanders to shorten stream length → Increased stream gradient → Increased flow velocity →

Increased unit stream power → Increased channel erosion, downcutting → Increased suspended solids load → Habitat degradation

Stream channelization should not be initiated without prior close examination of its interrelationships with bank stabilization.

3. Bank stabilization leads to increased downcutting erosion, so that streams with stabilized banks will tend to be deeper than natural streams, all other factors being the same. The depth of stabilized streams will increase with increased discharge, unless the banks are so rough that energy available for downcutting is reduced. With stabilization, bed materials become coarser, and are transported, leading to a potential continuous bank maintenance problem.

4. Bank stabilization precludes stream meandering, and will constrain channel migration within the floodplain. Streams with stabilized banks often will have a wider range of discharges, due to containment of flows in the armored channel which prevents normal widening and overflow during high stages. The velocity and depth of flow in a stabilized stream increase with discharge downstream, because of the funnelling of water through a more narrow channel than is natural; the increase in depth overcompensates for the decrease in slope.

5. Bank stabilization activities cause a temporary increase in suspended solids load and sedimentation downstream during construction, but long-term effects usually include a decrease in suspended solids and sedimentation problems. In streams with revetment armored banks, there will be a decrease in the bank sediment supply. Frequency and magnitude of precipitation are related to erosion caused turbidity of lotic waters. The physical and chemical properties of bank materials can affect stabilization.

6. Bank protection measures must be designed to resist the effects of rapid stage changes, bank saturation with water, and bank freeze - thaw cycles. A bank revetment should be founded deeply in the streambed, so that scouring erosion at the toe of the bank will not undermine the work. However, streambank protection structures that project far enough into the channel to produce a permanent scour hole will enhance the habitat for fishes. A particle analysis of streams with bank erosion caused turbidity may pinpoint sites in need of stabilization, and areas that do not need it.

7. Bank stabilization efforts have various indirect effects on the quantity and quality of water in streams. Degradation (downcutting) of stabilized streams, altered floodplain water regimes, and removal of vegetation (for installation and maintenance of structures) can result in alterations of groundwater flow laterally into the stream and surface runoff, often producing a more variable streamflow. These impacts have potential adverse effects on the chemical quality (especially oxygen levels) of water entering the channel.

8. Removal of streambank and floodplain vegetation affects the temperature and light transmissivity of flowing waters by reducing shade. Unobstructed winds may ruffle the water surface, enhancing light absorption early or late in the day.

Temperature of flowing water varies far more rapidly than does that of lakes, but the variation is over a much smaller range than that of equally shallow stillwaters. Turbulence of streams ensures a uniform distribution of dissolved substances.

9. Bank stabilization activities are attended by an identifiable suite of physical and chemical alterations of the aquatic environment that may extend for many kilometers downstream. Construction activities are frequently detrimental, owing directly to the use of large pieces of earth moving equipment in the streambed, bank, and floodplain and associated removal of vegetation. Indirect problems of bank stabilization

result from dam construction that affects discharge-energy relationships throughout the stream. Each physical or chemical modification induces a derived set of biological effects, many of which are predictable, at least in qualitative terms.

10. In small streams, the chance of success in bank stabilization is enhanced, if stabilization is begun at the head of the stream and proceeds downstream. In this way, treated sections can attain the maximum benefits of bank stabilization immediately. If work ceases at some point, stabilization already accomplished will continue to be beneficial.

11. The present admonition is to confine stream management activities to the shortest possible length of stream, to employ the least amount of artificiality, (i.e. to work with the stream rather than on it); we must "design with nature".

This report was submitted in fulfillment of contract number 14-16-0009-78-035 by the Missouri Institute of River Studies, University of Missouri, Rolla, under the sponsorship of the Office of Biological Services, U.S. Fish and Wildlife Service. Work was completed as of June 12, 1979.

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LIST OF ABBREVIATIONS

cfs	cubic feet per second
cm	centimeter
cm/sec	centimeter per second
cu km	cubic kilometer
ft	foot
ha	hectare
km	kilometer
km/hr	kilometer per hour
kw-hr	kilowatt hour
m	meter
mm	millimeter
mph	mile per hour
m/sec	meter per second
ppm	part per million
sec-ft	second foot
sq km	square kilometer

ACKNOWLEDGMENTS

We are grateful to the staff of the former National Stream Alteration Team, U.S. Fish and Wildlife Service, Columbia, Missouri, for their assistance in obtaining literature. We appreciate the guidance of Charles A. Segelquist, Project Officer, Eastern Energy and Land Use Team, U.S. Fish and Wildlife Service, Kearneysville, West Virginia. We thank Paul R. Munger, Director of the Institute of River Studies, University of Missouri-Rolla, for providing support throughout the project.

INTRODUCTION

Streams (lotic waters) are linear water bodies with directional flow and are the principal carriers of the products of weathering and erosion from land surfaces to the sea (Darnell et al. 1976). Even though streams and rivers are major topographic features of landscapes, their total area worldwide is only about 0.1% of that of the land surface as compared with lakes (lentic waters) that comprise 1.8% of the land surface area. Annually, streams carry about 37,000 cu km of water to the sea, which is equivalent to about 25 cm of rainfall spread evenly over the entire land surface (Hynes 1970). Schmitz (1961) has calculated that, assuming a mean height of the land surface of 825 m above sea level, the amount of energy expended by running water annually is 10^{14} kw-hr, or about 100 times that produced by all human endeavor in 1950. Only 2.8% of the world's total water (1,337,000 cu km) occurs on land. Of this, most (2.24%) is locked in polar icecaps and glaciers. Lakes constitute only 0.009% of the total, and at any given time only 0.0001% of the water is in river channels (Leopold et al. 1964).

In the U.S., streams have been modified for more than 150 years. (In 1839, Lt. Robert E. Lee of the Corps of Engineers, built a stone and brush dike across a chute (sidechannel) in the Mississippi River near St. Louis to improve the channel for navigation (Task Committee on Channel Stabilization Works 1965)).

Bank stabilization is generally carried out as one of four widely used techniques for channel modification or "improvement", the other ones being 1) widening, deepening, and straightening; 2) clearing and snagging; and 3) diking. Bank stabilization efforts are directed at reducing or preventing bank erosion problems. The reader is referred to Keown et al (1977) and Striffler (1960) for further discussion of bank erosion problems.

It is often essential to consider existing interrelationships between bank stabilization and channelization. Channelization has been used to control flooding, to drain wetlands for farming, to improve navigation, or to modify stream alignment in conjunction with a bridge crossing. However, channelization has caused degradation of stream ecosystems in the eyes of many workers. Recently, programs in stream restoration, also involving bank protection, have been instituted to rectify problems caused by channelization alone and to minimize the disruption of the stream environment by future pressures.

Bank stabilization generally entails some combination of the following (Keller 1976): 1) sloping of the bank by building up of the toe of the slope and pulling back on the top; 2) construction of a berm and planting of vegetation on the bank; and 3) placement of materials, often stone riprap. Many recent design approaches to bank stabilization have included an active desire to preserve the natural appearance and to minimize disturbances to the bank and water. The critical technical factors that affect structure design and stability of the bank in much of the U.S. are: bed scour at the toe (bottom) of the bank, weathering in the zone of stage variation, ice action, and filtering of fine river sediments through structure (U.S. Army Engineer District, Omaha, CE 1978).

The chances for success in bank stabilization in small streams will be enhanced, if stabilization is begun at the head of streams, succeeded by work downstream. In this way, treated sections of the stream can attain the maximum benefits of bank stabilization immediately. In addition, even if work is halted temporarily or permanently, stabilization already completed will be of some benefit (Hansen 1968).

This synthesis is focused primarily on small streams, defined as those that can be waded or used only by small pleasure boats (Hansen 1968). However, literature pertaining to larger navigable rivers is included, where appropriate. It is difficult for stream workers to describe adequately to one another even the most basic qualities of a given stream, e.g., large or small. Pennak (1971) has suggested a classification of lotic habitats that includes thirteen critical chemical, physical, and biological features. (This, or some other classification, is needed to facilitate communication.)

A number of physical-chemical factors can be affected by bank stabilization measures or other water development activities. Ten such factors were selected by Yorke (1978) as being sensitive to such activities, and will be examined individually in the following sections: 1) depth and stage; 2) water surface area of channel and floodplain; 3) channel configuration; 4) water current velocity; 5) water temperature; 6) suspended solids; 7) bed materials, including bedload; 8) dissolved substances; 9) light transmissivity; and 10) flow variability. Cause and effect relationships for each factor can be applied to decision-making by users of the Dual-Matrix System (Yorke 1978), a system that (1) relates bank stabilization or other stream modifications to physical change (s) and will, in turn (2) relate physical changes to biological impact(s).

To date, the natural regimes of streams are not understood completely. However, stream behavior is becoming better understood. The present admonition is to confine stream management procedures, including bank stabilization, to the shortest possible length of the stream and with the least amount of artificial control (Keller 1976, 1978). Simons et al. (1975) quote Mackin's observations concerning attempted control of large rivers. His thoughts pertain well to bank stabilization and management of all streams:

> "The personnel who alter natural stream equilibrium relations by channel improvement measures will find often that they have a bull by the tail and are unable to let go.... As work to correct or suppress undesirable phases of the chain reaction of a stream to an initial "stress" continues, personnel involved with alleviating the "stress" will necessarily place increasing emphasis on study of the genetic aspects of the equilibrium in an attempt to work <u>with</u> a stream, rather than <u>on</u> one."

In future years, additional demands will be placed on those persons entrusted with stream management. Land uses will diversify and intensify; urban dwellers will migrate into neighboring suburban and rural areas; watershed drainage patterns will be disrupted by roads, utilities, housing developments, and other engineering works; new and exotic waterborne pollutants will join traditional ones being discharged into groundwater supplies or directly into streams; and surface disruptions will add to the solids load in streams. Each stream is a dynamic open system whose water-land interface is great compared to that of even a lake with a heavily dissected shoreline. Future management techniques for bank stabilization in such dynamic systems will necessitate having the stream maintain itself, rather than employing all sorts of physical constraints of natural processes. Conceivably, stream management workers will adhere to the school of environmental planning of Ian McHarg (1971) who strives to "design with nature".

DEPTH AND STAGE

Bank stabilization will constrain channel migration within the floodplain. This, in turn, may diminish the variability in water depth that would occur, if no constraints were present, due to scour on the outside and bar formation on the inside of bends. Streams whose banks are reinforced with riprap or other stabilization materials will tend to be deeper than natural streams, all other factors being the same (Yorke 1978). The formula of Davis (1938) relates discharge, width, and mean depth, as follows:

$$D = \frac{wdal}{t}, \text{ where:}$$

D = discharge
w = width
d = mean depth
l = distance travelled by floating object in time (t)
t = time
a = roughness coefficient: 0.8, if bed is rough; 0.9, if bed is smooth

This crude formula may be modified in a number of ways. More accurate results may be achieved, if the stream is subdivided transversely into several sections. Additional roughness coefficients may be applied to account for drag by bank stabilization materials, if appropriate. Stream depth and cross section profile are related to bank material cohesion. For example, sand streams (noncohesive bank material) have parabolic channel cross sections. Streams with protected or cohesive banks are relatively deeper than are sand stream (Hynes 1970).

At any given point in a channel, width (w), mean depth (d), and mean velocity (v) vary as a power of discharge (D) as follows: $w = pD^x$; $d = qD^y$; $v = rD^2$; the sum of the exponents equals one (i.e. $x + y + 2 = 1$) (Leopold et al. 1964). Therefore, each exponent equals one or less, and all are usually less than 0.5 in natural streams. By definition, wdv = D, so: $pD^x \times qD^y \times rD^2 = D$, where p, q, r, x, y, and z are numerical coefficients, and $p \times q \times r = 1$. The erodability of banks relative to bed material (and thus whether the channel is wide or ditch-like) will determine which factor is most affected by variation in discharge. In streams with protected banks, the depth will be increased with increasing discharge, since the width will be held constant.

Further, the suspended solid load, which is a measure of erosive power, varies as some power (usually between 2 and 3) of the discharge, and the larger the ratio z/y, the higher is the power. Thus, the greater the ratio of velocity to depth, the greater the tendency for a stream to erode its bed and increase its channel depth (Hynes 1970).

In streams without major bank modifications, the width tends to increase as the square root of the mean discharge (Leopold et al. 1964): $w = pD^{0.5}$, where w = width and pD = mean discharge. However, with stabilized banks, the slope and depth will tend to increase. The velocity will increase with increased discharge due to the entrances of tributaries or increased watershed inflow as one proceeds downstream. This increase in velocity downstream exists in most streams (Leopold and Maddock 1953). Stream discharge exerted an overriding influence on most physical and chemical factors in the modified Mississippi River near Quincy, Illinois, from 1954 to 1956 (Dorris et al. 1963).

In the middle Mississippi River between St. Louis, Missouri, and Cairo, Illinois, revetment construction that produced a narrow channel and a change in sediment supply has caused riverbed degradation and a change in the stage vs. discharge relationship. During low discharge (<300,000 cfs or 8,490,000 liters/sec), stages are lower in the developed river. Any discharge greater than 300,000 cfs in the developed river results in higher stages than those that occurred during similar discharges in the natural river (Johnson et al. 1974).

Bank stabilization often causes scour at the toe of the bank and undermining of riprap or other materials used. The transporting capacity of a stream depends primarily on the water discharge, depth of flow, and slope. If a stream is degrading significantly, a bank revetment should be founded deeply in the streambed, so that erosion will not undermine the work. Revetment armoring will reduce the bank sediment supply, causing an increase in bed erosion and degradation, requiring a deep placement of the revetment toe. Whenever a stream is aggrading or degrading significantly, proper management will dictate an analysis of the entire watershed and an overall examination of the complete stream system (Apmann and Otis 1965).

Permeable fence streambank revetments were used in southern California sand streams for bank stabilization. Revetted channels generally had suspended sand loads less than those in unrevetted channels. Thus, an increase in bank roughness caused greater energy use that, in turn, left less energy to transport sediments in the channel (O'Brien 1951).

Witten and Bulkley (1975) found it difficult to assess the effects of bank stabilization structures on stream width and depth and on current velocity, because they could not separate the effects induced by stabilization structures from those due to natural variations in depth or current velocity. In the Soldier River, Iowa, permeable jetties located along straight reaches of the channel caused an increase in depth near the structures, as compared with a control area. Revetments that did not project into the stream, but acted solely to protect an existing bank, had no apparent effect on stream morphology. Older permeable jetties on the Soldier River influenced stream depth far more than did newer permeable ones in the East Nishnabotna River, Iowa. Bulkey et al. (1976) stated that streambank protection structures that extend far enough into the stream channel to produce a permanent scour hole encourage fish populations by providing cover. Further, structures made of rock enhance production of fishfood organisms, such as mayflies and caddisflies. Such rock structures should extend into a stream one-third or more of the channel width to produce a scour hole at the structure base.

SUMMARY

Width, mean depth, and mean velocity vary as a power of the discharge at any given point in the channel. In streams with protected banks, depth increases with increasing discharge due to bank armoring and a reduction in the sediment supply. Discharge exerts an overriding influence on most water quality factors. Structures can be designed to extend at an angle from the bank far enough into the stream channel to produce scour holes that provide fish cover, but care must be exercised to prevent undermining and the ultimate collapse of the structure.

WATER SURFACE AREA OF CHANNEL AND FLOODPLAIN

Constraint of the natural migration of a stream channel, due to bank stabilization will probably induce the deepening of the stream and possibly reduce low-flow stream surface area. The interface between water surface and bank will be made more homogeneous in the stabilized reach than would be the case in a natural stream (Yorke 1978). Stream banks, roughened with riprap or other stabilizing materials, will retard the flow, resulting in a tendency for surface water to be drawn toward the center of the stream (Hynes 1970).

The form of a channel is determined and maintained by discharges that flow through it. Approximately once a year, the discharge is sufficient to cause erosion of a channel to fit the load of water that it carries (Leopold et al. 1964). If stabilized banks do not yield to the flow, its energy will erode the bottom, and there is a strong possibility that the flow will overtop the streambank. Therefore, it may be advisable to construct berms set back from the stabilized banks to delimit floodplain inundation in streams subject to frequent flooding.

Floodplains are comprised of a series of deposits laid down by a stream or river, as it meanders back and forth across a valley. Natural floodplain modifications usually cease in a stabilized stream, unless there is frequent overtopping of the banks. For example, meandering, and the production of features, such as oxbow lakes, will not occur in stabilized streams. Due to bank stabilization in the middle Mississippi River, channel migration no longer occurs, and no new side channels are produced by the cutoff of meander loops due to flooding. Except for those side channels (chutes) that carry large river flows at high stages, natural side channels are filling with sediments reducing the water surface area of the river (Johnson et al. 1974). Altered floodplain regimes, as well as removal of vegetation to construct and maintain stabilized banks, will result in alterations in the species composition and relative abundance of both game and nongame bird and mammal species (Possardt and Dodge 1978).

The Missouri River has been "improved" extensively during the present century. The lower 500 miles (806.5 km) have been contained by the use of a combination of bank stabilization structures. The distance from Rulo, Nebraska, to the mouth above St. Louis, Missouri, was 544 river miles (877.4 km) in 1879. In 1972, it was 498.4 river miles (803.9 km), a loss of 45.6 river miles (73.6 km), over 8% of the area being considered.

An average river mile had a surface area of 138 acres (55.9 ha) in 1954. Therefore, more than 4,000 water surface acres (1,619 ha) were lost in 75 years by shortening of the river. The total water surface area of the Missouri River in 1879 was 121,739 acres (49,287 ha). By 1954, it was 71,151 acres (28,806 ha), a loss of 50,588 surface acres (20,481 ha). By 1972, 60,832 acres (24,628.3 ha) of water surface were lost, 50% of the original surface area of the river. The total area of the entire channel, bank to bank, including marginal bars, decreased from 250,252 acres (101,316.6 ha) in 1879 to 183,857 acres (74,436 ha) in 1954, a loss of 66,895 acres (27,083 ha) or 27%. This area, lost from the public domain, was annexed primarily by riparian land owners, and it is now probably in cultivation rather than being available as cover for wildlife and as a public recreational asset (Funk and Robinson 1974).

In any consideration of water surface area, the floodplain should be included. Maddock (1976) provides three definitions of floodplain: (1) Geological -- that area of a river valley covered with material deposited by flood; (2) Hydrological -- that area of a river valley overflowed by water periodically in excess of the stream channel capacity; and (3) a less precise definition used by some federal agencies -- that area covered by a flood with an average frequency of recurrence of 100 years. Using any of the three definitions, an estimated one acre in 10 or 12 of all potentially cultivatable land and an average of one acre in 6 of all urban land may be considered as floodplain. Whether the area is actually flooded, the frequency, and the severity, are dependent to some extent on the type of bank stabilization and bank design.

Stabilized banks can control overbank flow. This increases stress on the stream channel, which could normally result in an increase in stream width, a reduction in slope, or a combination of both, producing meanders. Instead, with stabilization, stream depth increases; bed materials become coarser and are transported; and a continual maintenance problem may result (Maddock 1976).

Much of the biology of lotic habitats is determined by stream width, especially when streams are narrow, and where overhanging shoreline vegetation afford shade and substrate for emerging and mating insects, major foods of stream fishes. Generally, both narrow brooks and broad rivers have more restricted bottom faunas, than do lotic habitats with widths between 5 and 20 meters. The mean width of a stream should be derived from readings taken during those ten months of the year when the stream is not carrying spring freshets or floods (spates) (Pennak 1971).

Zimmerman et al. (1967) found in their study of several small streams in the Sleepers River basin of northern Vermont that vegetation had a marked effect on channel form. Along five streams, for which there are complete records of variation in channel width, width does not increase in a downstream direction as far as drainage areas of 0.2 and 0.8 square miles (0.5 and 2.0 sq km) are concerned, presumably as a result of human disturbance and encroachment of vegetation. In one basin with an area of 0.8 square mile (2.0 sq km), channel width is related clearly to type of vegetation, as the channel is alternately wide under forest and narrow in sod.

In the Kiewa River (Victoria, Australia), early settlers introduced bank willows to aid in bank erosion control. Floods still caused heavy bank erosion. The eroded material accentuated siltation downstream, where the silt halted snags (logs and trees) and allowed the willows to establish themselves further. The willows reduced the capacity of the Kiewa River channel in one section from 55 to 5 cubic meters per second. In some areas, siltation and willow establishment caused the river to lose its identity as a main stream (Drummond 1972).

In Bushkill Creek, a coldwater Pennsylvania stream, gabions placed to protect the bank narrowed the stream channel and restricted the flow to the channel thalweg (central axis). The result was a stream of constant width, located in the wide original channel, bordered by shallow pools of semi-stagnant water. The pools were becoming filled with silt, and will probably become included in the streambank (Bradt 1974, Bradt and Wieland 1978).

SUMMARY

Bank stabilization will cause a diminution of channel migration, a reduction in bank heterogeneity, and an increase in stream depth with resulting loss of the pool/riffle bottom configuration. Annual floodplain modifications caused by stage changes will become less predictable. They may range from no change to effects caused by 100-year flood flows overtopping the banks. Frequently, stream length and available undeveloped floodplain will be reduced severely following bank stabilization. Side channels, chutes, oxbows, and other ancillary waters will cease to exist. Stream width has a marked effect on the abundance and diversity of the macrobenthos. Channel width is affected by the types and amounts of bank vegetation.

CHANNEL CONFIGURATION

Bank stabilization eliminates stream meandering (Yorke 1978). The nature of the bank stabilizing materials will affect the amount of frictional drag at the bank-water interface. Flow in contact with the bank may erode bank materials and will carry such materials downward and inward toward the thalweg in a straight reach. Such materials, at least in part, may be deposited further downstream on the same bank (Cunningham 1937, Hynes 1970). There will be little or no braiding, because stabilized banks preclude stream-widening that leads to locally diminished flow velocity and deposition of easily-worked sediments. As Leopold et al. (1964) have pointed out, braiding is a response by running water to passage through an area of readily eroded bank material and a large suspended sediment load. Without meandering, there will be only limited, or no, deposition of sediments on the floodplain. Such deposition will occur only when the stage exceeds bankfull.

The Task Committee on Channel Stabilization Works (1965) recognized that, in major river systems where channel stabilization works have been used extensively, the design of such works has been based largely on experience due to the complex nature of alluvial streams. Channelization often has caused a reduction in stream length and a change in width. Bulkley (1975) measured the extent of channel configuration modification in Iowa streams with drainage areas greater than 50 square miles (129.5 sq km) by measuring stream sinuosity (the degree of meander). He determined that from 1,000 miles (1,612.9 km) to 3,000 miles (4,838.7 km) of Iowa streams have been lost, since settlers first arrived in the mid-1800's. Nearly 100% of the 1,842 miles (2,971 km) of major streams in Missouri north of the Missouri River have been channelized, resulting in the loss of 103 miles (166.1 km) of river (Congdon 1971). Channelization of the Blackwater River, Johnson County, Missouri, 67 years ago has nearly doubled the gradient causing increased erosion leading to increased channel width and depth, serious bank erosion, and headward erosion of tributary gullies.

Where stream alignment has been changed and the stream shortened due to construction activities, such as bridge construction, a stream channel will tend to seek its hydraulic gradient through erosion and scour. Often, the upstream end of the realigned channel will degrade, while the downstream end aggrades. A possible solution, in small streams carried under a highway, is to place the stream channel on its natural slope upstream and downstream of the structure (Yearke 1971).

Workman (1974) alleviated erosion problems in Prickly Pear Creek, Montana, by installing artificial meanders into a new channel, so as to retain the length of the original channel replaced by a new 3,300 ft (1,006.1 m) channel during construction of Interstate Highway 15. Observations upstream and downstream from the altered channel disclosed no changes in the erosion and deposition patterns outside the study area. Berms were constructed along riprapped and soil-covered banks. Berms and riprap were invaded by native pioneer plant species, the soil was stabilized, and aesthetics were preserved.

Barton and Winger (1973a,b) rehabilitated a channelized reach of the Weber River, Utah. In comparing the profiles of the Weber River bottom in rehabilitated sections vs. unchanged ones, it was found that there were many holes in the rehabilitated sections as there were in unaltered stream reaches. Holes at the ends of structures are desirable for fish habitats, but are worrisome to hydrologists. Any structure extending into, and normal to, the flow will cause the formation of a deep scour hole immediately at, and downstream from, the outer end of the structure. This may cause the undermining and collapse of the structure (Bondurant 1963, Lund 1976). Rehabilitation structures used by Barton and Winger (1973a,b) included those composed of gabions (check dams, wing deflectors, double wing deflectors), rocks (random rock clumps, wing deflectors, check dams), and concrete check dams. A similar procedure, with comparable results, led to fish habitat restoration in the Clark Fork River, Montana (Hunt and Graham 1972).

Protection works, including flexible fence, jacklines, and riprap were recommended for use to reduce stream meandering, flooding, and bank and sheet erosion of agricultural land in the Russian River of California (U.S. Army Engineer District, San Francisco, CE 1972). Bank stabilization measures were recommended for previously modified streams of the Yazoo Basin delta of Mississippi to minimize bank cavings and recession that destroyed agricultural land. At the same time, bank erosion added sediments to unstable river channels that, in turn, resulted in reduced channel dimensions and flow capacities (U.S. Army Engineer District, Vicksburg, CE 1972).

One potential solution for control of floods in streams is to minimize changes in stream channel configuration by use of a specially constructed floodway. For example, in lieu of modifying 18 miles (29 km) of a meandering creek, a 9 mile (14.5 km) floodway was to be constructed in a manner that it would be operational only during flood periods. Most of the time, the grassed channel would carry only local drainage and could serve as pasture (Elliot 1971).

Underground roots from a dense growth of meadow grass and scrub willow provided riprap-like protection of channel banks in floodplain soil in Alberta, Canada (Smith 1976). Such vegetation may be especially useful, where aggrading river channel conditions provide channel-bank soils that must be stabilized and protected rapidly.

Charlton (1972) stated that stretches of streams attain a given channel configuration (straight, meandered, or braided), channel cross-section, and slope on the basis of discharge characteristics and sediment loads. He stressed the necessity of understanding the interrelations of these factors on stream behavior prior to undertaking the construction of training works that will affect the hydraulic geometry of the channel. Lund (1976) and Keller (1975, 1976) emphasized that our understanding of fluvial processes, channel form, and stream biological systems is incomplete. They suggested the use of minimum control to stabilize channels with uniform channel cross-section and gradient toward more natural appearing streams. Keller (1975, 1976) suggested that pools and riffles be included in channel design criteria with an optimal spacing of such structures averaging approximately six times the channel width. After channelization, Tarplee et al. (1971) maintained that near-natural conditions can be restored after approximately 15 years, if there are no further deteriorations of the stream bed, banks, or vegetation cover.

Channel maintenance structures along the Missouri River, such as wing dams and revetments, forced the flowing water to scour a narrow deep channel and to fill the backwater areas with sediment. The sedimentation and loss of variation in the bank configuration were associated with reduced fish standing crop (Groen and Schmulbach 1978). Menzel and Fierstine (1976) found that modified channels of central Iowa streams acted more as travel corridors between favorable habitats than as permanent habitats. They suggested a reduction of negative impacts through construction design of channels with greater habitat diversity.

Undoubtedly, bank protection must accompany channel stabilization. It is necessary to consider streamflow from one stabilized reach to the next to provide functional order without waste, misalignment, and undesirable flow characteristics (U.S. Army Engineer District, Omaha, CE 1973). The sequential effects of channel modification have been summarized by Darnell et al. (1976) and by Karr and Schlosser (1978) as follows:

Cut off of meanders to shorten stream length → Increased stream gradient → Increased flow velocity → Increased unit stream power →

Increased channel erosion downcutting → Increased suspended solids → Habitat degradation load

SUMMARY

Channel configuration changes in conjunction with "improvement" practices have usually caused a reduction in stream length and sinuosity, an increase in gradient and erosion, an increase in channel width (in streams with unstabilized banks) and depth, and headward erosion of existing tributaries. Stream meandering ceases with bank stabilization, and backwaters are lost. Once again, it is suggested that near natural conditions be maintained, including proper alignment, stream meanders, and a bottom alternating pool/riffle sequence without loss of stream length and increase in hydraulic gradient. Bank stabilization using vegetation plantings has been successful.

WATER CURRENT VELOCITY

Bank stabilization will probably cause the channel to narrow and deepen, resulting in more uniform and rapid velocities (Yorke 1978). When discharges are of equal frequency at different points along a stream (i.e., equalled or exceeded the same percent of time), the velocity and depth of flow (if the stream is contained within stabilized banks) increases with discharge downstream (Leopold and Maddock 1953). This is because the increase in depth overcompensates for the decrease in slope. The tendency for velocity to increase downstream exists in most streams despite the decreasing particle size downstream. Stream depth and velocity (as well as width in streams without stabilized banks) are all functions of the load transported in the channel.

The mean rate of flow is related to discharge as well as to the stream width and depth and the roughness of the bottom and banks (Hynes 1970). Even in times of flood, the velocity rarely exceeds 300 cm/sec (Einsele 1960). Above approximately 200 cm/sec, most streams enlarge their beds by erosion, unless they have banks protected by rock or other human-made structures. At speeds in excess of 300 cm/sec, air resistance begins to play a significant role. Although free-falling water does not normally exceed 600 cm/sec, flowing water may exceed this speed because it is physically contained in a channel. Leopold et al. (1964) state that a velocity of 660 cm/sec was measured in a rock gorge of the Potomac River near Washington during a flood, and that speeds up to 810 cm/sec are known.

Theoretically, the mean velocity of water in a channel is proportional to the square root of the product of the hydraulic radius and the slope:

$$v = c\sqrt{Rs},$$

where

- v = mean velocity
- c = a constant
- R = the hydraulic radius (cross-sectional area divided by the length of the wetted perimeter)
- s = the slope (effectively that of the water surface)

The constant, c, varies with the roughness (resistance to flow) of the streambed and stabilized bank and is related to depth. Overcoming the resistance to flow represents a loss of energy from the system, and there is a shear stress exerted by the water on the banks and streambed (Leopold et al. 1964).

Pennak (1971) has suggested that the current velocity for a stream should be derived from measurements taken during the ten driest months of the year. Spring runoff data can badly distort estimates of the mean annual velocity. If only a single velocity measurement is taken, it should be measured at midstream 0.6 of the way down from the surface to the bottom; such measurements may be difficult under field conditions. According to Pennak, a current slower than 14 cm/s (about 0.3 mph) is "sluggish" or "imperceptible". From 14 to 70 cm/s (0.3-1.5 mph) the current is "slow". From 70 to 140 cm/s (1.5-about 3.0 mph) the current is "moderate", while from 140 to 280 cm/s (3-6 mph) it is "in flood" or "fast". Anything in excess of 280 cm/s is "swift" to "torrential".

Campbell (1966) emphasized the need for field and laboratory studies prior to design of riprap-stabilized banks, since no single specification for riprap can cover all design instances. Good field data are essential for both curved and straight reaches. Measurements must include a vertical velocity profile of at least seven sequential velocity observations in a single vertical plane. More observations are needed on bends than in straight reaches. Knowledge of the velocity profile near the substrate can be expected to yield a reasonable average velocity acting on the rock. Rock size, in turn, affects the velocity distribution. If banks are vegetated, the current velocity may be reduced at the bank-water surface contact (Parsons 1963).

Bank erosion does occur in low-velocity streams (less than 1 m/sec). Such erosion in navigable rivers with clay, silt, and/or sand banks is due primarily to wave action (Fuquay 1972). Bank protection should be applied with end sections at right angles to streamflow, where adjacent materials are erodable. Experiences with wide, low-gradient and low-velocity streams, such as the Allegheny, Monongahela, and the upper Ohio Rivers, were cited to substantiate a predictable pattern of bank erosion and corrective measures needed.

In Iowa streams, Witten and Bulkley (1975) and Bulkley et al. (1976) found that permeable jetties and retards influenced stream depth, but they did not affect the velocity appreciably. In a Pennsylvania trout stream, Bradt (1974) and Bradt and Wieland (1978) observed that gabions narrowed the streambed and deepened the channel, so that current velocity increased in the unrestricted channel. In the summer when high water temperatures can be critical, the increased flow velocity and depth prevented the stream from becoming too warm.

Stevens et al. (1976) developed a numerical index for safety factors in given riprap designs. The value was based on the ratio of moments resisting particle movements to moments tending to rotate the particle out of the riprap blanket. From theoretical considerations, a relationship was established between the riprap safety factor and the magnitude and direction of the flow velocity in the vicinity of the riprap, the angle of the side slope, and the angle of repose for the riprap.

In their studies of four channelized North Carolina coastal plain streams, Kuenzler et al. (1977) found that the logarithm of stream flow was negatively correlated (.01 level, or less) with water temperature. Similarly, the concentration of many soluble constituents of the water in all four streams were negatively correlated with log-flow.

McMahon et al. (1972) studied the macrobenthos of channelized and unchannelized sections of the Missouri River in Iowa and South Dakota. The Chironomid midge (Diptera) density was 4.5 times greater in the main channel of the unchannelized section at Vermillion, South Dakota, than in the channelized Iowa section. This was due probably to stronger currents in the channelized section than in the unchannelized one.

SUMMARY

Rates of flow are related to stream discharge, hydraulic radius, roughness of stream banks and bottom, and slope. Bank stabilization will cause the channel to narrow and deepen, coupled with a tendency toward uniform water velocities at a given point and increases in discharge downstream, because the increase in depth overcompensates for the decrease in slope. Velocity and depth are both functions of load transported in the channel. Velocity affects most other water quality physical and chemical constituents.

WATER TEMPERATURE

Temperatures of flowing streams and rivers vary far more rapidly than do those of lakes, but this variation is often over a much smaller range than that of, at least, shallower parts of still waters (Hynes 1970). Installation of riprap or other forms of streambank stabilization requires the removal of streambank vegetation from at least one side, and usually both sides, of a stream. In addition, floodplain vegetation must be removed to permit access for heavy equipment. The impacts of insolation and winds will increase, causing greater variations in stream temperatures. Such impacts may be prolonged, because bank protection maintenance practices may preclude the reestablishment of overstory, and some bank and floodplain vegetation (Yorke 1978). Diurnal temperature changes, in the absence of tree cover, range from 6°C, in small streams in summer, to lower values in larger streams and rivers (Edington 1966). Temperature maxima occur generally in the afternoon, and minima between midnight and dawn.

In small streams, the deeper the water, the less is the daily variation caused primarily by radiation of heat to and from the water (Hynes 1970). Gabions placed in a Pennsylvania trout stream caused the stream channel to narrow and deepen, resulting in a cooler stream in summer (Bradt 1974, Bradt and Wieland 1978).

Pennak (1971) considered both summer maximum and winter minimum stream temperatures as important indicators for the presence and success of the biota, since they may be limiting factors. The summer maximum temperature distinguishes, although crudely, warm-water, and cold-water faunas. The separation also corresponds to differences in latitude and altitude of streams. Those having summer temperatures in excess of 30°C are chiefly tropical, subtropical, or warm-temperate. Those remaining below 5°C are high altitude or artic streams. The vast majority of streams in mountains and at latitudes above 35°C have winter minimum temperatures below 5°C. Even though ice may form for only one to several days per winter, the minimum must be considered to be 0°C.

In flowing streams, where water is well mixed, the temperature is more or less homogeneous throughout (Hynes 1970). In Iowa streams with stabilizing structures, water temperatures in control, structure, and below-structure areas were fairly uniform (Witten and Bulkley 1975). The greatest measured difference in temperature between control and structure areas was 5°C, at a revetment on the West Nishnabotna River. At the control area, however, the river was just emerging from a shaded stretch with wooded banks. In the structure area, there was little or no shade. Where stream water is not well mixed, insolation causes an increase in water temperature with passage downstream. This was the case in Crow Creek, Tennessee and Alabama (Winger et al. 1976).

Shade is effective in reducing high water temperatures and diminishing diurnal temperature fluctuations. Weekly maximum temperatures in cropland ranged from 5.0°C to 12.8°C (average of 4.6°C) above those of a nearby forested stream. Temperatures of a forested stream during the coldest month (February) ranged as high as 3.9°C above an unsheltered farm stream. Summer water temperatures for a stream inside a small woodlot (19°C) were much lower than those in a nearby unshaded area (28°C) (Karr and Schlosser 1978).

Rows of trees were used along canal banks in northwest Germany to control water weeds. The shade reduced stream temperatures as well as available sunlight (Christensen 1976). Shelterbelt tree species were planted, for the most part on only one side of the canal to allow access for maintenance. Even better results were obtained, when trees were planted on both sides of the canal. Bank erosion, and the need for edge mowing, were greatly reduced by tree plantings.

Channelized and unchannelized reaches of the Little Sioux River, Iowa, were studied between 1969 and 1971 by Hansen (1971). Stream channels were meandering and nonuniform, with a heavy vegetative cover in the unchannelized section, and relatively straight, of uniform depth, and without vegetation cover in the channelized sections. The channelized sections had rock riprap in certain sections. Diurnal fluctuations of water temperatures in July were greater, maximum daily water temperatures averaged 1.3°C higher, and mean daily water temperatures were 0.3°C higher in the channelized section, than were those in the unchannelized one.

Stream channelization in the Buena Vista Marsh in Wisconsin reduced instream cover and increased water temperature. Recommendations to alleviate the problems included maintenance of bank vegetation and installation of bank structures to encourage meandering and pool formation. These, in turn, provide conditions that will promote the growth of overhanging vegetational cover (Headrick 1976).

SUMMARY

Temperatures of streams and rivers vary far more rapidly than do those of standing waters, but the range of variation is often less. Impacts of wind and insolation, often themselves related to bank vegetation cover, affect stream temperatures materially. Both summer maximum and winter minimum temperatures are important limiting factors for the biota.

SUSPENDED SOLIDS

Streams and rivers are normally considerably more turbid than are still waters. In the Midwest, small streams are slightly turbid, even at times of low discharge (Striffler 1963, Hynes 1970). Bank stabilization activities cause a temporary increase in suspended solids load and sedimentation downstream from construction activities (U.S. Army Engineer District, Vicksburg, CE 1972; Barton and Winger 1973b; U.S. Army Engineer District, Omaha, CE 1973; U.S. Army Engineer District, Louisville, CE 1974; U.S. Army Engineer District, Portland, CE 1976), but long-term effects of stabilization usually include a decrease in suspended solids load and of sedimentation problems (Hansen 1968, Arner et al. 1976, Barton 1977, Yorke 1978).

Fivemile and Muddy Creeks, Wyoming, were analyzed to determine a comprehensive plan for bank stabilization. Dramatic reductions in sediment eroded from banks were achieved. In 1952, there were 2,000,000 tons of sediment measured at a gaging station near the mouth of Fivemile Creek, while the sediment discharge after bank stabilization in 1961 was 200,000 tons. In Muddy Creek, the measured sediment load was reduced from an annual average of more than 550,000 tons for the period 1950-1953 to approximately 60,000 tons during 1961. These data are particularly significant, since the average annual discharge increased following initiation of control measures (Miller and Borland 1963).

Mean turbidity can be calculated by averaging data from the ten months of a year in which the water is clearest. Data taken during spring runoff should not be used (Toronto 1973). Pennak (1971) suggested the following turbidity ranges (in ppm Fuller's Earth) and general equivalent terms: exceptionally clear -- less than 10 ppm; clear -- 11 to 50 ppm; slightly turbid -- 51 to 100 ppm; turbid -- 101 to 500 ppm; and highly turbid -- more than 500 ppm.

Stream channels are in delicate balance with their water discharges and sediment loads. Darnell et al. (1976) stated that construction activities, such as bank protection, are attended by an identifiable suite of physical and chemical alterations of the environment that may extend many kilometers from the site of the alteration. In turn, each physical or chemical modification has been shown to induce a set of biological effects, many of which are predictable, at least in general detail. The second most damaging effect of wetland construction activities is the addition of suspended solids to area waters. (The most important effect is direct habitat loss.) In a study of Arkansas streams, Dale (1975) found a high positive correlation between turbidity values and the channel "improvement" projects.

Karr and Gorman (1975) found that clearing and modification of streambanks to "beautify" a section of stream may result in significant negative effects, because unmodified streams often are in a dynamic equilibrium state with terrestrial environments. Accelerated erosion and bank slippage are frequent consequences of poorly planned bank modifications. In streams with severe bank erosion problems, Apmann and Otis (1965) suggest that bank revetments be founded deeply in the stream bed, so that erosion will not undermine the work. Armoring revetment placed on stream banks will reduce the sediment supply. This will, in turn, cause increasing bed erosion and degradation, requiring that the revetment toe be placed deep in the existing channel bed.

In a comparative study of channelized and unchannelized reaches of the Little Sioux River, a turbid warmwater Iowa stream, rock riprap prevented bank and channel erosion in certain channelized sections. In several other areas, the banks became irregular and the channel widened due to bank erosion, partly due to the lack of heavily rooted vegetation. Consistently higher turbidities were measured in the channelized section during low runoff, averaging 31.2% higher than those in the unchannelized section (Hansen 1971). Bank stabilization measures carried out in conjunction with channelization were inadequate.

Brusven et al. (1974) developed a model design for the physical and biotic rehabilitation of a silted stream by use of instream sediment-flushing devices. Working in Emerald Creek, a tributary of the St. Maries River of northern Idaho, log drop structures and two types of channel constrictors, rock-filled gabions and log dikes, were constructed. Instream alterations increased sediment transport and flushed fine sediments from both runs and pools. Insect community changes were most pronounced at gabion sites. Channel alterations led to increases in both insect diversity and standing crop.

Many workers (Byers 1962, Witten and Bulkley 1975) believed that structures that reduce current velocity and induce siltation, such as retards and jetties, could also be expected to reduce stream turbidity. However, Witten and Bulkley (1975) failed to find important differences in turbidity between structure and control areas in their studies of Iowa streams. Exceptionally high turbidity was present on one occasion at a retard site on the West Nishnabotna River, but samples were taken during rising water just after a rain storm.

High turbidities were recorded by Dorris et al. (1963) in the "improved" middle Mississippi River during periods of high discharge, with low turbidities during periods of low discharge. Not only the magnitude, but also the frequency of precipitation events that affect discharge, are important in relation to erosion-caused turbidity. Irregularly distributed rainfall occurring in storms of high intensity and short duration fails to ensure sufficient groundwater to support the growth of bank-stabilizing vegetation (Hansen 1971). At the same time, precipitation is effective in eroding the soil, especially in the Midwest (Douglas 1967). Banks stabilized with vegetation, such as willows, may be eroded with the resultant undermining of even well established trees that fall into the stream to form obstructions that cause flow variations (Drummond 1972).

Weller (1970) and Kumra et al. (1972) detailed the complex problem of bank erosion occuring in the Brahmaputra River, India. During the flood season, shoals form along the banks of the river because suspended sediments in the flood waters are in excess of the transport capacity of the river. These shoals subsequently divert flows into the bank resulting in increased erosion.

Bank material mineralogical properties can affect stabilization (New York 1971). Alluvial bank materials from nine unstable and six stable reaches of the Washita River, Oklahoma, showed little variation in physical and mineralogical properties. Sand-sized grains from stable areas were less rounded than grains from unstable ones. This angular shape may have produced an inter-locking between them to add stability to the bank material. Also, a clay coating on the sand-sized grains may have produced cementation adding to stability (Goss 1973).

In Black Creek, Indiana, 80% or more of the total tons of stream bank eroded were produced by two soil types, Eel 59.4% and Shoals 25.1%. Yet, these soils account for only 18.7% and 7.2%, respectively, of the total miles of streambank. A particle analysis of streams with bank erosion that causes turbidity may pinpoint problem areas in need of stabilization and reduce the necessity of protection for those reaches that do not need it. Not only physical properties, but also chemical properties of fine sediments, should be examined (Grissinger and McDowell 1970). Fine-grained sediments tend to modify the dissolved and suspended chemical load.

SUMMARY

Flowing waters are normally more turbid than still ones. Turbidity is increased temporarily by bank stabilization activities, but long-term effects of stabilization usually include a decrease in suspended solids load and a lessening of sedimentation problems. Armoring revetment used to stabilize banks will reduce the sediment supply. This will, in turn, enhance bed erosion and degradation that may undermine the revetment toe, unless the toe is placed deep in the original channel bed. By varying the flow regime as a consequence of bank stabilization, alterations occur in instream sediment quantity and particle size. Precipitation frequency and abundance, as well as bank material mineralogical properties, can affect erosion, suspended solids loads, and bank stabilization efforts.

BED MATERIALS, INCLUDING BEDLOAD

Pennak (1971) stated that no single factor is of greater biological significance than the physical nature of the substrate. He classified lotic substrates on the basis of particle size into five categories: (1) "rubble" (or "cobble") is composed of particles from 1 to 9 inches (2.5 to 22.5 cm) in diameter. Most "rubble" sections of a stream usually contain boulders and are described as "rubble and boulders" sections; (2) "gravels" are 2.1 to 2.4 mm in diameter; (3) "sand" particles range from 0.55 to 2 mm; (4) "silt" particles range from 0.004 to 0.55 mm. A silt substrate should be designated as either organic or inorganic, as the biotas and physical features are different; and (5) "clay" with or without "coarse organic debris" contains particles less than 0.004 mm in diameter. Such substrates are rarely composed of clay particles alone, but are compacted into "hardpan" -- a substrate with no interstices of biological significance. "Coarse organic debris" consists primarily of bits of dead allochthonous vegetation that will not pass through a 20-mesh sieve (0.84 mm aperature). Each lotic habitat is a mixture of particle types, but a stream section can usually be characterized in accordance with the dominant item forming the substrate.

The greater the velocity of the current, the larger the particle it can move. The larger particles can then protect smaller ones from being entrained. Silts are not major components of lowland reaches of stabilized streams except as thin temporary sheets over sand during periods of low flow. Silts are not major components of substrata in main channels of the majority of even base-level streams (Hynes 1970).

In a stream with stabilized banks, lateral channel movements will not occur, and channel adjustments will be made by downcutting. The bedload may increase (Yorke 1978). According to Apmann and Otis (1965), significant amounts of armoring revetment placed on streambanks would reduce the sediment supply, thereby increasing bed erosion and degradation and requiring the revetment toe to be placed deep in the existing channel bed. Arner et al. (1976) studied the Luxapalila River, Mississippi, and observed that sediments of the streambed in the unchannelized segment were larger than those in old or newly channelized reaches.

Dam construction often affects both channel and banks by changing the energy relationships previously inherent in the discharge. Problems often encountered include degradation of channels below dams and aggradation of channels above reservoirs leading to flooding and channel instability.

In the lower Colorado River below Davis Dam, clear water that carried almost no suspended load attacked the riverbed and banks, picking up a new load of sediment, until the well-graded bottom sediments developed a gravel armor by erosive plucking of the fine particles. The armored bottom was relatively stable, and consequently the river had erosive energy to dissipate in an attack on the banks. To correct problems caused by such attacks, stabilization measures were instituted that included dredging of the channel, placement of riprap on the banks, and construction of levees (Freeland 1972).

Construction of thousands of miles of new roads nationwide (Bullard 1963), and extensive use of bulldozers on steep slopes and in stream channels during road building and stream "improvement" during debris removal in northern California (Burns 1972) have caused excessive sedimentation in beds of narrow streams. Channelization of the lower 0.5 mile (0.81 km) of Big Beef Creek in Washington was carried out using heavy equipment to narrow and straighten the stream channel, ostensibly to improve salmon and trout spawning and rearing and for flood control. Artificial dikes within the channelized area were made of streambed gravels, and underwent much erosion during high flow periods. Two years after stream channelization, 54% (2,987 cubic meters) of the sediments deposited in the channelized area came from erosion of these dikes coupled with streambed degradation within the channelized area. Due to a greatly increased streambed slope and confining of flow by the dikes, the streambed had high rates of scour and fill (Cederholm 1972).

Bed sills were useful in stabilizing a high-gradient trout stream subject to severe headcutting. Gabions were installed in 1967 in Enfield Creek, New York. They were effective immediately in arresting headcutting and in accumulating gravel. The gabion sills had a definite stabilizing effect for almost 0.8 mile (1.3 km) downstream below the installation (Jackson 1974). In Black Creek, Indiana, rock drop structures were particularly useful in stabilizing the channel and banks (Lake and Morrison 1977). The structures decreased channel bottom erosion that caused the formation of unstable banks.

Another useful technique is bank fencing. Four miles (6.5 km) were fenced along the channel of Camp Creek, a tributary of the Crooked River, in central Oregon. Native riparian vegetation cover became well established, in turn affecting soil deposition and channel stabilization. The vegetation retained much of the suspended solids formerly carried by the flow. The sediments accumulated on the stream bottom and raised the water table within the protected channel. Within nine years, 36 inches (91.4 cm) of material had been deposited between the vegetated bank and the stony stream bed. This process buried the vegetation. Plants then regrew, and the process repeated itself to establish bankside meadow (Winegar 1977).

Cummins (1962) has recommended that materials be quantified using a modified Wentworth scale of particle size with the recording of data on the linear phi-scale (phi = the negative logarithm to the base 2 of the smallest particle in each size group). In samples made up of coarse materials exceeding 4 mm in diameter, Leopold et al. (1964) advocated the simpler technique of picking up and measuring 100 items located on a grid.

Most biologists have been descriptive, rather than quantitative, concerning the nature of the substrates with which benthic animals have been associated. Gore and Coyle (1978) compared benthic samples taken in 1978 with those collected prior to channelization (in 1942) from Rattlesnake Creek, Montana. Insect dominance changed from mayflies to Chironomid midges (Diptera) in unchannelized vs. channelized sections. The reason seemed to be the result of an increase in substrate particle size resulting from the falling into the stream of large bouldered embankments in the channelized portions. In streams of Champaign County, Illinois, canalization over the thirty years preceding 1959 tended to cause streams to decrease in gravel substrate, with attendant increases in silt and sand substrates (Larimore and Smith 1963, Smith 1968).

SUMMARY

There is a need to quantify, rather than simply to describe, stream bed and bank materials. In stabilized streams, downcutting of the channel may cause an increase in bedload. Swift flows will carry large particles, that will, in turn, prevent smaller ones from being entrained. Construction activities are often detrimental. Problems result directly from the use of large pieces of earth-moving equipment in bed and bank preparation, and indirectly when dam construction affects discharge energy relationships downstream.

DISSOLVED SUBSTANCES

The chemical content of running waters varies regionally and reflects local geography, climate, and human activities (edaphic factors). Rain containing salts and gases and dust containing inorganic and organic matter contribute to the water quality. Usually, much water enters streams as subsurface groundwater flow. Only when there is heavy precipitation or considerable snow melt does a large proportion enter as surface runoff. As a result, there is a fairly clear inverse relationship between temporal variation in discharge and the concentration of dissolved salts in the water (Hynes 1970).

In most stabilized streams, turbulent mixing ensures a uniform distribution of dissolved substances. In stream channels with tributaries, inflowing water tends to follow the bank on which it entered. However, rivers with stablized banks have often been channelized too, and tributary inflows have been altered. If stabilized streams undergo channel degradation, the downcut channel may receive large amounts of groundwater moving more or less laterally through pervious banks to enter the channel. Such flow is often almost or totally devoid of dissolved oxygen and contains large amounts of carbon dioxide, due to its exposure to organic matter and bacterial respiration in the soil (Hynes 1970). Removing streambank vegetation and preparing the banks for protective construction may release organic matter that may increase the biochemical oxygen demand and cause a decline in oxygen concentration downstream (Karr and Schlosser 1978, Yorke 1978).

Streams with stabilized banks often will have a wider range of discharges due to containment of flow in the armored channel, than would unchannelized streams in which the channel may widen during high stages, or streams in which high flows readily overtop banks to cover a floodplain. In the stabilized Mississippi River near Quincy, Illinois, periods of high stream discharge were accompanied by increased carbon dioxide and decreased dissolved oxygen contents (Dorris et al. 1963). In a Pennsylvania trout stream, gabions were placed to narrow the stream channel. This caused an increase in flow velocity, a lowered temperature, and increases in dissolved oxygen, total alkalinity, and specific conductance. The orthophosphate content decreased (Bradt 1974, Bradt and Wieland 1978).

In unchannelized coastal plain streams of North Carolina, the dissolved oxygen content varied seasonally. In channelized streams, it was high and relatively constant. With few exceptions, channelized streams had dissolved oxygen levels above 6 ppm throughout the year. All streams had levels ranging between 5-10 ppm dissolved oxygen per liter during cool seasons, but natural streams often had much lower dissolved oxygen levels in summer than in winter (Kuenzler et al. 1977).

In streams of the Village Creek Basin, Arkansas, a water quality comparison was made between unchannelized streams, channelized streams, and streams in which clearing was done on one side only. There was no correlation between water quality elements and channelization projects varying in age from two to more than fifty years old. However, there was a correlation between turbidity and dissolved oxygen values (Dale 1975). In six central Iowa streams subjected to short-reach channelization (151 to 429 m), there was no evidence that turbidity or dissolved oxygen concentrations differed in an upstream reach above the channelized area, or downstream below the channelized area (King and Carlander 1976).

During studies of the Weber River, Utah, Winger (1972) observed little difference in water chemistry above and below a stream section altered by channelization and modified to mimic the original stream by the addition of gabions and rock deflectors to form pools and riffles. The sole exceptions were elevated sulfate and phosphate values during the autumn of 1968 below the channelized reach.

In 1972, the U.S. Geological Survey began a pilot program of river quality assessments. The two objectives of the program were (1) to define existing problems and (2) to develop water quality information to provide a sound technical basis for assessing river quality problems and evaluating management alternatives. In a pilot assessment of the Willamette River basin, Oregon, the most important finding was that across-the-board advanced waste treatment was not the answer to the problem of meeting stringent water quality standards established for the river. The assessment also showed that existing water quality data generally are inadequate for defining critical cause-effect relationships that control river quality problems. Intensive synoptic surveys keyed to local problems and conditions are required in most river basins to develop an adequate information base for managing important river quality problems (Greeson et al. 1977).

SUMMARY

In most stabilized streams, turbulent mixing ensures a uniform distribution of dissolved substances. If stabilized streams undergo channel degradation, the downcut channel may receive larger quantities of groundwater moving more or less laterally through pervious banks to enter the channel. Such flow is often devoid of dissolved oxygen and contains much carbon dioxide. Streambank vegetation removal or bank preparation for stabilization may release organic matter that may increase the biochemical oxygen demand and cause an oxygen sag downstream. The water quality of a stream is often affected primarily or secondarily by bank stabilization activities.

LIGHT TRANSMISSIVITY

Flowing waters are generally more turbid than are still ones. The "muddy" Mississippi or Missouri Rivers or the "white" Nile River derive their names from persistent suspended solids loads that reduce the distance that light will travel in water (Hynes 1970). Light penetration is also reduced by shelterbelt plantings, because the intensity of light striking the water surface is reduced and bank shelter belts reduce surface ripples caused by wind. Light reflected from the water surface increases with increasing angle of incidence, and hence depends upon the latitude and the time of day. At large angles, however, this applies less to a ruffled surface than to a smooth one, and hence less to turbulent flow than to still water. Thus, wind-ruffling at the water surface allows more light to penetrate early and late in the day (Hynes 1970).

Bank protection construction activities frequently cause temporary increases in bank erosion and suspended solids load and an accompanying decrease in light transmissivity. However, the long-term impact of bank stabilization will be a reduction in bank erosion and an attendant increase in light transmissivity (Yorke 1978).

Installation of bank protection materials often entails removal of plants that grow on the bank and shade the stream. Removal of bank plants increases insolation and light transmission in the stream. In a Pennsylvania trout stream subjected to channel and bank modifications, including removal of bank cover, increased photosynthetic activity contributed to increases in dissolved oxygen content and oxygen saturation (Bradt and Wieland 1978). However, the authors recommended restoration of bank cover and overstream shade to reduce bank erosion and stream temperatures in summer. Christensen (1976) recommended tree plantings along canals to control growth of water weeds by reducing insolation. Dorris et al. (1963), in their study of the Mississippi River, found a high positive correlation between discharge and turbidity and photosynthetic activity.

SUMMARY

Flowing waters have generally characteristic levels of turbidity and light transmissivity. Bankside vegetation protects stream surfaces from wind-ruffling, thus decreasing early morning and late afternoon light penetration. Bank stabilization techniques often entail removal of bankside vegetation leading to increased insolation and light transmission, enhanced photosynthetic activity, and higher summer water temperatures. Bank construction activities adversely affect transmission of light by increasing erosion, but the long term effects of bank stabilization are to increase penetration of light.

FLOW VARIABILITY

Stream discharge is usually irregular, but many rivers do shown an annual mean pattern of flow that is related to climate. High floods are infrequent, but their detrimental effects may be great, and the periods during which rivers work on their banks and beds (about 0.75-1 bankfull) are short. Characteristically, bankfull flow is equalled or exceeded about once every 1.5 years. The mean annual flow is equalled or exceeded only about 25 percent of the time (Leopold et al. 1964, Hynes 1970, Popkin 1974, Williams 1975, Winger et al. 1976). Flows of smaller streams are far less stable than are larger ones. Larger rivers represent a summation of many minor local variations in discharge, and tend toward greater regularity of discharge than do smaller streams.

Dam construction on many streams and rivers has altered the stream flow regime and sediment discharge pattern. Many, if not most, of the rivers and streams of the world have had their flow regimes altered by human pressures. In America much of the alteration has occurred during the past 200 years.

Seasonal variation in erosion of the sinuous channel of Watts Branch, Maryland, was documented by Wolman (1959). The banks, comprised primarily of cohesive silt, underwent as much as 7 ft. (2.1 m) of lateral erosion during a five-year period (1953-1957). Approximately 85% of the observed erosion occurred during the months of December through March. As much as 0.4 ft (12.2 cm) of sediment was eroded at specific bank points in a period of several hours during which a bankfull of flow attacked banks that had been wetted thoroughly. Erosion was most severe at the water surface. Little or no erosion occurred in summer, despite the occurrence of the highest flood on record. Second in erosion effectiveness were cold periods during which wet banks, frost action, and low rises in stage combined to produce 0.6 ft (18.3 cm) of erosion in six weeks during the winter of 1955-1956. In addition, some erosion was produced by flash floods even on hard dry banks.

The clearance of riparian forest for bank protection construction and development, inevitably alters the pattern of stream discharges. Forests reduce the total volume of groundwater reaching a stream by evaporation and transpiration from the vegetation. At the same time, forests reduce immediate storm runoff and tend to maintain moist soils that usually result in more steady streamflows (Karr and Gorman 1975).

The amount and location of bank erosion along the Bollin-Dean an English stream with cohesive banks, were related to discharge and to current velocity. The effectiveness of the erosion-producing discharges was a function, not only of their magnitude, but also of their variability characteristics, which affected bank erodibility, and of the degree of asymmetry in the distribution of velocity. The rapidity of bank erosion could be attributed to a surprisingly wide range of flows and to the flashiness in the stream's regime (Knighton 1973). In streams that exhibit such flashiness in their regimes, channel downcutting may occur. This could, in turn, induce discharge from the groundwater table into the stream, leading to a reduction in streamflow during dry periods (Yorke 1978).

Heavy rains eroded sand and clay banks of Michigan's Pine River, and the silt load destroyed trout habitat and food organisms. Taube (1967) recommended the placement of effective deflectors, riprapping of the bases of steep cliffs with rocks, and planting of vegetation to augment natural seeding as means of reducing erosion. Posey (1957, 1973) refined a stabilization tool in the form of rock sausages. These wire-bound rocks can withstand inundation and high-velocity flows. If washed out by unexpectedly heavy flows, sausages can be salvaged and used in rebuilding, conserving rock, if it is scarce, and reducing costs.

In both natural and channelized North Carolina streams, measurements of water quality during one winter high discharge period showed that peak concentrations of ammonia-nitrogen, nitrate-nitrogen, filterable reactive phosphorus, particulate phosphorus, turbidity, and particulate silicon, aluminum, and iron usually occurred 1-2 days before maximal discharge (Kuenzler et al. 1977).

Bank protection measures, to be effective, must be designed to resist the effects of rapid stage change, bank saturation with water, and bank freeze-thaw cycles. In the Eel River, California, rock riprap and wire mattress were used to protect a stream with banks comprised of alluvial silt. Highwater spring discharges reached 300,000 sec-ft (91,463.4 sec-m), and the stream rose 30-35 ft (9.2-10.7 m) above the low-water stage (Tilton 1943). In Utah, where bank erosion was due to poor management and denudation of upstream watersheds, poor farming practices along streams, and poor stream channel management, Felker (1946) pointed out the need to keep irrigation ditches away from streambanks to preclude their saturation by irrigation water leading to bank collapse.

Steinberg (1966) evaluated bank stabilization works designed to halt erosion along a reach of California's Russian River. The Russian River rises and falls rapidly. The channel capacity is 20,000 cfs (566,000 liters/sec), and flood peaks reach 46,000 cfs (1,301,800 liters/sec). Works tested successfully included flexible fence, jacks, wire mesh and gravel blanket, willow pendants, belt planting, and check dams. Modular jacks placed in the river were considered hazardous to boaters (U.S. Army Engineer District, San Francisco, CE 1972). However, such criticism was deemed unjustified. Problems arose when jacks, placed by local interests, broke loose and rolled into the channel.

Bank stabilization test installations were designed using discarded tire and fiber mat techniques as alternatives to rock in Cottonwood Creek, California (U.S. Army Engineer District, Sacramento, CE 1971-1974). Creek flows varied from 50 cfs (1,415 liters/sec) in summer to a standard project floodflow of about 130,000 cfs (3,679,000 liters/sec). A 550-ft long (167.7 m) site was prepared using 250 linear ft (76.2 linear m) of discarded tires banded together with metal straps and about 300 ft (91.5 m) of fiber matting, with both groups of materials being anchored to the slope. Winter flood flows in 1973 of 23,000 cfs and 24,000 cfs (650,000 liters/sec and 679,000 liters/sec) did no significant damage to either type of material. A winter flood of 66,000 cfs (1,867,800 liters/sec) in 1974 damaged both types of protection. The tire bank was damaged for about 90 ft (27.4 m) of its reach, probably due to undermining of the tire band at its upstream end. About 210 ft (64.0 m) of the fiber mat was destroyed. Flood flows may have overtopped the levee about 40 ft (12.2 m) upstream from the downstream end of the matting test site initiating damage and the subsequent failure of the fiber mats.

SUMMARY

Removal of bankside and floodplain vegetation increases post-storm immediate runoff. This may exaggerate the irregular discharge patterns that characterize most streams, especially smaller ones. Bank protection measures, to be effective, must be designed to resist the effects of rapid stage change, bank saturation with water, and bank freeze-thaw cycles. In streams that have flashy flow regimes, channel downcutting may occur, expecially if banks are stabilized. This could, in turn, induce discharge from the groundwater table into the stream, leading to a reduction in streamflow during dry periods.

CONCLUSIONS AND RECOMMENDATIONS

Flowing waters with stabilized banks are dynamic systems that are frequently unstable morphologically and biologically, and are unpleasing aesthetically (Nunnally 1978). Stabilized channels respond to any alterations in bank or channel geometry and flow regime, such as depth, and stage, or sediment transport. When one variable changes, one or more additional variables, in turn, respond to that change and are themselves altered (Richardson and Simons 1976).

When a streambank is modified locally, banks above and below the modified reach exhibit responses observable over long distances. Energy that is no longer dissipated in eroding a newly riprapped bank will be transferred to an unprotected reach elsewhere. Piecemeal application of riprap may provide a short-run solution to an obvious problem, but may intensify long-run problems.

It is imperative that stream workers not only be aware of geologic, hydrologic, and geometric characteristics of a stream, but also that there be a continuous dialog between workers with differing orientations, such as biologists, chemists, engineers, geologists, hydrologists, and planners. The present approach to bank stabilization, and to stream modification generally, is to modify the stream minimally. Any modifications made should mimic natural configurations. The resilience (i.e. the degree, manner, and pace of restoration of the ecosystem after disturbance) of a modified stream will determine its ability to conform to those criteria established by its modifiers (Westman 1978).

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50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. FWS/OBS-80/11	2.	3. Recipient's Accession No.

4. Title and Subtitle Effects of Bank Stabilization on the Physical and Chemical Characteristics of Streams and Small Rivers: A Synthesis	5. Report Date July 1980 6.
7. Author(s) Daniel H. Stern and Michele S. Stern	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Department of Biology Univ. of Missouri-Kansas City Kansas City, MO 64110 MO Institute of River Studies Univ. of Missouri-Rolla Rolla, MO 65401	10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) 14-16-0009-78-035 (G)
12. Sponsoring Organization Name and Address Eastern Energy & Land Use Team, Office of Biological Services Fish and Wildlife Service, US Dept. of the Interior, Route 3, Box 44, Kearneysville, WV 25430	13. Type of Report & Period Covered Final report 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report is a synthesis of available literature relating the effects of bank stabilization to the physical and chemical characteristics of streams. A companion document contains the references to the literature which formed the basis for the synthesis. The synthesis provides guidelines for planning bank protection and stabilization activities.

17. Document Analysis a. Descriptors

Stream Stabilization, Stream Improvement, Stream Erosion, Environmental Effects, Aquatic Habitats, Bank Protection, Bank Stability, Channel Morphology, Channel Improvement

b. Identifiers/Open-Ended Terms

Streambank Stabilization, Water Resource planning, Riparian Vegetation, Riprapping

c. COSATI Field/Group 48G, 57H

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release unlimited	Unclassified	50
	20. Security Class (This Page) Unclassified	22. Price

(See ANSI-Z39.18)

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

GPO : 1980 O - 328-286

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