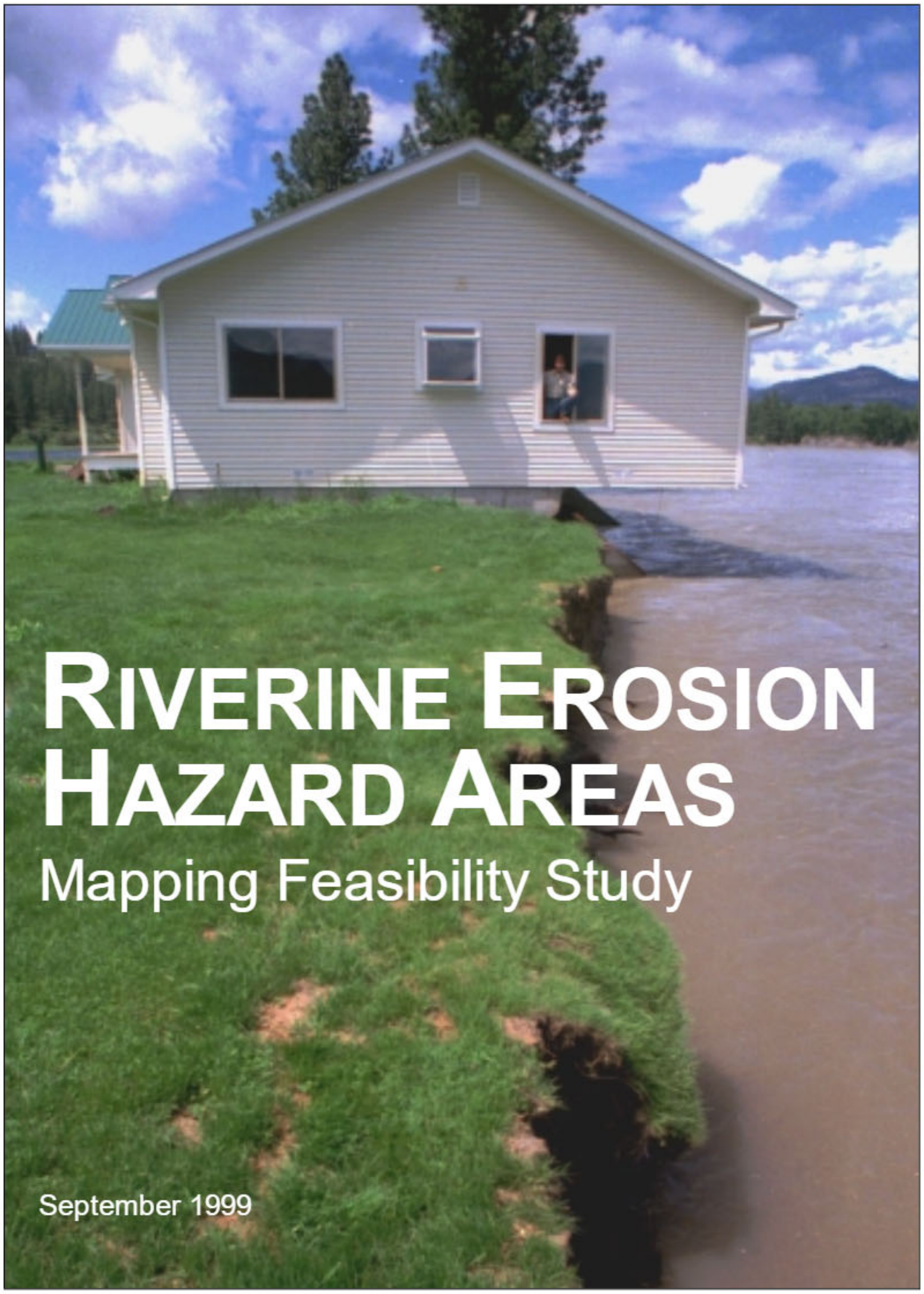
**FEDERAL EMERGENCY MANAGEMENT AGENCY**

TECHNICAL SERVICES DIVISION
HAZARDS STUDY BRANCH



# RIVERINE EROSION HAZARD AREAS

## Mapping Feasibility Study

September 1999

FEDERAL EMERGENCY MANAGEMENT AGENCY
TECHNICAL SERVICES DIVISION
HAZARDS STUDY BRANCH

# RIVERINE EROSION HAZARD AREAS

## Mapping Feasibility Study

September 1999

Cover: House hanging 18 feet over the Clark Fork River in Sanders County, Montana, after the river eroded its bank in May 1997. Photograph by Michael Gallacher.

# Table of Contents

# List of Tables

# List of Figures

# List of Photographs

# Report Preparation

In reponse to the National Flood Insurance Reform Act of 1994, Section 577, this report was prepared by the Hazards Study Branch, Technical Services Division, Mitigation Directorate, FEMA.

# Acknowledgements

The project team expresses sincere thanks to the following persons who assisted in the review of this report:

**Project Working Group (PWG)**

Nani Bhowmik, Ph.D., Hydrology Division, Illinois State Water Survey, IDNR, Champaign, Illinois.

Dan Bunting, Regional Building Department, Colorado Springs, Colorado.

Howard Chang, Ph.D., San Diego State University, San Diego, California.

David Froehlich, Ph.D., Parsons Brinckerhoff, Morrisville, North Carolina.

Jonathan Fuller, P.E., P.H., JEFuller/Hydrology & Geomorphology, Inc. Tempe, Arizona.

Doug Hamilton, P.E., Exponent, Inc., Irvine, California.

Tom Hegemier, Raymond Chan and Associates Inc., Austin, Texas

Peter Lagasse, Ph.D., Ayres Associates, Fort Collins, Colorado.

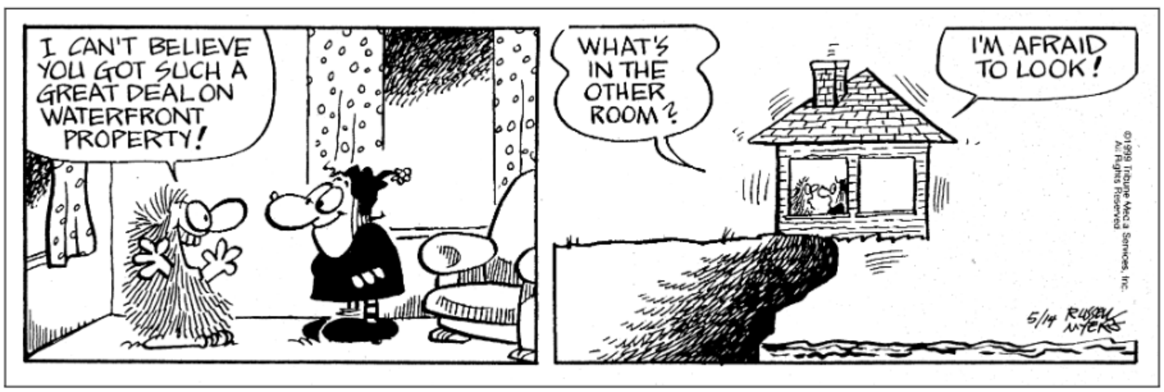
Tim Morrison, Floodplain Management Section, Pima County Department of Transportation and Flood Control District, Tucson, Arizona.

Robert Mussetter, Ph.D., Mussetter Engineering Inc., Fort Collins, Colorado.

John Parker, Ph.D., U.S. Geological Survey, Tucson, Arizona.

Mark Vian, New York City Department of Environmental Protection, Shokan, New York.

Alan Wald, Washington State Department of Ecology, Olympia, Washington.


I CAN'T BELIEVE YOU GOT SUCH A GREAT DEAL ON WATERFRONT PROPERTY!
WHAT'S IN THE OTHER ROOM?
I'M AFRAID TO LOOK!
©1999 Tribune Media Services, Inc. All Rights Reserved
5/14 RUSSELL MYERS

# Executive Summary

This Riverine Erosion Hazard Area (REHA) mapping feasibility study addresses requirements in the National Flood Insurance Reform Act (NFIRA) enacted in September 1994. Section 577 of NFIRA requires that FEMA submit a report to Congress that evaluates the technological feasibility of mapping REHAs and assesses the economic impact of erosion and erosion mapping on the National Flood Insurance Program (NFIP). The purpose of this study is to determine whether it is technologically feasible to map riverine erosion hazard areas.

Section 577 of NFIRA has specifically defined an erosion hazard area as follows:

> Erosion hazard area means, based on erosion rate information and other historical data available, an area where erosion or avulsion is likely to result in damage to or loss of buildings and infrastructure within a 60-year period.

In the context of this study, erosion is the removal of a volume of sediment from a stream reach. However, in riverine areas, a stream reach can be stable and still migrate back and forth. Channel instability occurs when natural or man-induced processes lead to excessive erosion or deposition. Therefore, when a stream migrates laterally but maintains its dimensions, pattern, and profile, stability is achieved even though the river is "active" and moves across the floodplain. For this study, a reach experiencing this type of lateral migration is considered to be "eroding," and thus has an associated REHA. This is because stream migration can threaten buildings and infrastructure.

Technological feasibility is defined as existence of:

> Methodologies that are scientifically sound and implementable under the NFIP. Scientific soundness means that the methodologies are based on physical or statistical principles and are supported by the scientific community. "Implementable" means that the approaches can be applied by FEMA as part of a nationwide program under the NFIP and for an acceptable cost.

In the present study, the project team conducted a search of existing methodologies used to predict riverine erosion, with emphasis on case studies. In general, case studies were categorized as:

1. *Geomorphic methods* - relying primarily on historic data and geomorphic investigations;
2. *Engineering methods* - relying primarily on predictive equations based on engineering and geomorphic principles; and
3. *Mathematical modeling methods* - relying primarily on computer modeling of fluvial processes.

A Project Working Group (PWG) of experts in the field of riverine erosion was organized. Their functions were to provide guidance to FEMA on technological feasibility of mapping REHAs, to act as an information source to locate and select case studies, and to review and comment on reports prepared during the study. The PWG included a nationwide mix of individuals from academia; Federal, State, regional and local government; and the private sector.

Based on the literature review, case study analysis, and input from the PWG, methodologies for analyzing and mapping REHAs were identified. A determination on technological feasibility was reached.

Using cost data associated with existing case studies, the study team estimated the approximate unit cost (*i.e.*, cost per river mile*)* of conducting riverine erosion hazard studies and adding the areas to existing Flood Insurance Rate Maps (FIRMs). The study team estimated the approximate overall costs for conducting studies and mapping the riverine erosion hazard areas nationwide.

## Riverine Erosion

Fluvial systems respond to perturbations that may be the result of naturally occurring inputs, such as precipitation, or human intervention in the form of urban development, forestry, mining, flow diversions, flood regulation, navigation, and other activities. Complex physical processes whose mathematical characterization is still imperfect govern the response, although there is reasonable qualitative understanding of the nature of this response. The basic premise is that streams are constantly attempting to attain a state of balance involving their geometry (dimensions, pattern, profile), the properties of the bed and bank material, and the external inputs imposed. The process to achieve this state of equilibrium can span long periods and affect large areas.

In the context of riverine erosion hazard areas, engineers are mostly concerned with migration of the channel alignment and various forms of erosion and deposition. These events can potentially occur in any stream environment but are often most dramatic in arid and semi-arid regions where the large sediment yields and the flashy character of floods can cause severe changes in channel configuration.

Numerous factors affect the spatial and temporal response of a stream channel. These factors encompass various aspects of geomorphology and fluid mechanics and include fluid properties, sediment characteristics, discharge, sediment transport, channel geometry, and fluid velocities. The behavior of these variables depends on the time scale under consideration: short term, long term, and very long (geologic) term. For example, channel geometry can be considered relatively constant in the short term of a few weeks but highly variable in the geologic time frame.

For most practical applications, engineers are interested in phenomena that take place in the short and long term; thus, certain variables can be considered independent. For instance, in the geologic time frame, valley slope is a function of geology and climate; however, short- and long-term channel formation processes occur at a much faster rate, and valley slope can be considered independent in many instances. For short and long term analyses, it can be assumed that the discharge regime and sediment supply are the driving variables that act on channel boundaries and vegetation to produce changes in channel cross section, longitudinal profile, and alignment.

Erosional and depositional processes in alluvial channels are defined as follows:

*Degradation:* Lowering of the channel bed on a substantial reach length occurring over a relatively long period of time in response to disturbances that affect general watershed conditions, such as sediment supply, runoff volume, and artificial channel controls.

*Aggradation:* Raising of the channel bed as a result of disturbances in watershed conditions that produce the opposite effect to those leading to degradation.

*General Scour:* Lowering of the streambed in a general area as a consequence of a short-duration event such as the passage of a flood. Examples are the erosion zones near bridge abutments and those in the vicinity of gravel pits.

*Local Scour:* Lowering of the bed due to localized phenomena such as vortex formation around bridge piers.

*Deposition:* Raising of the streambed due to a specific episode. An example is the formation of a sand bar after a flood event. Deposition is used in this document as the counterpart to general scour.

*Lateral Migration:* Shifting of the streambank alignment due to a combination of the above vertical erosional and depositional processes. The most common example is meander migration in the floodplain. Bank retreat due to mass failure is another example.

Vertical variations in the streambed are additive in that the net change is the result of long- and short-term processes. For instance, a reach that is undergoing aggradation due to increased sediment yield from the watershed can also experience general and local scour as a consequence of flood events.

Streams are constantly progressing towards a state of dynamic equilibrium involving water and sediment. The geometry of the stream undergoes adjustments so that the sediment transport capacity of the water is in balance with the sediment supply. Natural and artificial factors can upset this state of equilibrium. Earthquakes, large floods, climatic changes, urbanization, and construction of civil works in the waterway introduce changes in the sediment supply and amount of runoff reaching the stream. For example, development in the watershed typically increases the impervious area and hence the volume of runoff. Similarly, clear-cutting of forests increases the sediment yield to the stream. Dams trap sediment and have a regulating effect that increases low flows and reduces high flows. Channelization projects reduce channel length and therefore increase slopes. Diversions for irrigation or public water supply reduce the effective flows. Finally, an event such as a large flood can dramatically reshape the floodplain and increase channel width.

## Evaluation of Channel Changes

Mathematical representation of fluvial fluid mechanics is difficult due to imperfect knowledge of the complex physical phenomena involved. The many attempts to modeling of fluvial processes have shortcomings largely due to the fact that sediment transport equations commonly overpredict or underpredict sediment loads by orders of magnitude of actual measured sediment transport rates.

Some analysis methods are based on the hypothesis that the stream system tends toward a state of dynamic equilibrium in which the channel adjusts to changes in the water and sediment supply regimes. These methods include simple equations called "regime relationships," techniques based on mechanical stability conditions, and complex computer models. These equilibrium-based approaches have difficulties in accounting for ever-changing land use conditions.

In addition to fluvial processes, numerous climatic, environmental and geotechnical factors are involved. Hydrodynamically induced erosion and deposition and the occurrence of mass failure of the streambanks drive channel cross sectional changes. Induced effects include changes in roughness, bed material composition, vegetation cover, and planform. Prediction of cross sectional adjustments can only be accomplished for site-specific conditions after the most significant geomorphological factors have been identified. Therefore, any prediction of channel geometry should be based on sound field observations.

## Literature Review

Of several hundred pieces of literature, 108 articles and reports were evaluated to compile methods currently in use to predict channel changes. Of this set, the following 12 case studies were selected for detailed review:

| Case Study Title | Location |
|---|---|
| AMAFCA Sediment and Erosion Design Guide | Albuquerque, New Mexico |
| Inventory and Analysis of Stream Meander Problems in Minnesota | 14 streams in Minnesota |
| A Probabilistic Approach to the Special Assessment of River Channel Instability | Rillito Creek, Near Tucson, Arizona |
| Geomorphology and Hydrology of the Santa Cruz River, Southeastern Arizona | Santa Cruz River basin, Arizona |
| San Diego County Alluvial Studies | San Diego County, California |
| City of Austin Technical Procedures for Watershed Erosion Assessments | Austin, Texas |
| River Stability Study, Virgin River, Santa Clara River and Ft. Pierce Wash, Vicinity of St. George, Utah | Virgin River, Santa Clara River, and Ft. Pierce Wash basins, Utah |
| Hydrologic and Geomorphic Studies of the Platte River Basin, Nebraska | Platte River basin, Nebraska |
| Streambank Erosion Along Two Rivers In Iowa | East Nishnabotna River and the Des Moines River, Iowa |
| Channel Migration Studies in King County, Washington | Snoqualmie, Tolt, Raging, and Green Rivers, King County, Washington |
| Bank Erosion Field Survey Report of the Upper Mississippi River and Illinois Waterway | Upper Mississippi River and Illinois Waterway, Minnesota, Wisconsin, Iowa, Illinois, and Missouri |
| Arizona Standards for Lateral Migration and Channel Degradation | Arizona (statewide) |

In assessing the technical feasibility of mapping REHAs, each case study was analyzed for applicability, limitations, potential for mapping riverine erosion, cost, and regulatory potential. These documents revealed that numerous techniques are currently in use covering geomorphic methods, basic engineering principles, and mathematical modeling. This diverse collection of techniques is necessary because of the uniqueness of each site and to address the objectives of the specific projects.

## Assessment of Technical Feasibility

The case studies indicate that there are scientifically sound procedures for delineating riverine erosion hazard areas. Various geomorphic, engineering, and modeling procedures can be applied, depending on site-specific conditions. Specialized knowledge and experience are needed to draw conclusions that would lead to delineation of a hazard area.

A time frame of 60 years has been specified in Section 577 of NFIRA as the interval of interest for delineation of riverine erosion hazard areas. Although it is feasible to use the specified 60-

year time frame, the case studies and the opinions of the PWG indicate that existing techniques may be better suited for shorter time frames, *e.g.*, 30 years with periodic revisions to the particular REHA study and delineation. This limitation arises from data inaccuracies, imperfect knowledge of sediment transport mechanics, and unknowns in future watershed development, hydrologic conditions, and magnitude and sequence of future flooding events. However, most structures have a useful life well over 30 years and predictions should somehow address a longer time span.

Given a suitable time frame, future erosion could be estimated either extrapolating from historic data or through the use of mathematical models. In both cases, an estimate of the reliability of the prediction needs to be provided.

## Cost

An approximate analysis was performed to estimate the total cost to the Federal government of mapping riverine erosion hazard areas. The sources of cost data include information provided by the PWG, costs reported in the case studies, FEMA reports and other literature, and cost data from previous studies performed by the project team members. The data are not sufficient to make reliable nationwide cost estimation; however, they can be used to perform an educated guess for total costs.

Average study values are $2,000-$3,000 per mile for geomorphic methods, $6,000-$7,000 for engineering methods, and $10,000-$12,000 for mathematical modeling methods. If this effort were to be implemented as part of the NFIP, the cost to the Federal government would be between 200 and 300 million dollars. Section 577 of NFIRA specifies that, if REHA determination is found to be technically feasible, a cost-benefit study is to be conducted. The current study does not include these cost-benefit analyses.

## Implementation

There are at least two potential options for implementation of a nationwide REHA delineation program: a federally run program and a locally run program. The federally run program would be integrated into the NFIP. The fundamental principle of this first option is to expand the current floodplain regulations to encompass riverine erosion. This option emphasizes authority from the Federal government. The existing framework can be modified to accommodate the new responsibilities of regulating erosion-prone areas. Disadvantages are the additional cost to the Federal government and the challenge of developing appropriate guidelines for REHA delineation in a field that requires flexibility and accessibility to a wide array of analytical options.

The second option shifts the authority for regulating erosion-prone areas to the local jurisdictions. Implementation would be tailored to suit individual floodplain management needs. The Federal government would provide technical assistance, if required, and disseminate information. The main advantage is that the communities would have the flexibility to match their resources and needs with the complexity of the studies.

## Conclusions

- It is technologically feasible to map riverine erosion hazard areas. Flexibility in the choice of analysis techniques is needed to address site-specific conditions.

- REHA delineations for a period of 60 years are possible; however, better predictions may be achieved for a shorter time span, such as 30 years, with periodic revisions.

- The analytical methods used should be able to provide an indication of the reliability of REHA delineations.

- Average study values are $2,000-$3,000 per mile for geomorphic methods, $6,000-$7,000 for engineering methods, and $10,000-$12,000 for mathematical modeling methods.

- The cost of mapping REHAs nationwide ranges between approximately 200 and 300 million. This estimate is based on limited information.

- Implementation of erosion regulations can be either done as an extension of the NFIP or delegated to local jurisdictions with support from the Federal government.

# 1. Introduction

## 1.1. Description of the Problem

The National Flood Insurance Program (NFIP) administered by the Federal Emergency Management Agency (FEMA) covers damages caused by flooding and flood-related erosion. However, it does not cover damages caused by gradual (day to day) erosion. In fact, riverine erosion is not considered in insurance rates or shown on Flood Insurance Rate Maps (FIRMs). It was not until the Flood Disaster Protection Act of 1973 that Federal policy recognized the hazard of erosion by adding protection for flood-related erosion.

This Riverine Erosion Hazard Area (REHA) mapping feasibility study was conducted in response to requirements in the National Flood Insurance Reform Act (NFIRA) enacted in September 1994. Section 577 of NFIRA requires that FEMA submit a report to Congress that evaluates the technological feasibility of mapping REHAs and assesses the economic impact of erosion and erosion mapping on the NFIP. The purpose of this study is to determine whether it is technologically feasible to map riverine erosion hazard areas.

Because riverine flood damage assessments generally consider inundation alone, the potential flood-related damages for rivers in arid and semi-arid regions may be significantly underestimated (Graf, 1984; NRC, 1999). Despite this observation, bank erosion along alluvial channels, caused by moderate or large non-flood (within channel) flows, is not recognized as a significant hazard in Federal floodplain management regulations. Several photographs below show various locations in the country where riverine erosion has caused substantial damage to buildings and infrastructure. In some of the cases, the areas were marked as not subject to flooding in FIRMs.

The delineation of floodplains has generally been based on the application of established methodologies of hydrology and hydraulics for channels with fixed boundaries. In general, floodplain management and mapping have only relatively recently given more attention to the role of sediment and geomorphic and geologic controls on channel form and stability.

## 1.2. Legislative History

The NFIP legislative cornerstones and connections to erosion are:

- National Flood Insurance Act, 1968
- Flood Disaster Protection Act, 1973
- Upton-Jones Amendment, 1988
- National Flood Insurance Reform Act, 1994

**Photograph 1.** Collapsed house on eroding streambank along the Cimarron River in Logan County, Oklahoma (March 1998). Photograph courtesy of Kathy Schmidt.

**Photograph 2.** A portion of a house has fallen into the Cimarron River in Logan County, Oklahoma (March 1998). Photograph courtesy of Kathy Schmidt.

### *1.2.1. National Flood Insurance Act (NFIA), 1968*

Federal involvement in non-structural means to decrease flood losses was relatively minor until the enactment of the National Flood Insurance Act (NFIA) of 1968. The NFIA created the NFIP "to provide the availability of flood insurance, at actuarial premium rates, in communities which adopt and enforce floodplain management ordinances that meet minimum NFIP requirements" (FEMA, 1991). However, the first few years after passage of the NFIA of 1968 saw community participation and sales of flood insurance policies disappointingly low (Mrazik and Kinberg, 1989). Then, in 1972, Tropical Storm Agnes caused Congress to re-examine existing Federal policies under the NFIP (Crowell, *et al.*, 1999).

**Photograph 3.** House hanging 18 feet over the Clark Fork River in Sanders County, Montana, after the river eroded its bank in May 1997. Photograph by Michael Gallacher.

### 1.2.2. Flood Disaster Act of 1973

The repercussions caused by Tropical Storm Agnes provided the impetus for the formulation and passage of the Flood Disaster Protection Act of 1973 (P.L. 93-234) (Miller, 1992). The Act strengthened the NFIA and expanded the NFIP's coverage by requiring the purchase of flood insurance as a condition of receiving Federal or federally backed financing for acquisition or construction of structures in flood hazard areas.

### 1.2.3. Upton-Jones Amendment, 1988

The Housing and Community Development Act of 1987 authorized FEMA to provide insurance payments under the NFIP for structures subject to imminent collapse due to erosion or undermining caused by waves or currents. This legislation is commonly referred to as the Upton-Jones Amendment, and FEMA is responsible for determining whether a structure is subject to imminent collapse (FEMA, 1990).

The Upton-Jones Amendment was originally designed for application in coastal areas; however, it does not exclude riverine areas, and claims have been made for structures along streams and rivers. In coastal areas, where average annual erosion rates are established, a structure that lies within 10 feet plus 5 times the annual erosion rate from an existing reference feature, such as a beach scarp or bluff crest, is defined as being within the zone of imminent collapse. An attempt is made to apply the same criterion to riverine areas; however, historic bank change information is often unavailable.

In 1990, FEMA implemented a simple criterion for assessing stream bank and bluff stability in areas where no historical information was available. The purpose was to establish a procedure for determining if a structure lies within the zone of imminent collapse given limited information about the site. The procedure classifies a given slope as either stable or unstable, and determines the potential failure plane location if the bank were to fail. Given the height of the slope, angle of inclination, distance of the structure from the shoulder of the slope, soil strength, and the soil's angle of internal friction, these two criteria can be determined (FEMA, 1990). In summary, if the slope is stable, the structure is outside the zone of imminent collapse. If the slope is unstable, and the structure lies within the potential failure plane, it is said to be within the zone of imminent collapse and eligible for benefits of the Upton-Jones program.

The main purpose of the Upton-Jones Amendment was to provide funds for pre-flood mitigation activities to reduce future flood losses. However, review of the Upton-Jones claims history demonstrates that the program failed to generate interest; few insured eligible for Upton-Jones payments were applying for benefits. Moreover, although the intent of the Amendment was to encourage relocation and ultimately save money for the NFIP, most homeowners opted for demolition payments, thereby increasing expenditures to the NFIP (Davison, 1993).

The Upton-Jones Amendment allowed claims for structures subject to imminent collapse due to bank erosion caused by waves and currents. Of the approved riverine Upton-Jones claims filed from May 1988 to December 1994, there was a total settlement of $3,200,000 and an average settlement of $43,000 (FEMA, 1998). Approximately 60 percent of these claims are from the southwest and northwest United States The Streambank Erosion Control Evaluation and Demonstration Act (SECEDA) of 1974 report (USACE, 1981) confirms that these areas are particularly vulnerable to riverine erosion and comprise approximately half of the estimated annual damages due to erosion.

**Photograph 4.** Duck Creek in Las Vegas, Nevada, after the July 8, 1999, storm. The stream eroded the railroad bridge foundation. Bank retreat reached the house behind the bridge. Photograph courtesy of Leslie Sakumoto.

**Photograph 5.** Duck Creek just upstream of the railroad bridge. The house foundation has been damaged although the bank has not fully collapsed. Photograph courtesy of Leslie Sakumoto.

**Photograph 6.** Mobile home destroyed after bank collapse in Flamingo Wash during the July 8, 1999, flood in Las Vegas, Nevada. Photograph courtesy of Leslie Sakumoto.

**Photograph 7.** Trailer park destroyed due to erosion in Flamingo Wash during the July 8, 1999, flood in Las Vegas, Nevada. Sedimentation substantially closed one of the spans of the bridge on the right. Photograph courtesy of Leslie Sakumoto.

### *1.2.4. National Flood Insurance Reform Act (NFIRA), 1994*

When Congress enacted the Upton-Jones program into law, it was meant to be an interim program that would stay in effect until a more comprehensive erosion management program was legislated by Congress. As a result, between 1990 and 1994 a number of Congressional proposals were introduced that would have established erosion management authority under the NFIP and would have required FEMA to map erosion hazard areas for the entire Coastal and Great Lakes shorelines. Some proposals would have denied the availability of flood insurance for new or substantially improved structures located in 30-year erosion hazard areas; others would have made flood insurance available in erosion hazard areas, but at actuarial rates. These proposals were extensively deliberated, but ran into considerable opposition from real estate, developer, and property rights advocates who strongly opposed any form of erosion mapping or erosion-based insurance rate modifications that could potentially devalue or restrict use of property. As a result, none of the proposals were enacted (Davison, 1993). Ultimately, a compromise proposal was formulated between proponents and opponents of an FIA-administered erosion management program.

The compromise proposal required that FEMA study the issue of erosion mapping and erosion-based insurance modification, rather than mandate immediate change to the NFIP. This proposal was included in the National Flood Insurance Reform Act, which was enacted into law on September 23, 1994. In this Act, Section 577, Evaluation of Erosion Hazards, authorizes that the FEMA "Director may map a statistically valid and representative number of communities with erosion hazard areas throughout the United States, including coastal, Great Lakes, and , if technologically feasible, riverine areas."

The major goals of Section 577 are to 1) list the communities likely to be identified as having erosion hazard areas, 2) estimate the number of flood insurance claims under the NFIP that are attributable to erosion, 3) determine the amount of flood insurance claims under the NFIP that are attributable to claims under the Upton-Jones program, 4) assess the full economic impact of erosion on the National Flood Insurance Fund, and 5) determine the costs and benefits of mapping erosion hazard areas.

A distinction was made between open coast erosion and riverine erosion due to differences in the magnitude of these problems, and the physical processes involved. FEMA has been directed to map a statistically valid and representative number of communities with erosion hazard areas along the open coasts of the United States. An economic analysis has been conducted to determine the costs and benefits of mapping such areas based on actual and projected flood insurance claims attributable to coastal erosion. A similar economic analysis may be required for riverine sites, if mapping such areas is found to be technologically feasible.

This project was conducted to determine the technological feasibility of mapping REHAs for communities within the United States.

## 1.3. Extent of the Problem

In recognition of the serious economic losses occurring throughout the United States due to stream bank erosion, Congress enacted The Streambank Erosion Control Evaluation and Demonstration Act (SECEDA) of 1974 (Section 32, Public Law 93-251), which authorized $50 million for a national demonstration program. The U.S. Army Corps of Engineers (USACE) conducted this program. One of the purposes of this program was to evaluate the extent of streambank erosion in the United States SECEDA is one of the few initiatives that attempt to assess the erosion problem on a national level; therefore, the lessons learned from this Act are essential in determining if technologically feasible erosion prediction techniques are possible on this scale. However, the main focus of the SECEDA report, bank protection methods, differs from the purpose of the present study. Also, the SECEDA report (USACE, 1981) is 25 years old, and there have been significant advances in technology. In addition, urbanization in the last 25 years has had an impact on the predicted number of bank miles affected. Due to urbanization, formerly stable channels become unstable as a result of increased flood peaks and/or flow volumes and reduced sediment loads (NRC, 1999).

Approximately one-third of the nation's streams experience severe erosion problems, and landslides and mudslides are commonplace in some areas (NRC, 1999). As stated in the SECEDA report, there are approximately 7 million streambank miles in the United States, of which 8 percent or approximately 600,000 miles, are experiencing at least some degree of erosion (USACE, 1981). Of the 600,000 miles of eroding stream, approximately 142,000 bank miles (2 percent of the total bank miles) are experiencing extensive erosion. Due to rapid urbanization, especially for rivers with smaller watershed areas, the actual figure for bank erosion mileage could be significantly higher. The average damage per year of extensive erosion-related damage is approximately $450 million (in 1998 dollars), or approximately $3,000 per bank mile per year (USACE, 1981). Of this damage, over half is experienced in the southwest and northwest. It is important to note that the southwest is one of the most rapidly growing areas in the United States Cities such as Tucson, Phoenix, Las Vegas, and cities in southern California have documented problems associated with REHAs.

One of the most important lessons learned from the SECEDA is quoted as follows (USACE, 1981):

> Prediction of when, where, and extent of streambank erosion and/or bank instability remains clouded. The forces contributing to streambank instability are generally known and understood; however, application of these principles to the real world are complicated by the many processes acting simultaneously throughout a given river reach. Streams displaying very active tendencies to erode their banks often seem to reverse themselves and display periods of relative stability.

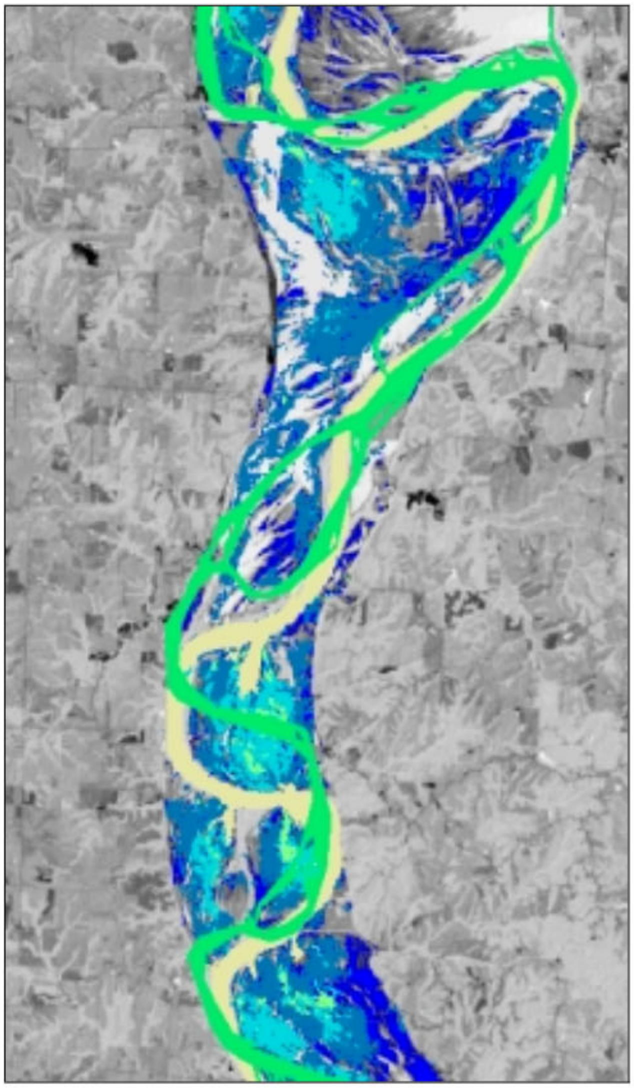
Since the USACE report was published, there have been many advances in the field of river mechanics, some of which are compiled in publications such as the Arizona Design Manual for Engineering Analysis of Fluvial Systems (Simons, Li & Associates,1985) and the AMAFCA Sediment and Erosion Design Guide (Musseter, *et al.*,1994).

Section 577 of NFIRA has specifically defined an erosion hazard area as follows:

> Erosion hazard area means, based on erosion rate information and other historic data available, an area where erosion or avulsion is likely to result in damage to or loss of buildings and infrastructure within a 60-year period.

In the general context of this study, "erosion" is defined as the removal of a volume of sediment from a stream reach. However, in riverine areas, a stream reach can migrate back and forth without necessarily resulting in a sediment deficit for the reach. For example, a channel can have stable dimensions even though the stream is migrating laterally at a fairly constant annual rate. Thus, the amount of sediment entering the reach is about equal to the amount of sediment exiting it, with no net erosion occurring within the reach. Channel instability occurs when natural or man-induced processes lead to excessive erosion or deposition. Therefore, when a stream migrates laterally but maintains its dimensions, pattern and profile, stability is achieved even though the river is "active" and moves across the floodplain. Photograph 8 shows a satellite image of the

Missouri River floodplain near Glasgow, Missouri. The green area corresponds to the channel in 1879. The light yellow area is the present day channel. The area in between the two channel positions experienced erosion at some point after 1879. The current channel has been stabilized with revetments that prevent further migration.



**Photograph 8.** Satellite image of the Missouri River floodplain near Glasgow, Missouri. The green area shows the channel in 1879. The light yellow area corresponds to the present day channel. Photograph by USGS.

For this study, a reach experiencing this type of lateral migration is considered to be "eroding," and thus has an associated REHA, even though it is simply migrating back and forth. This is because such stream migration can significantly threaten buildings and infrastructure.

Floodprone areas are determined according to national standards, which assume a stable channel. Computer programs used for floodplain studies, such as HEC-RAS, do not include the effect of moveable boundaries, varying erosiveness of bed and bank materials, and sediment transport, which is typical of alluvial streams. Therefore, additional interdisciplinary techniques based on the principals of fluvial geomorphology and hydraulic engineering must be considered for use in floodplain management studies aimed at REHA mapping.

Changes in alluvial channels can be dramatic. The Santa Cruz River, an ephemeral river in southeastern Arizona, has a long history of channel instability. Since the late 19th century, lateral channel erosion has caused extensive property damage, particularly in Pima County. During the 1983 flood, 13 people died and about $100 million of damage was caused in the Tucson area alone (Kressan, 1988). Most of the 1983 flood damage resulted from bank erosion on the Santa Cruz River and its tributaries, rather than inundation from over-bank flow. From 1982-84, the area of floodplain occupied by the channel along certain reaches has increased up to 137 percent (Hays, 1984).

Alluvial channels in the Tucson basin have exhibited lateral bank migration, which caused land outside the designated 500-year floodplain to collapse into the channel (Kressan, 1988). Documented shifts in Rillito Creek of nearly 1,000 feet have occurred since the 1940s (Kressan, 1988). Bank erosion can also be a significant hazard, even for moderate to large non-flood flows along the alluvial channels, such as those in the Tucson basin.

Incised channels, such as the Santa Cruz River, present special problems in the interpretation of the flood hazard. Entrenchment occurs from entrainment and transport of alluvial materials by channel erosion. As a result, channels are frequently so deep that floods with recurrence intervals greater than 100 years are required for overflow. The geomorphic complexity of such alluvial streams creates difficulties for implementing Federal floodplain regulations that are based primarily on flooding. In fact, channel changes, such as meander migration and bank erosion, may constitute a greater hazard than overbank flow in some areas.

In response to the 1983 flood, Pima County passed a revised floodplain management ordinance with a setback provision for structures on all property along unprotected channel banks for major river courses. In addition, recognizing riverine erosion as a statewide concern, the State of Arizona Department of Water Resources has adopted standards for identification of and development within erosion hazard areas (see Chapter 4). The state standards establish procedures for estimating setback distances for development along watercourses to allow for the lateral migration that may occur during future floods (Simons Li & Associates, 1984, 1985). Setbacks in naturalistic channels can provide protection to adjacent property similar to that provided by hard-lined channels.

## 1.4. Purpose and Scope of the Study

### *1.4.1. Purpose*

The purpose of this study is to determine the technological feasibility of mapping REHAs for communities within the United States. Technological feasibility is defined as existence of:

> Methodologies that are scientifically sound and implementable under the NFIP. Scientific soundness means that the methodologies are based on physical or statistical principles and are supported by the scientific community. "Implementable" means that the approaches can be applied by FEMA as part of a nationwide program under the NFIP and for an acceptable cost.

### 1.4.2. Scope

The study included the following tasks:

*Task 1 - Literature Search and Case Study Analysis*

The study team conducted an in-depth search of existing methodologies used to predict riverine erosion. The following groups were contacted:

- Federal agencies
- State authorities
- Regional agencies
- Research universities
- Private firms
- Professional organizations
- Local government agencies

The information was collected, categorized, and compared. Emphasis was placed on the critical review of existing case studies. In general, case studies were categorized as:

1. Geomorphic methods - relying primarily on historic data and geomorphic investigations;

2. Engineering methods - relying primarily on predictive equations based on engineering and geomorphic principles; and

3. Mathematical modeling methods - relying primarily on computer models.

Critical technical issues were identified related to frequency, statistics, definitions, data availability, data collection, and data accuracy and interpretation.

*Task 2 - Establish the Project Working Group*

A Project Working Group (PWG) of experts in the field of riverine erosion was organized. The responsibilities of the PWG were to provide guidance to FEMA on issues of technological feasibility of mapping REHAs, act as an information source to locate and select case studies, and review and comment on reports prepared during the study. The PWG included a mix of individuals who have similar expertise and come from throughout the United States representing academia; Federal, state, regional and, local government; and the private sector. The members of the PWG are cited in the acknowledgments.

*Task 3 - Input from the PWG*

Input from the PWG was solicited via the Internet and/or teleconference. Specific tasks conducted by the PWG were to:

1. Review the preliminary results of the literature search.

2. Identify other methodologies or new advancements and future research needs in riverine erosion studies.

3. Discuss major technical issues identified in Task 1.

4. Discuss the technologically feasibility of preparing REHA studies and identifying conditions and limitations for these studies.

*Task 4 - Selected Methodologies*

Based on the literature review, case study analysis, and input from the PWG, various methodologies were identified for analysis and mapping of REHAs.

*Task 5 - PWG Review*

A series of teleconferences were conducted to discuss the technological feasibility of mapping REHAs. Prior to the teleconferences, the PWG received reports for review and comment. The overall objective of determining the technological feasibility of mapping REHAs was addressed by the PWG at these times.

*Task 6 - Unit Costs of Riverine Erosion Hazards*

Using cost data associated with existing case studies, the study team estimated the approximate unit cost (*i.e.*, cost per river mile) of conducting riverine erosion hazard studies and adding the areas to existing FIRMs.

*Task 7 – Select Study Areas and Estimate Number of Communities Affected*

An approach for selecting study areas was recommended. A preliminary estimate of the number of studies and affected map panels was conducted for all participating communities covered by the NFIP.

*Task 8 - Overall Costs Within NFIP*

The approximate overall costs for conducting studies and mapping the riverine erosion hazard areas was estimated.

*Task 9 - Prepare Report with Recommendations*

This report was prepared.

## 1.5. Mapping of Riverine Erosion Hazard Areas

Mapping of riverine erosion hazards has a rather short history and has been done mostly at the local level and for specific projects. The purpose of mapping areas associated with natural hazards is to delineate zones and provide an assessment of the relative risk to which structures would be subject if they were located in such zones. In some cases, hazard-zone maps also include information that can be used for hazard forecasting and monitoring. A variety of hazard-zone maps have been developed and published in the United States for various natural disasters. These hazard area maps include tornado maps, published by National Weather Service, earthquake fault zone maps developed and maintained by the State of California, and FEMA's FIRMs.

Riverine erosion hazards have not been defined consistently except for a few cases. An example presented in Chapter 4 is the State of Arizona guidelines to define setbacks along erosion-prone streams. Another example also described in Chapter 4 is the "Prudent Line" approach used in Albuquerque, New Mexico, to define setbacks along arroyos. There have been other attempts at mapping that identify locations potentially subject to erosion and define the relative risk of erosion but do not specify the lateral extent of those risks. These relative measures of risk are of limited use for regulatory purposes.

A viable methodology to characterize erosion hazards necessitates that the resulting maps allow users to determine whether a structure in or near the floodplain will have a high probability of being affected by erosion during its useful life. Therefore, the maps must show clearly defined areas in which, to the best information available, development must be regulated due to the dangers expected from erosion. In summary, the test for applicability of a procedure is its ability to determine REHAs and then be able to delineate them on a map so that those assets at risk can be identified.

The main objective of this report is to determine if there are scientifically sound REHA delineation procedures. An additional consideration is whether a feasible framework can be proposed to develop erosion hazard maps on a nationwide scale. For this purpose, the report investigates the state-of-the-art in riverine erosion hazard characterization and summarizes several initiatives to develop erosion hazard maps and regulations. Chapter 2 presents background material on riverine erosion, Chapter 3 describes the literature search to arrive at the information used in this study, Chapter 4 describes 12 case studies in which various historical, engineering, geomorphic, and numerical modeling methods were used to define erosion hazard areas. Chapter 4 also analyzes the potential of such methods to develop hazard maps. Chapter 4 assesses the technological feasibility of mapping REHAs. Chapter 5 presents an approximate cost analysis of applying erosion characterization methodologies on a nationwide basis, and Chapter 6 discusses regulatory aspects of mapping REHAs. Chapter 7 summarizes conclusions and recommendations, and Chapter 8 lists the numerous references consulted in the development of this document.

# 2. Background of Riverine Erosion

Proper evaluation of erosion processes requires an understanding of the geomorphologic variables affecting a fluvial system. This section provides a concise overview of fluvial processes and their effects on channel formation, physical stream characteristics, response to watershed changes, and riverine erosion and deposition. This section also summarizes key research and references that have addressed the topic of characterization of riverine erosion problems.

## 2.1. Fluvial Systems

A watershed is a complex drainage system in which streams are the final receptors of water and sediment. In general, this drainage system has three zones (Schumm 1977; USACE, 1994):

1. The erosional zone is the upper portion of the watershed, which is the source of most of the water and sediment. Streams in this zone are rather unstable and may present a braided pattern.
2. The sediment transport zone is the middle part of a stream where a state of dynamic equilibrium tends to develop. Nevertheless, changes could be significant.
3. The depositional zone is the lower portion of the stream where it is subject to the influence of the water body into which it empties. A delta typically forms in this zone.

Figure 2.1 shows a schematic of the zones in a fluvial system. Specific features can create local depositional areas in the upper zone or local erosional areas in the lower zone. An example is an alluvial fan that creates a depositional zone. Nevertheless, in the very long term, the tendency of the stream is to flatten its channel slope by degradation in the upper reaches and aggradation in the lower portions. Engineered features placed in the channel can drastically hasten the naturally slow progression of processes. For example, a channelized portion of the stream increases the slope and may trigger erosion and formation of bends and deposition in unchannelized areas .

Fluvial systems respond to perturbations that may be the result of naturally occurring inputs, such as precipitation, or human intervention in the form of urban development, forestry, mining, flow diversions, flood regulation, navigation, and other activities. Complex physical processes whose mathematical characterization is still imperfect govern the response, although there is reasonable qualitative understanding of the nature of this response. The basic premise is that streams are constantly attempting to attain a state of balance involving their geometry (dimensions, pattern, profile), the properties of the bed and bank material, and the external inputs imposed. The process to achieve this state of equilibrium can span long periods and affect large areas.

In the context of riverine erosion hazard areas, engineers are mostly concerned with migration of the channel alignment and various forms of erosion and deposition. These events can potentially occur in any stream environment but are often most dramatic in arid and semi-arid regions where the large sediment yields and the flashy character of floods can cause severe changes in channel configuration. Similar behavior can occur in humid climate areas where rapid land use changes take place.

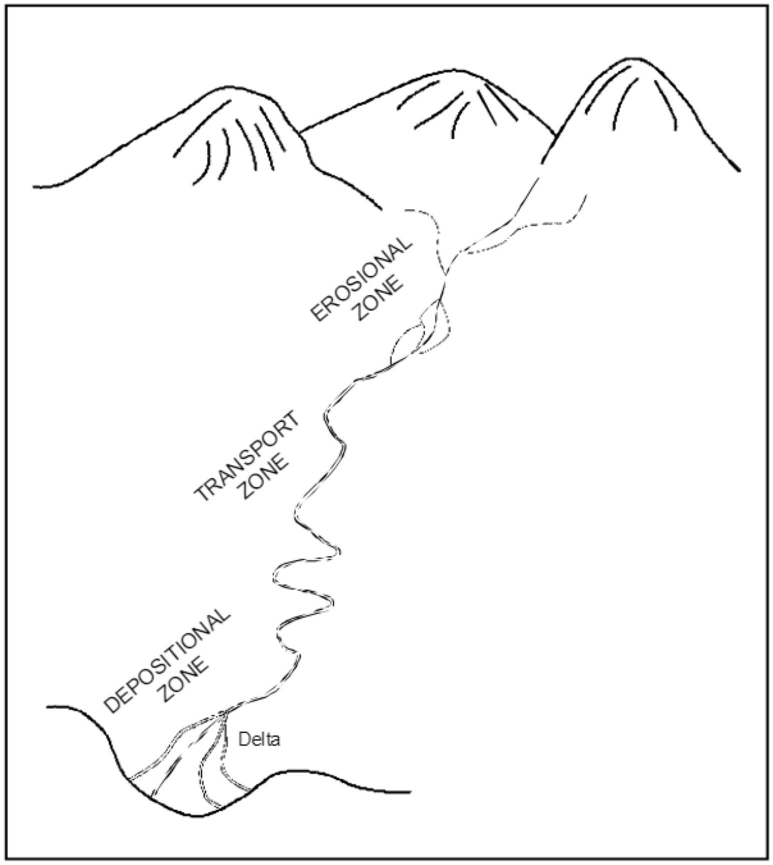



**Figure 2.1.** Zones in a fluvial system.

## 2.2. Factors Affecting Alluvial Channels

Numerous factors affect the spatial and temporal response of a stream channel. These factors encompass various aspects of geomorphology and fluid mechanics and include fluid properties, sediment characteristics, discharge, sediment transport, channel geometry, and fluid velocities.

The time scale is an important differentiator in the nature of fluvial changes. Schumm (1971) called short-term "steady time" and associated it with duration of the order of days. Long-term was labeled "graded time" spanning a few hundred years. Finally, very long-term was called "geologic time," and it is measured in millions of years. Depending on the time scale under consideration, fluvial variables could be dependent or independent. For example, in the short-term, sediment transport is a function of flow velocity, which in turn is a function of channel geometry and discharge; therefore, sediment transport and velocity can be considered dependent. However, in the long-term, both discharge and sediment transport are independent because they are the result of watershed processes to which the river must adjust itself (Chang, 1988a). Table 2.1 shows a summary of these variables and their dependency according to time scale.

**Table 2.1.** Variables affecting alluvial channels and their dependency (Schumm, 1971; Chang, 1988). I = Independent; D = Dependent; X = Indeterminate.

| **Variable** | **Status of Variable** | | |
|---|---|---|---|
| | *Short-Term (Steady Time)* | *Long-Term (Graded Time)* | *Very Long-Term (Geologic Time)* |
| Geology | I | I | I |
| Paleoclimate | I | I | I |
| Paleohydrology | I | I | D |
| Valley slope, width, and depth | I | I | D |
| Climate | I | I | X |
| Vegetation type and density | I | I | X |
| Mean water discharge | I | I | X |
| Mean sediment inflow | I | I | X |
| Channel morphology | I | D | X |
| Observed discharge and load | D | X | X |
| Hydraulics of flow | D | X | X |

For most practical applications, engineers are interested in phenomena that take place in the short (steady) and long (graded) term; thus, certain variables can be considered independent. For instance, in the very long (geologic) term, valley slope is a function of geology and climate; however, short- and long-term channel formation processes occur at a much faster rate, and valley slope can be considered independent in many instances. For the time scales under consideration in this document, the most significant relationships are depicted in Figure 2.2, which indicates that channel geometry depends on discharge and sediment transport.

## 2.3. Channel Types

Various schemes have been developed over the years in an attempt to classify channels according to broad morphological aspects. According to Leopold *et al.* (1964), channel patterns were initially classified broadly as straight, braided or meandering. Despite its general usefulness, this classification has limitations in describing channel shapes. For instance, it is unlikely to find channels that are straight for more than a short distance; therefore, the term “straight” is relative and should refer to sinuous, irregular alignments. An exception is a channel controlled by fractured rock, which may actually show straight reaches along fractures and joints. Even in straight reaches, the flow pattern is such that the flow lines move from one bank to the opposite causing alternating point bars within the channel. Because of this natural tendency towards a sinuous channel, the term “meandering” should be applied to streams that have a relative periodicity in its planform; however, it is not easy to make this determination for all cases. Leopold *et al.* (1964) defined straight channels in terms of the sinuosity, which is the ratio of thalweg length to down-valley distance. Typical values of the sinuosity vary between 1 and 3. A channel with a sinuosity of 1.5 or less is said to be straight.

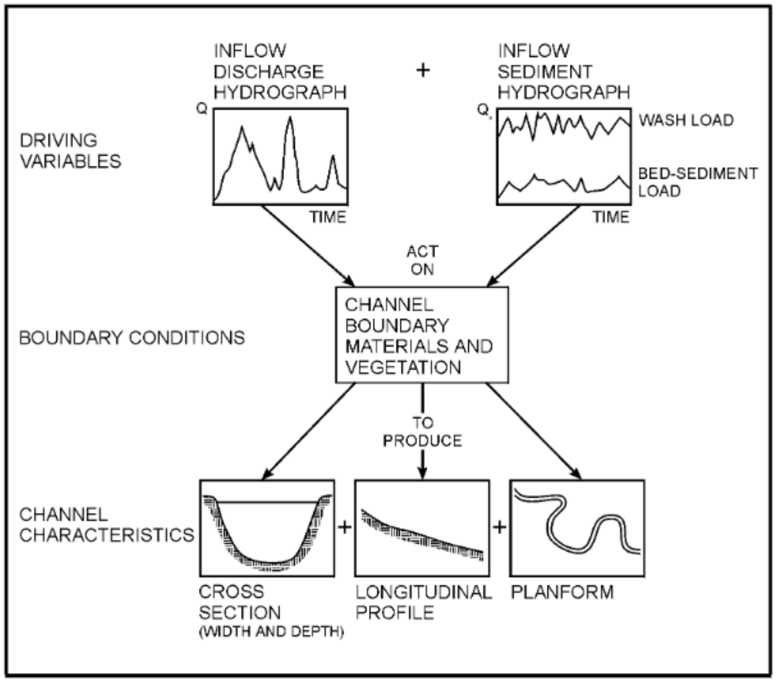



**Figure 2.2.** Relationships among variables for channel response (USACE, 1994).

Other classification systems were developed as the study of river geomorphology evolved and more knowledge was acquired. Culvertson *et al.* (1967) created an alphanumeric system based on variability of channel width, braiding patterns, sinuosity, natural levees, floodplain width, vegetation, presence of oxbow lakes, meander type, and bank height. Brice (1983) introduced a classification system based on sinuosity, presence of point bars, braiding, and anabranching (Chang, 1988). Channels were classified as sinuous canaliform, sinuous with point bars, sinuous braided, and nonsinuous braided. Other classification schemes were proposed by Rosgen (1994, 1996) and Clark *et al.* (1995). The USACE (1994) developed the comprehensive system summarized in Table 2.2.

**Table 2.2.** Stream classification system based on USACE (1994).

| Stream Type | Description |
|---|---|
| Mountain Torrents | High velocity streams on steep slopes with a drop-and-chute structure often achieved by obstacles such as large boulders or debris. These streams are subject to scour and degradation caused by flood events. Very steep slopes can lead to debris flows that produce substantial movement of boulders and gravel. |
| Alluvial Fans | Occur usually in arid and semi-arid lands where a stream flowing through a stream valley enters a flat area. The coarse sediment carried by the stream deposits in a delta-like configuration characterized by multiple channels subject to shifting. The chief stability problem is caused by the unpredictability of the flow paths, which may cause erosion and deposition in unexpected places. Most recently, NRC (1996) defined alluvial fans as "a sedimentary deposit located at a topographic break, such as the base of a mountain, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and that has the shape of a fan either fully or partially extended." |
| Braided Rivers | The main characteristic of these streams is a series of interlaced channels defined by bars and islands. Braided streams often occur in upper and middle zones of the watershed and usually involve gravel and cobbles, although braiding may also occur in sands. Scour and deposition often cause shifting of the main channel. |
| Arroyos | Present in arid and semi-arid lands, these are streams that remain dry most of the time and carry flow only during flood events. Discharge and sediment transport can be substantial during flow episodes. Incising channels, width enlargement, and deposition are typical problems associated with arroyos. |
| Meandering Alluvial Rivers | These occur primarily in the middle and lower portion of the watershed. The planform of the stream is characterized by meanders that erode the streambank in the outer side of the bend and deposit material on the inner side. Meanders may migrate in the floodplain and can often become cut off periodically when two bends advance toward each other and curvature becomes severe. Cut-off meanders become isolated features called "oxbow lakes" that eventually fill with sediment. Traces of old meanders (scrolls) are easily distinguishable in aerial photographs. Measures that alter the supply of water or sediment have the potential to change cross sections, planforms, and gradients. |
| Modified Streams | This term generically encompasses those streams whose natural configuration has been modified by human intervention. These modifications include straightening, channelizing, enlargement, and base level changes caused by regulation of the receiving stream. Increased runoff from surrounding development also results in modifications. |

**Table 2.2.** Stream classification system based on USACE (1994) (continued).

| Stream Type | Description |
|---|---|
| Regulated Streams | Regulation of tributaries by upstream reservoirs or diversions reduces flood flows and increases baseflow. These changes in the flow regime translate into altered morphological activity. If regulation facilitates sediment deposition in the channel and vegetation growth, the stream cross section will be reduced. However, if the stream carries substantial sediment loads that become trapped in the reservoir, the stream may cause erosion downstream of the dam. |
| Deltas | These features occur on flat slopes of the lower portion of the stream where it empties into relatively quiescent water such as the ocean or a lake. Sediment deposition due to reduced velocity forces the river to split into distributaries whose base level rises as the delta progresses into the water body. Deltas also exhibit the formation of natural levees along the distributaries. |
| Underfit Streams | These are streams common in regions whose landscape formed as a result of glacial activity. Underfit streams occur in wide valleys formerly shaped and occupied by larger streams, usually the outlet to glacial lakes. Underfit streams are also found in abandoned riverbeds or channels downstream from reservoirs. Flat slopes, low velocities, and established vegetation make underfit streams generally stable. |
| Cohesive Channels | These are channels cut in cohesive materials such as marine clays, silted lakes, and glacial till plains. In marine deposits, these streams behave somewhat like meandering alluvial streams, although the meanders are flatter, wider, more uniform, and usually more stable. In glacial till the planform tends to be irregular. |

## 2.4. Channel Form and Processes

Alluvial channels are characterized by movable bed and streambanks that change configuration according to erosion and deposition phenomena. Therefore, these phenomena have a direct effect on the geometry of the channel in that they can introduce changes in the cross section, planform, longitudinal profile, and bed topography of the stream. Modification of these channel features may occur at various rates depending on the intensity and variability of imposed conditions and on the time scale under consideration. This section describes the characteristics of these processes and their relationship to channel geometry.

### *2.4.1. Definitions*

The determination of erosion hazard areas involves evaluation of several erosional and depositional processes that take place either gradually over long periods or episodically during isolated events. These processes are defined as follows (Simons, Li & Associates, 1985):

*Degradation:* Lowering of the channel bed on a substantial reach length occurring over a relatively long period of time in response to disturbances that affect general watershed conditions, such as sediment supply, runoff volume, and artificial channel controls.

| | |
|---|---|
| *Aggradation:* | Raising of the channel bed as a result of disturbances in watershed conditions that produce the opposite effect to those leading to degradation. |
| *General Scour:* | Lowering of the streambed in a general area as a consequence of a short-duration event such as the passage of a flood. Examples are the erosion zones near bridge abutments and those in the vicinity of gravel pits. |
| *Local Scour:* | Lowering of the bed due to localized phenomena such as vortex formation around bridge piers. |
| *Deposition:* | Raising of the streambed due to a specific episode. An example is the formation of a sand bar after a flood event. Deposition is used in this document as the counterpart to general scour. |
| *Lateral Migration:* | Shifting of the streambank alignment due to a combination of the above vertical erosional and depositional processes. The most common example is meander migration in the floodplain. Bank retreat due to mass failure is another example. |

Vertical variations in the streambed are additive in that the net change is the result of long- and short-term processes. For instance, a reach that is undergoing aggradation due to increased sediment yield from the watershed can also experience general and local scour as a consequence of flood events.

### *2.4.2. Geomorphic Characteristics*

Streams are constantly progressing towards a state of dynamic equilibrium involving water and sediment. The geometry of the stream undergoes adjustments so that the transport capacity of the water is in balance with the sediment supply. As sediment is deposited, the newly created terrain may be colonized by vegetation that contributes to the stability of the soil.

In earlier stages of the field of geomorphology, a stream that exhibited the ability to adjust itself was called "graded" (Davis, 1902) to signify that there was a balance between erosion and deposition. Mackin (1948) defined the "graded stream" as "one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change." These concepts have been superseded, as more knowledge became available. For instance Leopold (1964) points to the excessive emphasis on slope and the fact that lateral movement is also important but is neglected. Nevertheless, the "graded stream" is the classical concept that expresses the idea of equilibrium in rivers. Although difficult to define, equilibrium is a condition that implies the ability of the channel to adjust to changes in the independent variables (sediment load and discharge) and to attain a stable cross-sectional and longitudinal geometry. As mentioned earlier, the concept of equilibrium is relative to the time scale under consideration.

Natural and artificial factors can upset this state of equilibrium. Earthquakes, large floods, climatic changes, urbanization, and construction of civil works in the waterway introduce changes in the sediment supply and amount of runoff reaching the stream. For example, development in the watershed typically increases the impervious area and hence the volume of runoff. Similarly, clear-cutting of forests increases the sediment yield to the stream. Dams trap sediment and have a regulating effect that increases low flows and reduces high flows. Channelization projects reduce channel length and therefore increase slopes. Diversions for irrigation or public water supply reduce the effective flows. Finally, an event such as a large flood can dramatically reshape the floodplain and increase channel width.

Engineers are interested in predicting changes in stream geometry that could ensue from modifications introduced elsewhere in the channel or the watershed. Thornes (1977) points to several difficulties in obtaining reliable predictions. One is the fact that there are many ways in which a channel can respond to change (indeterminacy). Another is that the same final configuration can be the result of different sequences of phenomena (equifinality). Finally, changes may induce streams to cross certain thresholds and completely alter their morphology.

Nevertheless, adequate predictions can be made using the "regime" concept, which states that, for relatively constant discharges, channels reach a state of equilibrium where no net scouring or deposition occurs. Natural streams are far from experiencing relatively constant discharges; however, regime theory is still suitable for geomorphic analyses as long as the predictions are applied to adjustments to equilibrium and not to the overall transient behavior (Chang, 1988). Under this assumption, the discharge is assumed to be an independent variable affecting channel variables such as width, depth, meander wavelength, and velocity.

An example of a tool for geomorphic analysis is the widely-used Lane Relationship (Lane, 1955), which describes the state of equilibrium as

$$Q_s d \propto QS \tag{1.1}$$

Where $Q_S$ is the sediment discharge, $d$ the median sediment size, $Q$ the water discharge, and $S$ the channel slope. A net increase in the left side of the relationship will cause aggradation. Conversely, a net increase in the right-side product will lead to degradation. The state of equilibrium can be viewed in two ways. The first is one in which the geometry is in balance with a moving sediment discharge. The second is more applicable to cohesionless sand beds in which the sediment is at the threshold of movement. However, both views imply that there is a threshold that controls the channel geometry (Leopold, 1964).

The Lane Relationship does not include channel geometric parameters but still allows qualitative analysis of channel response. For example, a reservoir raises the base level for the stream and hence decreases the upstream slope. In consequence, aggradation must take place to restore the original slope. Downstream from the dam, the sediment supply will be drastically reduced; therefore, degradation will occur. The channel will become more sinuous to decrease the slope, and the size of the sediment transported will increase (Chang, 1988).

Schumm (1969) used Lane's and other "regime" relations to determine qualitative responses to various changes in channel processes. These relationships are summarized in Table 2.3. However, these are only general trends; channel response depends on numerous factors and varies with the scale of the phenomenon.

**Table 2.3.** Schumm's summary of channel responses (adapted from Chang, 1988).

| Process | B | D | F | λ | S | P |
|---|---|---|---|---|---|---|
| Q increases alone (*e.g.*, downstream of a treatment plant) | ↑ | ↑ | ↑ | ↑ | ↓ | ↓ |
| Q decreases alone (*e.g.*, downstream a diversion) | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ |
| $Q_s$ increases alone (*e.g.*, downstream of mining operations) | ↑ | ↓ | ↑ | ↑ | ↓ | ↓ |
| $Q_s$ decreases alone (*e.g.*, afforestation or vegetation buffering along streams) | ↓ | ↑ | ↓ | ↓ | ↑ | ↑ |
| Q and $Q_s$ both increase (*e.g.*, during urbanization) | ↑ | ↑↓ | ↑ | ↑ | ↑↓ | ↓ |
| Q and $Q_s$ both decrease (*e.g.*, downstream of a reservoir) | ↓ | ↑↓ | ↓ | ↓ | ↑↓ | ↑ |
| Q increases and $Q_s$ decreases (*e.g.*, climate change toward a more humid pattern) | ↑↓ | ↑ | ↓ | ↑↓ | ↓ | ↑ |
| Q decreases and $Q_s$ increases (*e.g.*, irrigation diversion plus clearing for farming) | ↑↓ | ↑↓ | ↑ | ↑↓ | ↑ | ↓ |

B = width; D = depth; F = Width/Depth ratio; λ = Meander wavelength; S = Slope; P = Sinuosity.
↑ = Increase; ↓ = Decrease; ↑↓ = Indeterminate

Table 2.3 indicates that, in general, width increases with aggradation and decreases in a degrading channel. The trends shown in the table are generalizations that must be validated using site-specific data. The trends also depend on the time scale involved. Analytical determination of responses in width, depth, slope, and bank geometry must be conducted with physically based relationships. Some of these relations are well known; for instance, friction formulas such as Manning's formula can be used to determine flow depths. Other variables such as channel width and planform are not so readily defined.

### 2.4.3. Planforms

Stream planform can vary in numerous complex patterns (Table 2.4). A comprehensive set of possible configurations was presented by USACE (1994), developed after Mollard and Janes (1984).

There have been many attempts to derive relationships between planform and other geometric stream characteristics. Examples are the various equations relating meander wavelength and amplitude to variables such as radius of curvature and stream bankfull width. In general, the bankfull width is the top width resulting from the channel-forming discharge. Some of these expressions were later shown invalid for numerous situations (Chang, 1988). For instance, Leopold and Wolman (1960) concluded that the radius of curvature of a meander $r_c$ was given by

$$r_c = 2.4B \qquad (1.2)$$

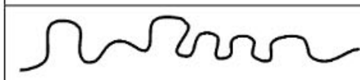
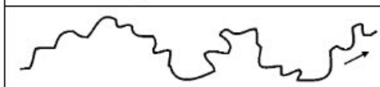
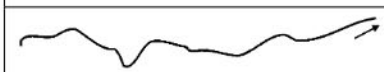
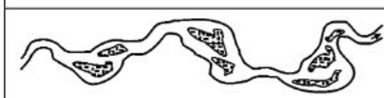
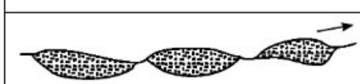
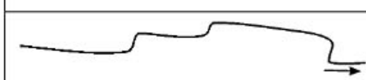
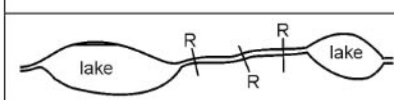
where $B$ is the bankfull width. However, although derived from data ranging from laboratory flumes to the Mississippi River, this expression appears to be valid only for developed meanders. As an improvement, Hey (1976) presented an alternate relationship that included the arc angle subtended by the meander curve. In another approach, Anderson (1967) used laboratory data to relate meander wavelength to cross sectional area, Froude number, and discharge. However, Edgar and Rao (1983) showed that the results were not applicable to field data. The conclusion is that these types of relationships cannot be generalized for generic cases and that their applicability must be closely examined before making any decisions based on their results.

Nevertheless, research efforts have been valuable in providing numerous observations throughout the years that allowed drawing of useful qualitative relationships. For instance:

- Braided rivers are usually shallow and wide and tend to exhibit a stable width of the braided area,
- Meanders can migrate downvalley or undergo a periodic process of bed cut-off,
- Extreme meandering patterns are associated with flat slopes and low width-to-depth ratios,
- The total length of a natural channel tends to remain constant. For example, subsequent lengthening of other bends or creation of new meanders compensates bed cut-off.

Research indicates that, beyond these qualitative relations, a general methodology is not available to predict planform changes in all physical settings. The most effective tools rely on developing site-specific information based on observations conducted at various points in time.

**Table 2.4.** Planform patterns (USACE, 1994).

| CHANNEL APPEARANCE | CHANNEL TYPE | TYPICAL ENVIRONMENT | TYPICAL BED AND BANK MATERIALS |
|---|---|---|---|
|  | (a) Regular serpentine meanders<br>(b) Regular sinuous meanders | Lacustrine plain | Uniform cohesive materials |
|  | Tortuous or contorted meanders, no cutoffs | Misfit stream in glacial spillway channel | Uniform cohesive materials |
|  | Downstream progression | Sand-filled meltwater channel | Slightly cohesive top stratum over sands |
|  | Unconfined meanders with oxbows, scrolled | Sandy to silty deltas and alluvial floodplains | Slightly cohesive top stratum over sands |
|  | Confined meandering | Cohesive top strata over sand substratum in steep-walled trench | Slightly cohesive top stratum over sands |
|   | Entrenched meanders | Hard till or uniform rock | Till, boulders, soft rock |
|  | Meanders within meanders | Underfit streams in large glacial stream spillways | Cohesive materials |
|  | Irregularly sinuous meanders | Thin till over bedrock in plains | Hard and softer materials |
|  | Wandering | Foothills and mountain valleys | Cobble-veneered sand |
|  | Anastomosing | Foothills, plains, sand bed or gravel paved rivers | Sand and gravel |
|  | Classical braided | Glacial outwash, foothills | Sand and gravel |
|  | Irregular channel splitting | Large rivers in bedrock | Alternate sand, gravel and rock |
|  | Rectangular channel pattern | Jointed rocks, mostly flat-lying sedimentary rocks | Rock |
|   | Lakes and rapids (R) | Till-veneered shield terrain | Till, cobbles, boulders, hard rock |

### *2.4.4. Cross Section*

The shape of cross sections depends on runoff, sediment yield, bed and streambank materials, and vegetation. A stream in a state of dynamic equilibrium may exhibit relatively constant cross sections that are substantially altered only by flood events of large magnitude. After these infrequent episodes, the stream tends to recover its original configuration. Sustained erosion and deposition are usually the result of a fundamental change in the fluvial system; for instance, increased flows or sediment input. Figures 2.3 and 2.4 show the main mechanisms of cross sectional changes.

The schemes in Figure 2.3 correspond to (a) widening without incision, (b) scour greater than deposition in meanders, (c) erosion due to flow deflected by a growing bar, (d) catastrophic bank failure due to instability caused by incision, and (e) erosion due to flow acceleration caused by aggradation that reduces the flow area. In Figure 2.4, the mechanisms depicted correspond to (a) formation of berms that are later colonized by vegetation, (b) deposition greater than scour in meanders, and (c) abandonment of a secondary channel or anabranch, or attachment of bars to the floodplain.

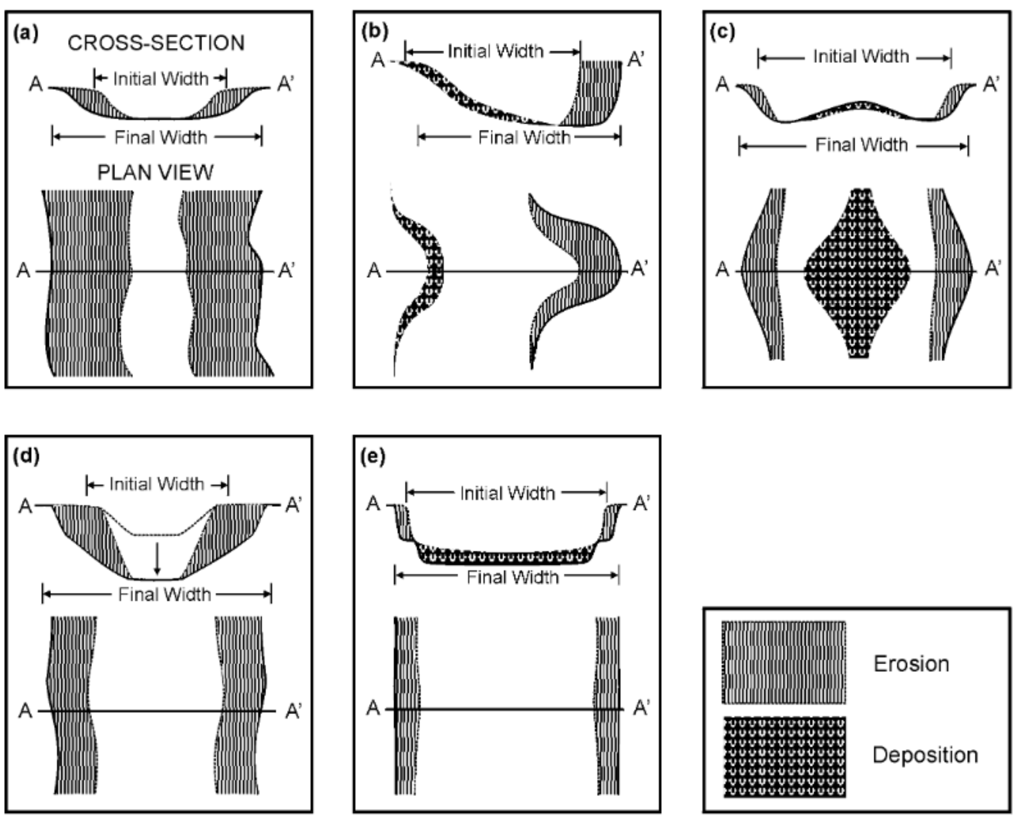



**Figure 2.3.** Main mechanisms of cross sectional widening (adapted from ASCE, 1998a).

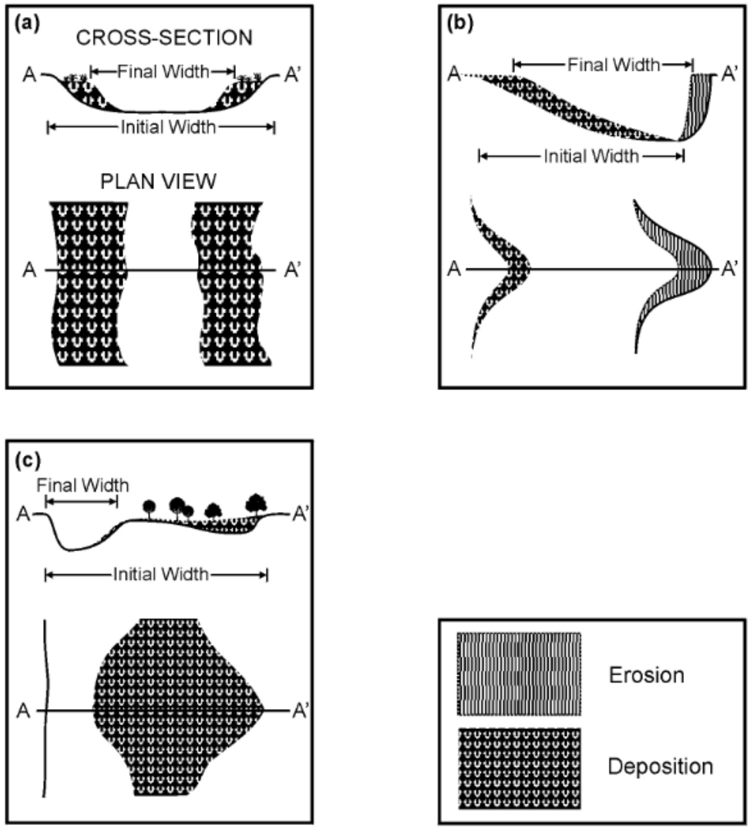



**Figure 2.4.** Main mechanisms of cross sectional narrowing (adapted from ASCE, 1998a).

The spatial and temporal variability in the geometry of cross sections has a major influence in hydraulic modeling and hence in floodplain delineation. Cross sections may be considered relatively constant for low flows, but large differences may be present for greater flows. In addition, cross sections may change significantly in a short distance. For example, a meandering stream has a deep portion near the outer bend whereas the straight portions between meanders are more uniform and shallower. Cross sectional changes may also take place in engineered channels. For instance, aggradation may occur in a channel that was improperly designed with excessive width.

### 2.4.5. Slope

As discussed earlier, downvalley slope can be considered an independent variable for the time scales of interest in engineering applications. The channel slope is usually flatter than the valley slope and can be subject to modifications as a result of aggradation and degradation. The most common example is the reduction in the channel slope as a result of meandering. If a stream is in a state of dynamic equilibrium and the channel is straightened by cutting off one or more meanders, the resulting slope will be steeper than the initial condition and the stream will tend to lengthen its path through erosion and deposition.

In general, channel slopes have a somewhat concave profile, which is steeper in the upper reaches of the watershed and becomes flat toward the mouth. This shape is the result of degradation in the steeper portions and aggradation in the lower regions. Near the mouth, the aggradation process commonly leads to the formation of deltas.

Local features can affect this natural tendency, sometimes severely. Geologic controls created by rock outcrops in the channel can slow down the progression of erosion. A reservoir in the stream causes settling of sediment and reduces its availability downstream. Aggradation takes place upstream and degradation downstream of the dam. Channelization can cause headcutting, which encourages degradation moving upstream and aggradation proceeding downstream. The point along the stream marking the progression of upstream degradation is known as the nick point. Figure 2.5 shows how these processes affect channel slope.

### *2.4.6. Roughness and Bed Configuration*

The ability of flow to remove from and deposit material on the streambed induces the formation of features that change the bed configuration and affect the roughness properties of the channel. Form roughness includes the bed, streambanks, and alignment. The total resistance is given by the grain roughness plus the form roughness.

Depending on the local flow conditions, bed forms may include ripples, dunes and antidunes, and bars. Other sources of form roughness are vegetation, bank protection measures, rock outcrops, and scour holes. Figure 2.6 shows the most commonly found features and their variation as flow accelerates. Increasing velocities induce crossing of a threshold at which the bed becomes flat. These changes trigger further adjustments in other river geomorphologic variables (Chang, 1988).

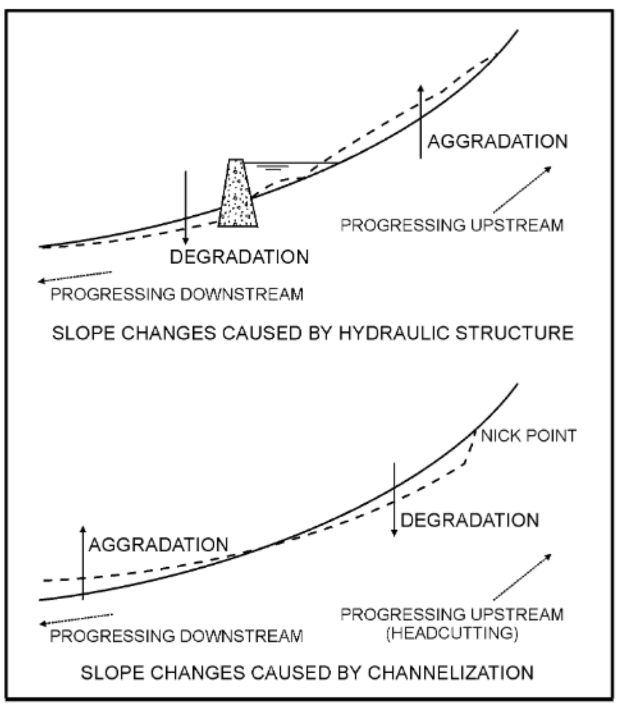



**Figure 2.5.** Processes affecting channel slope (USACE, 1994).

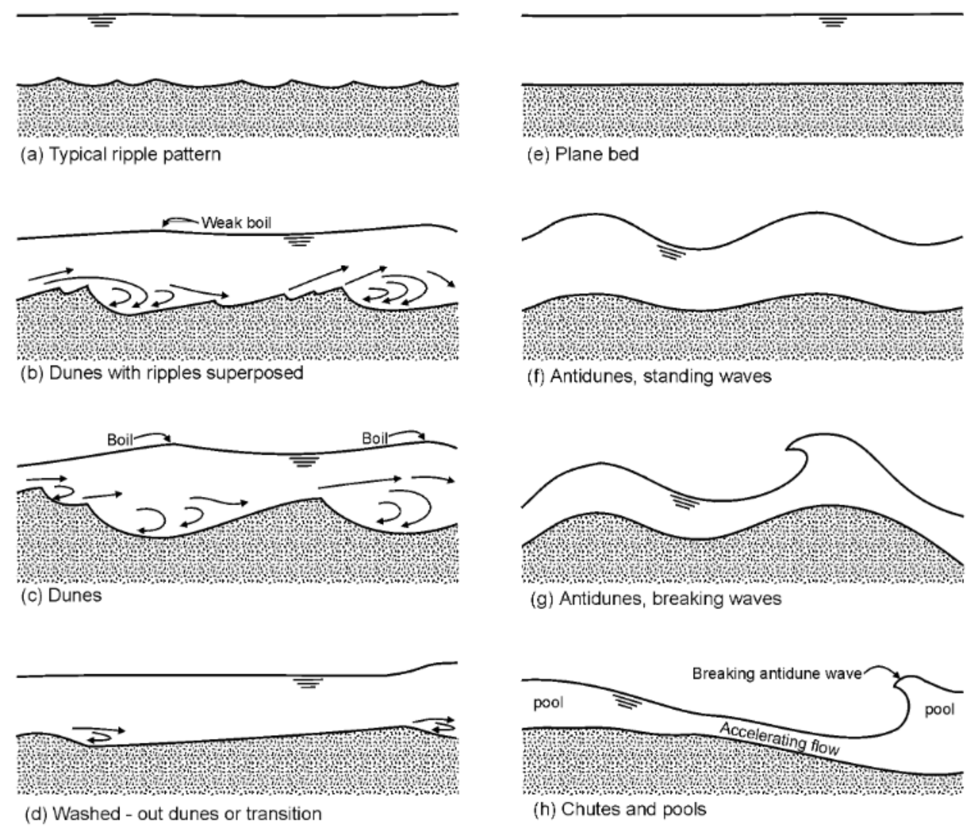



**Figure 2.6.** Various bed forms and their progression under accelerating flow (USACE, 1994).

Ripples are the smallest bed forms and have wavelengths of approximately one foot and heights of less than one inch. Their shape is smooth and almost symmetrical although the slope upstream could be milder than downstream.

Dunes are larger than ripples and are usually accompanied by gravity water waves, which are out of phase with the dunes so that the water depth is greater over the troughs than over the crests. The shape is usually triangular with a mild upstream slope and a steeper downstream slope nearly equal to the angle of repose of the bed material. Ripples are sometimes found on the upstream slope. Eddies take place on the downstream side and lead to surface boils and turbulence.

Antidunes are bed forms in phase with the gravity water waves and are sometimes called "standing waves." Antidunes are associated with greater flow velocities. For high velocities, the water waves become unstable and break towards the upstream direction. The shape of antidunes varies from triangular to sinusoidal as the flow velocity increases.

Bars are bed forms of dimensions greater than dunes and of the order of the channel width. Their vertical dimensions may be comparable to the flow depth. The term "point bar" usually refers to the depositional area near the inside of a bend. Point bars may change configuration but remain at the same location. "Alternating bars" refers to the periodic system of bars near alternate channel banks. These bars introduce sinuosity to the flow paths even if the channel is relatively straight. Alternating bars are much narrower than the channel width and tend to move slowly downstream.

Beds with coarse materials tend to develop a pool-and-riffle structure. The pools have milder slopes and finer material whereas the riffles are steeper and contain coarser material. Armoring is also common in these types of channels.

The formation of bed forms explains the hysteresis effects noted in rating curves. A flood event can reshape a channel reach to the point that the roughness characteristics when the flood is receding are different from those during the initial stages. Therefore, for the same flow, the stage may be different depending on the hydrograph limb, and the rating curve may exhibit a loop.

Three empirical methodologies are available to predict bed forms: Simons and Richardson (1961), Athaullah (1968), and van Rijn (1984). The methodologies are applied through diagrams that, for a given particle size and flow parameters such as Froude number, stream power, or shear stress, indicate the type of bed form likely to be present. Chang (1988) presents methods to estimate bed-form dimensions and include bed-form roughness in stage-discharge friction formulas.

### 2.4.7. Mechanics of Sediment Transport

The boundaries of the stream channel are usually soil material with a given resistance to erosion. Bed material can range from large boulders to very fine clay particles. In general terms, sediment can be cohesive, including clay, silt, and mixtures, or noncohesive, including sand, gravel, and larger particles. Transport of noncohesive materials is strongly dependent on particle size. The entire size distribution of the material is needed to ascertain its erodibility. The bond between particles in cohesive soil dictates its resistance to erosion and is far more important than size distribution. However, size becomes important once the material has been eroded and is transported by the flow (Simons, Li & Associates, 1985).

An important sediment transport process is the development of an armor layer in beds containing gravel and cobbles. Water flowing over the mixture of sand and coarser material lifts the smaller grains and leaves an upper layer or armor of large particles. This armor protects the underlying sediment from further erosion and controls the subsequent behavior of sediment transport. A flood event of large magnitude can disturb the protective layer, and the armoring process will start again.

Sediment transport exerts substantial control over morphology and channel geometric configuration. An indicator of this influence is the sediment load, which is the rate at which material moves in the stream as quantified in units of weight per unit time. The transport rate is closely dependent on the water discharge. The sediment load has several components. The *bed load* is that portion of the sediment that moves along the bottom by sliding, rolling or saltation. The *suspended load* is material carried in suspension and consists of particles that can be found in the bed, which become suspended due to turbulence. The sum of bed load and suspended load is known as *bed-material load* or *total load*. As will be seen later, there are equations to estimate bed loads, suspended loads, and bed-material loads. In addition, the stream carries the *wash load,* which is made of fine materials not found in the bed. The wash load does not depend on the carrying capacity of the stream but on the amount supplied by the watershed. There are no general expressions to predict the wash load, although site-specific regression equations may be available.

Quantification of sediment transport is fraught with uncertainty because of the complexity of the phenomenon and its inherent spatial and temporal variability. Existing mathematical representations have relied heavily on experimental results. Chang (1988) groups the available sediment transport formulas according to the approach used to derive them. Three major approaches have been used: shear stress, power, and parametric. Formulas can also be grouped according to the component of the total load they attempt to quantify: bed load, suspended load, or bed-material load. Table 2.5 summarizes the more commonly used formulas.

Despite the intense efforts expended in the development of these formulas, evaluation against field data indicates that they commonly overpredict or underpredict sediment loads by orders of magnitude of actual measured sediment transport rates (Gomez and Church, 1989; Yang and Wan, 1991). This discrepancy is likely due to imperfect knowledge of the physics of sediment transport and also to the extensive variability and heterogeneity in hydrologic and geologic factors. For these reasons, no one formula is better than the others. Selection of a sediment transport formula must be dictated by how well the conditions of the problem at hand match the assumptions underlying the formula. If possible, applicability of the formula should be verified with site-specific field data. Collection of water samples for sediment analysis needs to be conducted carefully and using proper sampling protocols. When a water sample is collected, the sediment will include both the suspended and wash loads; therefore, it is necessary to separate the two components to verify sediment transport formulas.

**Table 2.5.** Sediment transport formulas and classifications.

| | | **Sediment Transport Formula** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Criteria** | **Grouping** | DuBoys (1879) | Shields (1936) | Einstein Bed Load (1950) | Einstein Suspended Load (1950) | Meyer-Peter-Muller (1948) | Einstein-Brown (1950) | Parker *et al.* (1982) | Engelund-Hansen (1967) | Ackers-White (1973) | Yang (1972) | Colby (1964) |
| *Approach* | Shear Stress | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | |
| | Power | | | | | | | | ✓ | ✓ | ✓ | |
| | Parametric | | | | | | | | | | | ✓ |
| *Load Component* | Bed Load | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | | |
| | Suspended Load | | | | ✓ | | | | | | | |
| | Bed-Material Load | | | | | | | | ✓ | ✓ | ✓ | ✓ |

## 2.5. Evaluation Methods for Channel Response to Imposed Changes

The previous discussion presented the generally accepted concept that streams tend to a state of dynamic equilibrium in which the geometry adjusts over time in accordance with discharge and sediment influx patterns. Various geomorphologic variables were examined and qualitative relationships were discussed to predict channel geometry changes. This section presents a review of currently available methods to predict the magnitude and direction of these geometric changes.

### 2.5.1. Equilibrium Approaches

Several equilibrium-based techniques have been used to describe cross section geometry. These techniques range from "regime" relationships to complex computational models. This section presents a brief description of these techniques.

The basic approaches used in the derivation of these techniques can be divided into three broad areas: regime theory, extremal hypothesis, and tractive force (ASCE, 1998a). The first two categories correspond to a state of dynamic equilibrium in which sediment moves but the system tends to a stable configuration. Tractive force methods refer to a state of static equilibrium in which sediment particles are at the threshold of motion.

*Regime relationships* are based on empirical methods, and numerous equations have been published in the literature. A few of the most widely used equations for sand beds are those proposed by Lindley (1919), Lacey (1920), Simons and Albertson (1963), and Blench (1969). Hey and Thorne (1986) present a summary of gravel-bed formulas. Regime relationships have significant shortcomings. Examples of these limitations are:

- The relations can be used reliably only in the geographic region where the basic data were collected.
- Lateral migration is generally not included in the determination of hydraulic geometry.
- The use of one representative discharge (*e.g.,* the bankfull discharge, which is generally considered the channel-forming discharge) as one of the main independent variables may be insufficient to evaluate the effect of discharges in modifying the cross section. In addition, there is uncertainty in the determination of this representative discharge.
- Vegetation, material resistance, sediment loads, groundwater levels and other variables have been sometimes included in the determination of geometry, but there is no consistency among researchers regarding their significance.
- Sediment load is considered an independent input variable, but its magnitude is often unknown or uncertain at best.

*Extremal hypotheses* are additional mathematical conditions that complement the fundamental fluid mechanics equations to allow computation of all variables in sediment transport. These conditions are usually expressed in terms of minimization or maximization of quantities such as stream power, energy dissipation, or sediment concentration (ASCE, 1998a). For example, Chang (1988) establishes that the state of dynamic equilibrium in a channel reach requires continuity of sediment, minimum stream power per unit channel length, and uniform streamwise power expenditure (energy slope). The computer program FLUVIAL-12 was developed on the basis of these assumptions (Section 3.5.2). Another application of extremal approaches can be found in Yang *et al.*, (1981).

*Tractive force* methods define a set of conditions that are conducive to mechanical stability of cross sections. These conditions arise from the momentum equation applied locally to particles on the boundary and requiring equilibrium among gravity, friction, and hydrodynamic forces. The previously discussed Lane's Relationship (Lane, 1955) is one result from this approach. Tractive force methods imply a threshold channel geometry that can change in response to any variation in the force balance. Limitations associated with tractive force formulas are:

- Channels must be straight.
- Secondary flows are negligible. This condition limits applications in meandering channels.
- Sediment must be noncohesive and uniform throughout the channel.
- The theory does not allow sediment transport, which contradicts field observations.

ASCE (1998a) reports developments that enhanced the applicability of tractive force methods. Parker (1978) extended the formulation to allow sediment transport. The resulting equations are complex and were solved only for special conditions. Ikeda *et al.* (1988) considered sediment heterogeneity, Ikeda and Izumi (1990) included the effect of vegetation, and Diplas and Vigilar (1992) applied numerical solutions of the differential equations to solve for the shape of the cross section.

All three equilibrium approaches (regime theory, extremal hypothesis, and tractive force) have limitations when applied to channels of interest in engineering applications. For the purposes of this report, the two most important limitations are:

- Watershed land-use changes impose ever-changing scenarios on the fluvial system to which the streams are constantly adjusting.
- Streams in arid climates are subject to drastic changes in response to infrequent flow events. For example, some alluvial fans exhibit random behavior in the paths preferred by flow episodes. An equilibrium cross section cannot be defined for these situations.

In addition, research indicates that changes occur over a wide range of time scales and that, in addition to fluvial processes, numerous climatic, environmental and geotechnical factors are involved. Induced effects include changes in roughness, bed material composition, vegetation cover, and planform (ASCE, 1998a). These observations suggest that prediction of cross sectional adjustments can only be accomplished for site-specific conditions after the most significant geomorphological factors have been identified. Therefore, any prediction of channel geometry should be based on sound field observations.

### 2.5.2. Fluvial Hydraulics

This section introduces the complexities and modeling difficulties in representing the mechanisms involved in fluvial hydraulics. A general review of the subject can be found in Knight and Shiono (1995).

Fluvial processes are characterized by complex fluid mechanics phenomena. This complexity is the result of spatial and temporal variabilities, some of which have been discussed in previous sections. The following is a summary of these variabilities (ASCE, 1998a):

*Topography:* Variability is due to planform configuration and the presence of bed forms. In addition, overflow into the floodplain during large-magnitude events can produce geomorphologic changes, which are very different from those stemming from in-channel flows.

| | |
|---|---|
| *Roughness:* | Varies according to the different materials along the banks and the bottom and the additional resistance of bed forms. |
| *Sediment:* | Materials in the bed and the banks are heterogeneous and may include both cohesive and noncohesive soils. Armoring produces a sediment distribution different from that of the bulk material. |
| *Water and Sediment Transport:* | These quantities are governed by unsteady phenomena. In addition, sediment supply is the limiting factor and does not depend solely on transport capacity. Therefore, floods of similar magnitude may carry different amounts of sediment. |
| *History of Events:* | The current geometric configuration of channels is a cumulative result of past events. |

Models have been developed to simulate some of the processes; however, the need to simulate variations in the cross section geometry implies that these models must be capable of some two-dimensional representation. Three-dimensional models are required to simulate important mechanisms such as secondary currents in bends; however, these models are not cost-effective for most engineering applications. Therefore, two-dimensional models remain the most appropriate to make predictions on cross sectional changes.

One of the most significant parameters associated with movement of sediment is the shear stress because its magnitude determines if bed and streambank materials will be eroded. In consequence, shear stress is a critical parameter in the definition of cross section geometry. ASCE (1998a) presents a summary of research efforts directed at determining the value of the shear stress. An important phenomenon is the redistribution of shear stresses under overbank flow conditions during large floods, which tends to affect the sediment transport rate. Depending on the direction of the effect, this stress redistribution can lead to erosion or deposition and thus to significant cross section adjustment.

Variations in the longitudinal direction present computational challenges. For instance, many simulation models depend on the definition of cross sections representative of channel reaches. Therefore, some kind of averaging must be conducted to produce computational sections, which are not what exists in the channel in reality. The need for a similar procedure arises when selecting a value for the friction slope representative for the channel reach. This slope directly affects stream power, which is a fundamental quantity in movable-boundary models based on extremal hypotheses. As a consequence of these facts, any prediction in cross section changes should not be applied to a particular section but must be associated with the reach. In addition, streamwise averaging can be particularly complicated during overbank flow due to new flow patterns that may develop (ASCE, 1998a). For example, in meandering streams the sinuosity of the flow paths can vary depending on the elevation of the water surface.

In principle, processes occurring at the banks are directly responsible for changes in the cross section geometry. Velocity, shear stress, secondary currents, and turbulence in the near-bank area control these processes. Knowledge of these processes is imperfect, as evidenced by the above-mentioned difficulties in ascertaining the physics of these phenomena. Tools based on empirical analyses are available to determine the magnitude and distribution of shear stresses (ASCE, 1998a). Within the computational limitations, determination of shear stresses is an important step. However, although the shear stress is the most important variable, it is not the only one, and its role must be analyzed in conjunction with a general geomorphic context, the channel type, and the location in the watershed.

### 2.5.3. Streambank Stability

In addition to hydrodynamically induced erosion and deposition, another important mechanism in defining changes in cross section geometry is the occurrence of mass failure of the streambanks (Photograph 9). ASCE (1998a) discusses seven factors affecting the loss of material in the streambanks:

| | |
|---|---|
| *Bank Erosion:* | This erosion is the result of hydrodynamic drag, which detaches particles and mixes them with the flow. Grain size and its distribution and the bonding mechanism among particles dictate resistance to erosion. Erodibility varies in space due to the various strata along the streambank and the presence of local heterogeneities. Noncohesive materials resist primarily by means of their submerged weight and, to some degree, from grain interlocking. Cohesive materials resist through particle electrochemical bonding. Critical shear stresses for cohesive materials are difficult to determine; however, research indicates that they are greater than for noncohesive particles. Consequently, cohesive banks tend to erode less than noncohesive banks. |
| *Weakening of Erosion Resistance:* | Erodibility can be increased by weathering processes that tend to loosen particles. Some of these processes include, freeze-and-thaw cycles and cracking caused by swelling and shrinkage. |
| *Mass Failure:* | Geotechnical stability of banks is similar to slope stability and depends on the height of the bank and cohesion and friction forces. Failure can occur as a plane slip or rotational slip of the soil wedge (Thorne, 1982) or toppling of a vertical slice triggered by a tension crack (Thorne and Tovey, 1981). Another possibility is the failure of a cantilever configuration associated with toe erosion (Thorne and Tovey, 1981). Mechanisms that trigger mass failure include incision of the channel that increases bank height or, as mentioned earlier, erosion of the bank toe. Figure 2.7 shows schematics of these failure mechanisms. Applications of these failure schemes can be found in Darby and Thorne (1996a), Thorne and Osman (1988), and Osman and Thorne (1988). |
| *Basal Endpoint Control:* | This factor refers to the ability of fluvial erosion to remove the material deposited by mass failure. If the flow can remove this material and continue eroding the bank, the section will be enlarged. If the flow is unable to remove all of the material, a berm will be formed and the section will be narrowed. |
| *Vegetation:* | Vegetation tends to increase the stability of material and hence reduce erosion rates. Vegetation may aid or prevent mass failure. Despite the evidence that vegetation influences soil erosivity and erodibility and mass failure, there is insufficient understanding about the complexity of this role. |
| *Seepage:* | Pore pressure increases can be triggered by rapid drawdown of water in the channel, leaving saturated banks. The water then seeps from the banks into the stream and may cause piping that leads to erosion of soil layers. |

*Bank Advance:* This term encompasses all mechanisms that lead to narrowing of the section due to deposition. Morphological changes can cause aggradation and creation of berms. Colonization by vegetation improves the stability of these berms.

An important limitation of the Osman-Thorne stability analysis procedures is the fact that pore-water and hydrostatic confining pressures are not included. Another limitation is that the plane of failure is assumed to pass through the toe of the embankment. This prevents applicability to upper bank failures, which have been found to be common (ASCE, 1998b). Simon *et al.* (1991) solved some of these shortcomings.

**Photograph 9.** Mass failure of streambank caused by minor flooding event.

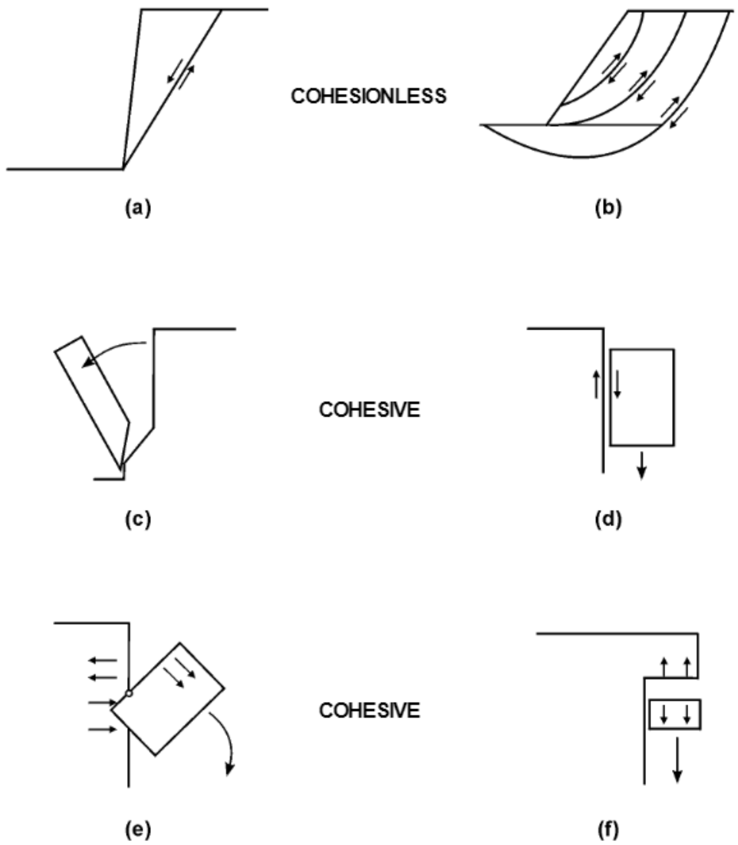



**Figure 2.7.** Mechanisms of bank failure. (a) planar slip, (b) rotational slip, (c) toppling, (d) cantilever shear, (e) cantilever rotational, (f) cantilever tensile (ASCE, 1998a).

## 2.6. Computational Models

The foregoing sections evidence the fact that quantification of geometric changes in channel geometry is a difficult task and that prediction tools need to be improved to obtain reliable results. Several techniques have been introduced in previous sections. This section presents a summary of currently available computational models to predict geometry changes. The material in this section is a summary of a comprehensive review prepared by the American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics, and Modeling of River Width Adjustment (ASCE, 1998b).

Simulation of these complex temporal and spatial phenomena depends on the formulation of a conceptual model to represent the physical setting. Spatial conceptualization can be accomplished by selecting cross sections at given intervals to represent the channel configuration. For most practical applications, the simulation time spans years or decades. The soil material must be represented by a discrete selection of representative grain sizes.

The next step is to select a computational model for the problem. Models can range from empirical equations based on field data to physically based numerical models. Numerical models are comprised of modules that simulate individual but coupled processes. Some of these modules are:

*Hydraulic Module:* Quantifies the fluid mechanics variables in the flow field, chiefly velocities and water-surface elevations.

*Bank Process Module:* Defines streambank retreat or advance as a result of hydrodynamically induced erosion and deposition.

*Sediment Transport Module:* Simulates the movement of sediments through the channel reach.

ASCE (1998b) reviews 12 numerical models available to the engineering and scientific communities to simulate channel geometry changes. The following paragraphs describe the main features of these models.

### *2.6.1. Modeling Approach*

The 12 models are based either on a geofluvial or extremal approach. The "geofluvial" approach couples flow and sediment transport modules with bank erosion and failure modules. As described in Section 2.5.1, the "extremal" approach is an equilibrium approach based on minimization of energy expenditure that tends to yield the final configuration of the channel. The models are listed in Table 2.6 along with the modeling approach they follow.

**Table 2.6.** Twelve computational models to predict channel geometry changes (ASCE, 1998b).

| Model | Approach | Reference |
|---|---|---|
| Darby-Thorne | Geofluvial, cohesive bank | Darby and Thorne (1996b) |
| CCHEBank | Geofluvial, noncohesive bank | Li and Wang (1993) |
| Kovacs-Parker | Geofluvial, noncohesive bank | Kovacs and Parker (1994) |
| Wiele | Geofluvial, noncohesive bank | Wiele (1992) |
| RIPA | Geofluvial, cohesive bank | Mosselman (1992) |
| Simon *et al.* | Geofluvial, cohesive bank | Simon *et al.* (1991) |
| Pizzuto | Geofluvial, noncohesive bank | Pizzuto (1990) |
| STREAM2 | Geofluvial, cohesive bank | Borah and Bordoloi (1989) |
| GSTARS | Extremal hypothesis | Yang *et al.* (1988) |
| FLUVIAL-12 | Extremal hypothesis | Chang (1988) |
| Alonso-Combs | Geofluvial, cohesive bank | Alonso and Combs (1986) |
| WIDTH | Geofluvial, cohesive bank | Osman (1985) |

## 2.6.2. Hydraulics

Models can be one-, two-, or three-dimensional. A fourth category, quasi two-dimensional, represents the cross section with a series of one-dimensional stream tubes.

Models can be steady or unsteady. An intermediate approach is to discretize the hydrographs into steps where flows are assumed steady. This approach is termed "stepped hydrograph" in ASCE (1998b). Other special enhancements to the hydraulic module include secondary flows, near-bank lateral shears, and spatial and temporal variability of friction factors.

Friction losses can be modeled using a variety of flow resistance formulas. An important enhancement would be the inclusion of bed-form resistance, which is not implemented in any of the models investigated.

Table 2.7 summarizes the main features of hydraulic modeling for the 12 models.

**Table 2.7.** Features of flow routing submodels of reviewed models (ASCE, 1998b).

| Model | Dimension | Discharge Variation With Time | Secondary Flows | Lateral Shear | Friction Factor | Flow Resistance Formulas[b] |
|---|---|---|---|---|---|---|
| Darby Thorne | Quasi 2D[a] | Stepped hydrograph | No | Yes | Time and space variable | Strickler |
| CCHEBank | 3D | Unsteady flow | Yes | Yes | Constant | Keulegan |
| Kovacs-Parker | 2D | Steady flow | No | Yes | Constant | Keulegan |
| Wiele | 2D | Steady flow | No | Yes | Constant | Keulegan |
| RIPA | 2D | Stepped hydrograph | Yes | No | Constant | Specified |
| Simon *et al.* | Quasi2D[a] | Stepped hydrograph | No | No | Time and space variable | Strickler, Darcy, and Chezy |
| Pizzuto | 2D | Steady flow | No | Yes | Constant | Einstein |
| STREAM2 | 1D | Stepped hydrograph | No | No | Constant | Specified |
| GSTARS | Quasi 2D[a] | Stepped hydrograph | No | No | Time and space variable | Strickler, Darcy, and Chezy |
| FLUVIAL-12 | 1D | Unsteady flow | Yes | No | Time and space variable | Strickler and Brownlie |
| Alonso-Combs | 1D | Stepped hydrograph | No | No | Constant | Specified |
| WIDTH | 1D | Stepped hydrograph | No | No | Time and space variable | Strickler |

[a]Quasi2D models refer to those models that simulate lateral variation of bed topography through use of multiple one-dimensional stream tubes.

[b]Strickler = Strickler (1923); Keulegan = Keulegan (1938); Einstein = Einstein (1950); Brownlie = Brownlie (1983). None of these formulas account for the effects of bed forms.

### 2.6.3. Sediment Transport

Sediment transport is usually estimated by applying the velocity field to the bed material properties. The sediment continuity equation is used to determine if sediment will be eroded or deposited.

The models reviewed use a variety of sediment transport methods (Table 2.4). Some models only allow the use of one formula, whereas others offer multiple choices to the user. As discussed in Section 2.4.7, sediment transport calculations should use formulas that were derived with materials that resemble the conditions of the problem to be solved. Even under these circumstances, large variations in the sediment transport rates should be expected.

Changes in the bed topography are a result of the net accumulation or removal of material, which can be computed through the sediment continuity equation. Net flux across the channel reach should account for longitudinal and transversal variations of the sediment influx. Nevertheless, a simplified version of the continuity equation is routinely implemented along with assumptions to distribute the sediment loss or gain along the channel reach and across the flow section. These assumptions are more restrictive for one-dimensional models. Only three of the models reviewed do not allow variations of the sediment influx in the longitudinal direction. However, only six out of the twelve allow transversal sediment influx variations.

All of the models perform bed load computations. Seven models allow computation of suspended loads. Sorting of sediments is related to armoring and is an important mechanism because it dictates the hydraulic resistance properties of the bed. Only six of the models allow for modeling of sorting.

Table 2.8 summarizes the properties of sediment transport equations used in the models reviewed.

### 2.6.4. Stability of Streambanks

Table 2.9 compiles the key features of the reviewed models related to the handling of mechanical stability of the streambanks.

As described in earlier sections, changes in streambank geometry are caused by gradual erosion and deposition and mass failure episodes distributed along the length of the river reach. Most models simulate bank retreat due to shear erosion, but only one of the models reviewed simulates channel narrowing due to deposition. Models based on extremal hypotheses (GSTARS and FLUVIAL-12) do not have modules to simulate bank stability processes.

Simulation of fluvial entrainment of bank materials is crucial to determine the rate of bank movement as a result of both mass failure, gradual erosion, and deposition. Only one of the models reviewed does not simulate this process. None of the models include the effects of vegetation, wave action, seepage-induced piping, or other nonfluvial processes on bank advance or retreat. None of the models has the capability to account for layered or otherwise heterogeneous streambank materials. Erosion of cohesive materials is simulated by some of the models, but the empirical methods employed are not very reliable (ASCE, 1998b). Mass failure of cohesive streambanks is simulated in several of the models using the procedures developed by Osman (1985) and Osman and Thorne (1988). Some of the models can simulate planar and curved failure surfaces.

**Table 2.8.** Sediment transport characteristics of reviewed models (ASCE, 1998b).

| Model | Transport Equations | Routing Method | Bed Material | Stream-Wise Flux Difference | Trans-Verse Flux Difference | Bed Load | Susp. Load | Sorting |
|---|---|---|---|---|---|---|---|---|
| Darby-Thorne | Engelund and Hansen (1967) | Quasi 2D | Sand | Yes | Yes | Yes | Yes | Yes |
| CCHEBank | Meyer-Peter-Muller (1948) | 2D | Gravel | Yes | Yes | Yes | No | No |
| Kovacs-Parker | Kovacs and Parker (1994) | 2D | Gravel | No | Yes | Yes | No | No |
| Wiele | Parker (1979) and Meyer-Peter-Muller (1948) | 2D | Sand/ Gravel | No | Yes | Yes | No | No |
| RIPA | Engelund and Hansen (1967) and Meyer-Peter-Muller (1948) | 2D | Sand/ Gravel | Yes | Yes | Yes | No | No |
| Simon *et al.* | Yang (1973, 1984), Ackers and White (1973), and Engelund and Hansen (1976) | Quasi 2D | Sand/ Gravel | Yes | No | Yes | Yes | Yes |
| Pizzuto | Parker (1983) | 2D | Sand | No | Yes | Yes | No | No |
| STREAM2 | Yang (1973), Graf (1971) and Meyer-Peter-Muller (1948) | 1D | Sand/ Gravel | Yes | No | Yes | Yes | Yes |
| GSTARS | Yang (1973, 1984), Ackers and White (1973), and Engelund and Hansen (1976) | Quasi 2D | Sand/ Gravel | Yes | No | Yes | Yes | Yes |
| FLUVIAL-12 | Yang (1973), Parker *et al.* (1982), Ackers and White (1973), Engelund and Hansen (1967), and Graf (1971) | 1D | Sand/ Gravel | Yes | No | Yes | Yes | Yes |
| Alonso-Combs | Alonso *et al.* (1981) | 1D | Sand/ Gravel | Yes | No | Yes | Yes | Yes |
| WIDTH | Engelund and Hansen (1967) | 1D | Sand/ Gravel | Yes | No | Yes | Yes | No |

**Table 2.9.** Streambank stability characteristics of the reviewed models (ASCE, 1998b).

| Model | Deposition | Fluvial Entrainment | Type of Bank Failure | Longitudinal Extent of Failure Included | Cohesive | Non-cohesive[b] |
|---|---|---|---|---|---|---|
| Darby-Thorne | No | Yes | Planar/Curved | Yes | Yes | No |
| CCHEBank | Yes | Yes | None | No | No | Yes |
| Kovacs-Parker | No | Yes | None | No | No | Yes |
| Wiele | No | Yes | None | No | No | Yes |
| RIPA | No | Yes | Planar | No | No | No |
| Simon *et al.* | No | Yes | Planar | No | No | No |
| Pizzuto | No | Yes | None | No | No | Yes |
| STREAM2 | No | Yes | Planar | No | No | No |
| GSTARS | [a] | [a] | [a] | [a] | [a] | [a] |
| FLUVIAL-12 | [a] | [a] | [a] | [a] | [a] | [a] |
| Alonso-Combs | No | No | Planar | No | No | No |
| WIDTH | No | Yes | Planar/Curved | No | No | No |

[a] Models based on extremal hypotheses do not include bank mechanics modules

[b] Assumed uniform in size

For noncohesive banks, an important improvement was the introduction of the vectorial bed load equation by Kovacs and Parker (1994), which extended sediment transport computations for large angles. With this capability, the method can be applied to longitudinal and transversal slopes up to the angle of repose of the material. Nevertheless, the method could be further improved with the coupling of two- or three-dimensional flow models to describe the near-bank flow field.

All but one model assume that mass failure occurs uniformly along the reach length. This assumption could overpredict mass waste material and was relaxed in the Darby-Thorne model with the introduction of a probability of failure.

Models FLUVIAL-12 and GSTARS based on extremal hypothesis attempt to predict equilibrium channel morphology, and hence the result is total change in the cross sections instead of the rate at which this change occurs. A portion of the total change is assigned to the banks and the remainder to the bed. However, the user must specify the distribution of the streambank change between the two banks. According to ASCE (1998b), the procedures implemented in these models are plausible for noncohesive materials but inapplicable to cohesive sediments.

### *2.6.5. Future Directions*

The ASCE (1998b) review of available models to simulate geometry changes concludes the following:

- Some level of prediction is possible with the existing knowledge and tools.

- Of the two major approaches, extremal and geofluvial models, the latter seems to be the most promising although at this time the models have not fully transitioned to the engineering community.

- No one of the existing models seems to be universally applicable to all cases.

- Few appropriate data sets exist for rigorous testing of available models.

The ASCE (1998b) review lists a series of topics that are critical to improve current knowledge of fluvial geometry adjustment:

- Improvement of currently available models through use of better submodels for hydraulics and bank mechanics.

- Acquisition of comprehensive field and laboratory data for model testing and verification. These data must include cross sectional surveys, bed material size distribution and geotechnical characteristics, and discharge and sediment transport records.

- Better characterization of the boundary shear stresses.

- Improved bank mechanical stability modules to properly simulate erosion of cohesive material and distribution across the channel.

- Definition of the longitudinal extent of mass failure.

- Definition of the role of vegetation on flow and geotechnical stability.

- Quantitative models for bank advance and retreat.

- Improvement in the definition of shear stresses for entrainment of cohesive materials.

- Better understanding of the dominant discharge.

- Expansion of bank failure mechanisms to other commonly observed collapse scenarios.

- Understanding of the role of overbank flows in cross sectional adjustment.

# 3. Literature Review

## 3.1. Research Sources and Search

The study team began with an in-depth search of existing methodologies in use to predict riverine erosion with emphasis on case studies. A search on the Internet led to identification of several databases that contained information on the subject. These databases included American Geophysical Union, American Society of Civil Engineers, U.S. Geological Survey, Uncover (commercial database) and university library databases. The publication types included manuals, journal articles, proceedings, case studies, reports, and textbooks. In addition, applicable literature was also found through the team's knowledge and experience in this subject.

There were three levels of screening: an initial screening for relevance, a second screening for apparent applicability, and final screening to select key documents. The initial screening was performed using key words in database search queries. This initial screening yielded several hundred articles. Abstracts were read when available, and documents were selected for apparent applicability.

This second screening yielded 108 pieces of literature (see Appendix). These pieces of literature were obtained and briefly reviewed. From this list of 108, 35 articles were selected and then further culled to12 that appeared to have the most promise.

## 3.2. Literature Summary

To document the results of the literature search, a database application was specifically developed using Microsoft Access. The documents found in the second level of screening (108) were entered into the database using two forms. The first form contains initial basic data elements including: article title, reviewer's initials, review date, where it appeared (journal, periodical, etc.), authors, date of article, number of pages, initial reaction to article, and an assessment as to whether or not the article requires further investigation. If the article required more in-depth investigation, the second, more detailed form was completed.

The second form included the following elements: geographical location, state and flooding source, category of analysis (historic, geomorphic, mathematical), regulatory application or potential cost information, mapping feasibility, limitations or qualifications, short summary of the document, key words, and a list of relevant references mentioned in the article.

## 3.3. Selected Documents

From the final screening, 35 documents remained, and additional criteria further reduced this set of documents to 12. These criteria included geographic coverage, practical applicability, mappability, and potential to derive cost information. An attempt was also made to have representation among the three categories of analysis: historical, engineering and geomorphic methods, and mathematical models. Each of the 12 documents was studied in detail. A summary for each is presented in Chapter 4.

# 4. Analysis of Case Studies

The twelve case studies selected covered portions of the Midwestern and Western United States. Figure 4.1 shows approximate locations of the study areas. The states involved are:

- Arizona
- California
- Illinois
- Iowa
- Minnesota
- Missouri
- Nebraska
- New Mexico
- Texas
- Utah
- Washington
- Wisconsin

A summary of basic characteristics of the study sites is shown in Table 4.1.

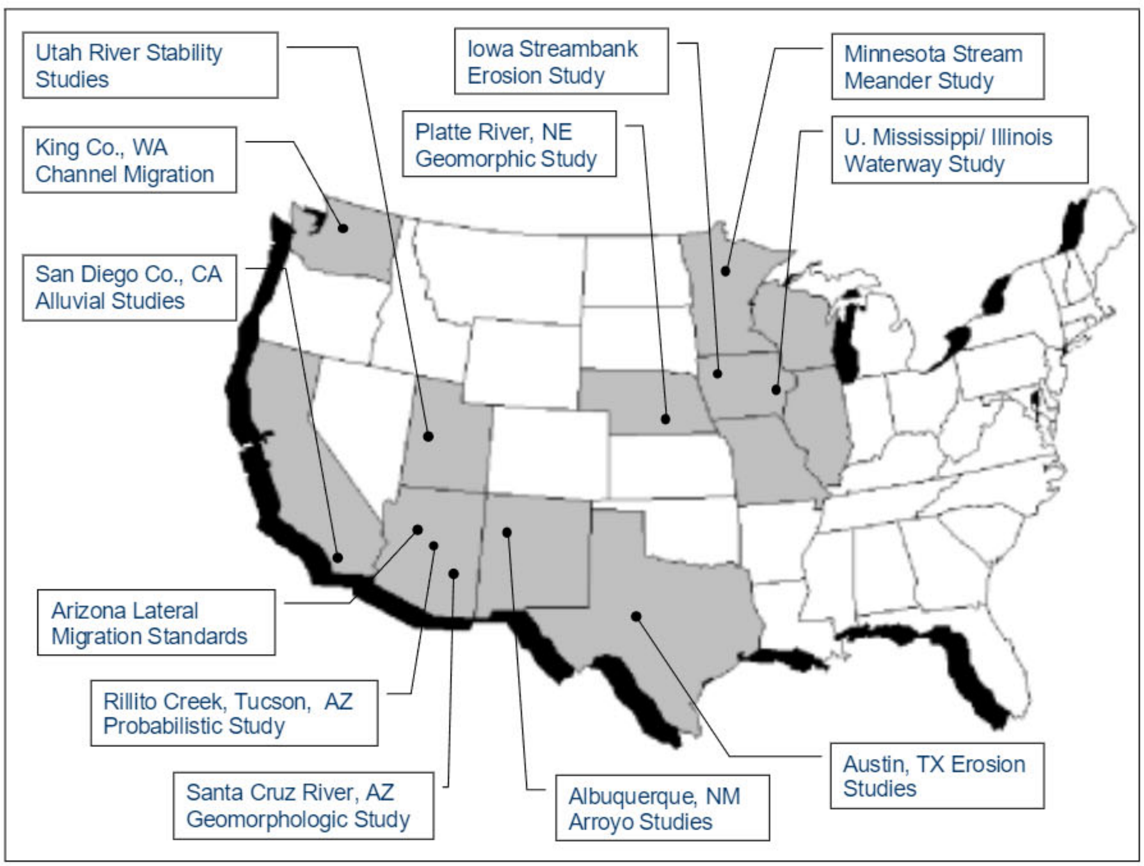



**Figure 4.1.** Location of case studies.

**Table 4.1.** Summary of case studies

| Case Study Title | Location | Drainage Area ($mi^2$) | Stream Type | Study Method Category |
|---|---|---|---|---|
| AMAFCA Sediment and Erosion Design Guide | Albuquerque, New Mexico | 1 - 100 | Arroyos | Geomorphic and engineering analysis |
| Inventory and Analysis of Stream Meander Problems in Minnesota | 14 streams in Minnesota | Information not available | Perennial | Geomorphic (using historic data) |
| A Probabilistic Approach to the Special Assessment of River Channel Instability | Rillito Creek, near Tucson, Arizona | 920 | Ephemeral | Mathematical (using historic data) |
| Geomorphology and Hydrology of the Santa Cruz River, Southeastern Arizona | Santa Cruz River basin, Arizona | 3,640 | Ephemeral and perennial | Geomorphic (using historic data) |
| San Diego County Alluvial Studies | San Diego County, California | 40. (Model has been run for 1 – $10^5$ $mi^2$) | Ephemeral and perennial | Mathematical modeling |
| City of Austin Technical Procedures for Watershed Erosion Assessments | Austin, Texas | 1 - 30 | Ephemeral and perennial | Engineering and geomorphic analyses |
| River Stability Study, Virgin River, Santa Clara River and Ft. Pierce Wash, Vicinity of St. George, Utah | Virgin River , Santa Clara River, and Ft. Pierce Wash basins, Utah | 550 - 3,800 | Ephemeral and perennial | Geomorphic |
| Hydrologic and Geomorphic Studies of the Platte River Basin, Nebraska | Platte River basin, Nebraska | Information not available | Perennial | Geomorphic |
| Streambank Erosion Along Two Rivers In Iowa | East Nishnabotna River and the Des Moines River, Iowa | 960 - 1,450 | Perennial | Engineering analysis with geomorphic analysis using historic data |
| Channel Migration Studies in King County, Washington | Snoqualmie , Tolt, Raging, and Green Rivers, King County, Washington | 30 - 360 | Perennial | Geomorphic and engineering analysis (using historic and field data) |
| Bank Erosion Field Survey Report of the Upper Mississippi River and Illinois Waterway | Upper Mississippi River and Illinois Waterway, Minnesota, Wisconsin, Iowa, Illinois, and Missouri | 28,900 $mi^2$, for Illinois Waterway | Perennial | Geomorphic and engineering analysis (using the field data) |
| Arizona Standards for Lateral Migration and Channel Degradation | Arizona, statewide | Information not available | Ephemeral and perennial | Geomorphic and engineering analysis |

## 4.1. AMAFCA Sediment and Erosion Design Guide

| | |
|---|---|
| *Document Title:* | Sediment and Erosion Design Guide (AMAFCA, 1994) |
| *Agency:* | Albuquerque Metropolitan Arroyo Flood Control Authority |
| *Authors:* | Robert Musseter, Peter Lagasse, and Michael Harvey |
| *Date:* | March 1994 |
| *Study Method Category:* | Geomorphic and engineering analysis |

### 4.1.1. Overview

The AMAFCA Sediment and Erosion Design Guide is a comprehensive design manual containing procedures to analyze arroyos and to design control projects. In this document, hydrologic, hydraulic, geomorphic, and sediment transport aspects are evaluated for the Albuquerque, New Mexico, area and specifically for the arroyo drainage system. The analysis procedures consist of three levels of analysis with increasing degree of complexity.

Level 1 is a qualitative study based on planform analysis and bed material evaluations. This level of analysis is appropriate for cases with limited sources of information. Level 2 is an engineering analysis that provides a cumulative assessment of channel adjustment based on detailed studies of bed and bank materials, sediment transport properties, and quantification of channel changes and local scour. This level of analysis can be implemented using a moderate amount of resources. Level 3 is the most complex level and requires application of mathematical and physical models to simulate the effects of flooding on channel geometry. The Guide concentrates on Levels 1 and 2; a brief description of Level 3 is given.

The AMAFCA Sediment and Erosion Design Guide defines hazard areas in the form of setbacks and discusses several erosion control and countermeasure criteria. This manual is an application and update of a similar document prepared by Simons, Li & Associates (1985).

### 4.1.2. Detailed Description

This manual provides specific relevant information on hydrologic analysis, the hydraulics of alluvial channels, and sediment transport analysis. The document also proposes guidelines for assessing the evolutionary stage of arroyos and forecasting the impact of development in the transformation of existing drainageways into arroyos.

The information presented defines channel design criteria and areas subject to erosion. Setbacks, defined in terms of the concept of "Prudent Line," are used to mark a zone of unacceptable erosion risk. The "acceptable risk" in the Prudent Line concept is defined in terms of the potential flooding effects of a 100-year event occurring at any time within a 30-year period. Also included is the cumulative erosion effect of all other storms weighted by their probability of occurrence.

The AMAFCA Guide provides concise descriptions of geomorphology, watershed processes, and arroyo channel dynamics. Related topics include rainfall-runoff processes, sediment yield, channel incision and widening, alluvial channel hydraulics, sediment transport, channel adjustments and stability, and local scour. However, the most important component of the manual in connection with REHAs is the application of the Prudent Line concept.

The general approach is to analyze a given problem with progressively more complex techniques. Following the premise that accurate results can be obtained while minimizing costs, analyses can begin with a qualitative approach, continue with basic quantitative techniques, and, if necessary, use complex modeling procedures. The three levels of the approach are as follows:

- Level 1 – Geomorphic and Other Qualitative Analysis
- Level 2 – Basic Engineering Analysis (Hydrology, Hydraulics, and Sediment Transport)
- Level 3 – Mathematical and Physical Model Studies

The purpose of this multilevel approach is twofold. First, it allows appropriate characterization techniques to be selected according to available data. Second, the sequence provides insight and direction for progression to the next more complex level based on information gathered at the previous level. As more data become available, iterations among the levels allow for more accurate solutions. In addition, the approach allows conclusions among the levels to be cross-checked.

#### *4.1.2.1. Level 1 — Geomorphic and Other Qualitative Analysis*

The foundations of a Level 1 study lie primarily on fluvial geomorphology and channel mechanics. Successful application of these concepts requires sound knowledge and considerable practical experience. The goal of a Level 1 study is to develop an understanding of the fluvial system's response to watershed changes and thus be able to predict changes in bed geometry. In Level 1, geomorphic principles that are applied to predict channel response require limited data but provide a qualitative assessment.

Data for Level 1 must be able to characterize the conditions of the channel and demonstrate evidence of trends and changes in the fluvial system and the watershed. The following are examples of this information:

- Area, vicinity, site, geologic, soils, and land use maps
- Aerial photographs
- Notes and photographs from field inspections
- Historic channel profile data
- Bridge as-built drawings and cross-section data
- Existing and planned human activities (urbanization, clearing, channelization, sand and gravel mining, bend cutoffs, dam construction, reservoir operations)
- Bed and bank material characteristics
- Discharge regime
- Data on morphological changes

The steps involved in Level 1 investigations are described below.

*Step 1 – Define Channel Characteristics*

Knowledge of the arroyo or drainageway characteristics provides a basic description of channel behavior in time and space. Channel incision, widening, and other features are indicators of past and present stability of channel alignment and banks. Bank stability is measured in terms of the "geotechnical stability number," which is equal to the ratio of bank height to a critical bank height. Channel stability is assessed by means of the "hydraulic stability factor," which is the ratio of the desired sediment supply to the actual supply.

*Step 2 – Evaluate Watershed Conditions*

This step seeks to evaluate sediment yield in response to watershed processes. Evaluation factors include land use, human activity, and vegetation. Changes in these variables are classified qualitatively; for instance, vegetation can be increasing, damaged, destroyed, or unchanged. The objective of this step is to correlate watershed changes with channel instability to understand the system's response.

*Step 3 – Assess Overall Stream Stability*

The AMAFCA Guide includes charts to interpret planform characteristics as predictors of stability. Possible channel forms cover straight, meandering, and braided patterns. The charts allow overall stability to be evaluated based on the geotechnical stability number and the hydraulic stability factor.

*Step 4 –Evaluate Lateral Stability*

Field inspections and material analysis can reveal bank configurations that may lead to failure. Alternatively, the bank stability analysis can be completed from data on bank position at different points in time as indicated in aerial photographs. This step should also seek to identify any potential avulsion effects.

*Step 5 –Evaluate Vertical Stability*

Data records during several years are usually necessary to detect changes in bed elevation. Qualitative assessment of vertical stability problems can be obtained through the use of the Lane Relationship (Lane, 1955), sediment continuity, or channel dynamic equilibrium concepts.

*Step 6 –Evaluate Channel Response to Change*

The previous steps provide information for understanding channel responses to changes or potential responses to proposed changes in the watershed. The Lane Relationship is an example of a tool to predicts overall channel changes.

#### *4.1.2.2. Level 2 — Quantitative Geomorphic and Basic Engineering Analysis*

Level 2 improves the general information provided by Level 1 because it assigns quantitative measures to the general changes predicted. Level 2 relies mostly on basic engineering principles to quantify responses. The techniques used include evaluation of longitudinal slope changes, analysis of bed and sediment materials, sediment transport relationships, and frequency analysis for water and sediment.

The data needed for this analysis includes the following types of hydrologic, hydraulic, and sediment transport analyses and information:

- Watershed geometry
- Channel geometry
- Hydraulic channel data (roughness, cross sections, alignment)
- Streamflow records
- Land use, soils, and geologic data
- Sediment discharge records

- Flood frequency records
- Flood hydrographs and dominant discharge
- Particle size gradations
- Reservoir operation policies and sedimentation data
- Hydrologic and hydraulic modeling

The following are the steps to be conducted during Level 2 investigations.

*Step 1 – Evaluation of Flood History*

Hydrologic characterization is critical in understanding the response and morphologic evolution of arid lands. For instance, arroyos in the Albuquerque area only exhibit flow in response to individual rainfall events. Analysis of changes in arroyo channels requires the development of a flood frequency curve for the 2-, 5-, 10-, 25-, 50-, and 100-year events. The AMAFCA Guide recommends making an analysis of hydrographs in arroyos using the Development Process Manual for the City of Albuquerque (City of Albuquerque, 1993).

*Step 2 – Evaluation of Hydraulic Conditions*

Stability analysis requires knowledge of flow characteristics, including velocity, flow depth, top width, and other similar variables, to assess scour and sediment transport capacity. A hydraulic evaluation can be conducted using uniform flow equations and hydraulic-profile computer models (*e.g.*, HEC-2, HEC-RAS). The AMAFCA Guide provides guidelines to evaluate the relationships between water surface and bed configuration in sand beds. Equations are provided to determine the amount of resistance opposed by sand-bed channels. Classic concepts of water surface superelevation at bends and supercritical flow are used to complement the analysis.

*Step 3 – Bed and Bank Materials Analysis*

This step is essential to establish channel stability conditions and to conduct sediment transport analyses. Level 2 requires a detailed analysis of bed and bank materials to evaluate the erodibility and stability of the channel, which are functions of the grain size distribution. Techniques to measure grain sizes and determine distributions include sieving, photographic methods, and sedimentation methods.

When the above methodologies are not applicable because of particle weight limitations or the presence of thin surficial layers, sampling techniques should be applied. The document provides a reference to areal, grid, and transect sampling (Kellerhalls and Bray, 1971) and discusses the application of grid sampling.

*Step 4 – Estimation of Watershed Sediment*

Sediment production and transport in a watershed ultimately determine the amount of material reaching the stream network. Detention facilities are an important consideration. For instance, reservoir trapping of the sediment load may have serious consequences in the sediment transport regime downstream of the dam. The analysis must first obtain a qualitative evaluation of sediment sources and erosion processes. Nevertheless, sediment quantification tends to be imprecise. For this reason, assessments are better conducted by analyzing changes induced by disturbances in the watershed with respect to a baseline condition. The AMAFCA Guide recommends the use of the Pacific Southwest Interagency Committee's rating methodology for sediment yield (PSIAC, 1968) and the application of the Modified Universal Soil Loss Equation (MUSLE).

*Step 5 – Evaluation of Bed Armoring Potential*

Incipient motion analysis can be used to assess relative channel stability. The critical point of balance between hydrodynamic and friction forces can be determined through the use of the Shields relation, which relates particle diameter to shear stress. Determination of the critical particle size for a range of discharges provides insight into the potential disruption to bed materials. In the sand beds typical of Albuquerque, even the smallest flows are capable of setting some of the bed material in motion. The formation of an armor layer provides a threshold discharge below which no degradation will occur. Conversely, degradation will occur for discharges exceeding this threshold. The potential for armoring can be evaluated using a simple relationship developed by the U.S. Bureau of Reclamation (USBR, 1984).

*Step 6 – Evaluation of Degradation/Aggradation Potential*

Degradation or aggradation in a channel can be investigated through analysis of sediment continuity. Comparison between the estimated sediment inflow and the transport capacity of the channel indicates the change in the sediment stored in the reach. This analysis is usually conducted assuming a fixed bed but could be performed more accurately if the geometry of cross sections is allowed to vary in time according to sediment removal or deposition. However, the AMAFCA Guide states that this additional degree of complexity is not usually warranted for arroyos in Albuquerque.

The procedure consists of subdividing the channel reach into subreaches and determining hydraulic characteristics using uniform flow calculations or a computer program such as HEC-2. The next step is to determine the sediment transport capacity of each subreach using a suitable method; for instance, the Meyer-Peter/Muller-Einstein Method (Simons, Li & Associates, 1985), Yang's Bed Material Equation, Colby's Method, or a power function such as the Zeller-Fullerton Relation. These methods are described in sufficient detail in the AMAFCA Guide. The continuity principle is applied assuming that the sediment transport capacity of an upstream subreach is equal to the sediment inflow to the next downstream subreach.

*Step 7 – Evaluation of Lateral Erosion Potential*

Lateral erosion is best analyzed with a combination of Level 1 and Level 2 techniques. Field reconnaissance and comparison of channel patterns in aerial photographs can be used to estimate historic rates of lateral migration. Level 2 techniques include examining the stability of banks subject to undermining and tension fracturing. Several researchers have assumed various modes of wedge-shaped failure. The AMAFCA Guide suggests that those proposed by Ponce (1978) and Osman and Thorne (1988) are suitable for arroyos in Albuquerque.

The method for assessing lateral migration can be chosen depending on the results of the sediment continuity analysis. If the reach is degrading, undercutting of the banks provides the supply of sediment and bank failure is the principal cause for lateral changes. If the channel is nearly in equilibrium and neither erosion nor deposition is expected, lateral migration is due to local erosion of bank material due to planform configuration. In this case, the best method for estimating lateral changes involves examining empirical or historic migration rates. In the absence of this information, the AMAFCA Guide presents a calculation method for sediment transport capacities based on the optimal shape of bends, bend shear stress, and sediment continuity.

*Step 8 – Evaluation of Local Scour*

This step analyses the local erosional phenomena caused by bridge piers and other similar obstacles in the flow. The Colorado State University equation is recommended for computation of pier scour (Richardson *et al.*, 1991). Local scour also occurs downstream of check dams and other grade control structures. Estimation techniques include procedures in the *Design Guide for Riprap-Lined Flood Control Channels* (AMAFCA 1983) and the Veronese equation (Pemberton and Lara, 1984). The scour effects of revetments, spurs, and abutments can be quantified using the methods in the paper "Evaluating Scour at Bridges, Hydraulic Engineering Circular No. 18," (Richardson *et al.*, 1991). The AMAFCA Guide suggests procedures to evaluate scour induced by the presence of floodwalls. An equation presented in "Hydraulic Design of Highway Culverts" (FHWA, 1985) can be applied to quantify local scour at culvert outlets.

#### *4.1.2.3. Level 3 — Quantitative Analysis Using Numerical Models*

This level involves the application of numerical models that implement the governing equations for physical processes in sediment transport and erosion. The Guide provides only a general description of the procedures involved. Various scenarios using these mathematical models need to be simulated on computers. Because Level 3 demands considerable resources, its application must be considered against project requirements, time, and budget constraints.

Models are subject to the limitations in the theories that attempt to assign a mathematical representation to a physical phenomenon. The large degree of uncertainty in current understanding of sediment and erosion processes suggests that modeling results must be examined critically. In the end, the information from Levels 1 and 2 must be used to understand and validate the predictions of numerical modeling.

There are numerous models available. The simplest ones are movable-bed models that simulate hydraulics while updating channel geometry to account for the effects of sedimentation and erosion. Examples of these models are the USACE's HEC-6 and BRI-STARS (Molinas, 1993).

Other models, such as the FLO-2D or FLUVIAL-12, incorporate sediment transport calculations in hydraulic simulations. FLO-2D is a two-dimensional, finite-difference flood routing model that applies the full dynamic equations for channel flow and includes aggradation and degradation. The FLO-2D model offers the option to include any sediment transport equation. FLO Engineering, Inc., distributes FLO-2D.

FLUVIAL-12, developed by Dr. Howard Chang, of San Diego State University (Chang, 1988), was developed to simulate water and sediment routing in channels. River change includes aggradation and degradation and allows the inclusion of physical constraints affecting channel erodibility. This model is one-dimensional, and the space domain is represented by cross sections along the channel.

Physical models can be built in a hydraulics laboratory and often produce better results than numerical simulations due to the computational limitations in the mathematical models. Physical models are expensive, and their need must be justified by the project objectives.

#### *4.1.2.4. Prudent Line Analysis*

The definition of an erosion hazard by means of a Prudent Line is based on the concept of acceptable risk. The standard used in the AMAFCA Guide considers both the short-term flooding and erosion impact of the 100-year event and the long-term cumulative erosion effect of less severe events over the span of 30 years.

These are the steps for determining Prudent Lines:

1. Conduct a Level 1 analysis to characterize vertical and lateral stability of the arroyo.

2. Conduct a Level 2 analysis to determine the hydraulic behavior of the system.

3. Conduct a Level 2 analysis to characterize sediment transport in the channel and assess the potential for lateral migration caused by both the 100-year event and the cumulative effect of less severe events.

4. Use the results of the previous steps to delineate erosion hazard areas by plotting the estimated extent of both short- and long-term erosion at several cross sections. Figure 4.2 shows three cases of hazard area delineation.

The AMAFCA Guide refers to computer programs that have been developed to assist in the determination of Prudent Lines.

The final portion of the guide is devoted to selection and implementation of erosion control measures. In addition to the Prudent Line, the document recommends the definition of a "maintenance line" beyond which protective measures must be implemented to prevent further erosion.

### *4.1.3. Applicability*

This manual offers a systematic approach to characterization of riverine erosion hazards. It does not appear plausible that the results from Level 1 analyses alone will be sufficiently accurate. Level 3 analysis requires information and resources that may not be available to most communities. A combination of Level 1 and Level 2 appears to provide a adequate accuracy while imposing only moderate demands on the effort that must be undertaken.

The AMAFCA Guide is directed specifically to arroyos in the Albuquerque area. However, the methodology can be readily expanded to other fluvial systems.

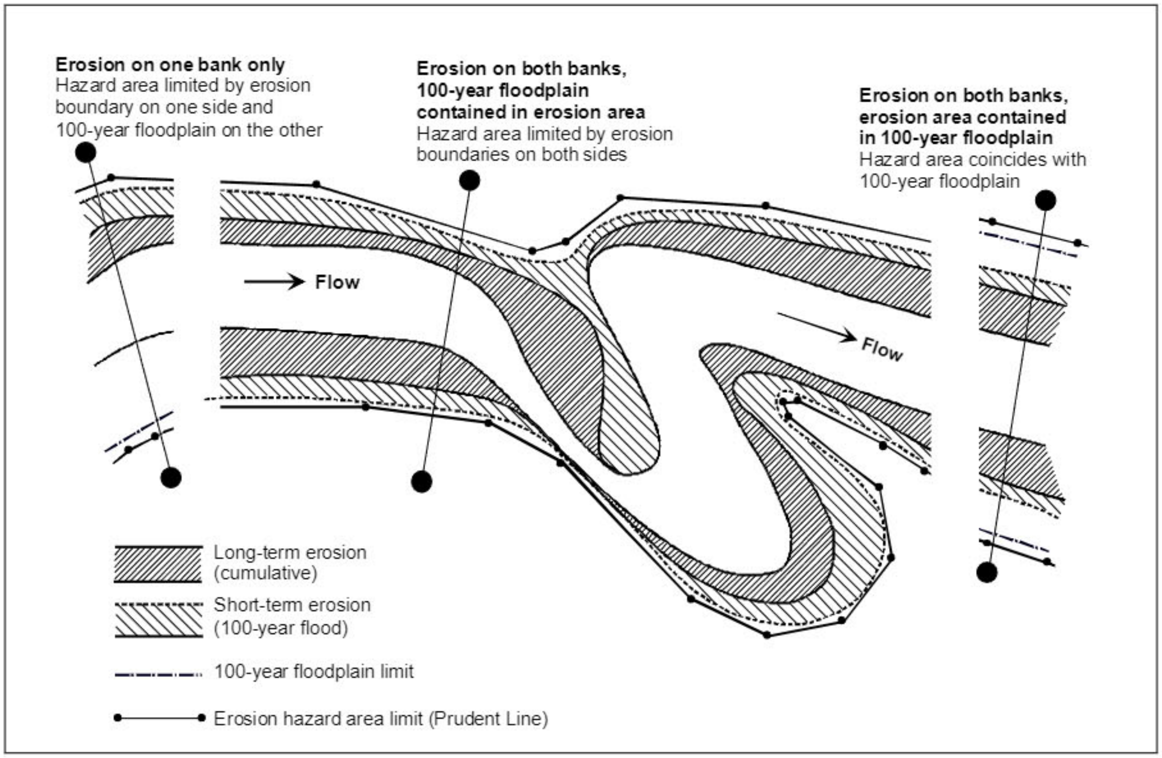



**Figure 4.2.** "Prudent Line" definition (AMAFCA, 1994).

### *4.1.4. Limitations*

The limitations in the methodology stem mostly from those in the individual analysis techniques utilized. The main sources of uncertainty are the inherent inaccuracies in sediment transport computations.

One important assumption is that bank-related sediment is provided by only one bank. This is usually the case for curved reaches but not for initially straight channels. In this case, the methodology adopts a conservative approach by extending the erosion area on both sides unless there is evidence that a geologic feature might exert some degree of erosion control. In addition, the Prudent Line concept may not be applicable in cohesive soils.

The methods proposed can be applied in vertically stable or degradational reaches; however, behavior of aggradational reaches is more difficult to predict due to uncertainty in the development of flow paths.

### *4.1.5. Relevant References*

Albuquerque Metropolitan Arroyo Flood Control Authority (1983), *Design Guide for Riprap-Lined Flood Control Channels.*

Chang, H. H. (1988), *FLUVIAL-12: Mathematical Model for Erodible Channels – User's Manual,* San Diego, California.

City of Albuquerque (1993), *Development Process Manual*, Section 22.2, "Hydrology," Volume 2, Design Criteria, prepared by the DPM Drainage Design Criteria Committee.

Federal Highway Administration (1985), *Hydraulic Design of Highway Culverts*, U.S. Department of Transportation, Hydraulic Design Series No. 5.

Kellerhalls, R. and D.I. Bray (1971), "Sampling procedures for coarse fluvial sediments," ASCE Journal of the Hydraulics Division, V. 97, No. HY8, p. 1165-1179.

Lane, E. W. (1955), "Design of stable channels," Transactions of the American Society of Civil Engineers, 120, p.1234-1260.

Molinas, A. (1993), *User's Manual for BRI-STARS (Bridge Stream Tube Model for Alluvial River Simulation)*, National Cooperative Highway Research Program, Project No. HR15-11.

Osman, A. M., and C. R. Thorne (1988), "Riverbank Stability Analysis I: Theory," ASCE Journal of Hydraulic Engineering, vol. 114, HY2, pp.134-150.

Pacific Southwest Interagency Committee (1968), *Factors affecting sediment yield in the Pacific Southwest areas*, Water Management Subcommittee, Sediment Task Force.

Pemberton, E.L., and J. M. Lara (1984), *Computing Degradation and Local Scour*, Technical Guidelines for Bureau of Reclamation, Engineering Research Center, Denver, Colorado.

Ponce, V.M. (1978), "Generalized Stability Analysis of Channel Banks," American Society of Civil Engineers Journal of the Irrigation and Drainage Division, V. 104, No. 1R4, p. 343-350.

Richardson, E.V., L.J. Harrison, and S. R. Davis (1991), *Evaluating Scour at Bridges*, Hydraulic Engineering Circular No. 18, U.S. Department of Transportation, Federal Highway Administration, Turner Fairbanks Highway Research Center, McLean, Virginia.

Simons, Li & Associates, Inc. (1985), *Design Manual for Engineering Analysis of Fluvial Systems*, prepared for Arizona Department of Water Resources.

U.S. Bureau of Reclamation (1984), *Computing Degradation and Local Scour,* Technical Guidelines for the Bureau of Reclamation.

### *4.1.6. Mappability*

The methodology proposed is suited for mapping purposes and allows differentiation between short-and long-term erosion areas. A certain degree of engineering judgement must be applied during the actual delineation of erosion-prone areas when erosion appears to be controlled by localized features.

### *4.1.7. Cost*

No information on cost is presented in the AMAFCA document. Dr. Peter Lagasse, member of the PWG, estimates $10,000 per stream mile, of which $5,000 are used for conventional baseline hydrology and hydraulic studies.

### *4.1.8. Regulatory Potential*

The concept of the Prudent Line as a regulatory tool was implemented by AMAFCA following the example of other jurisdictions. These jurisdictions, for instance Fort Collins, Colorado (Grimm, 1996), and Tucson, Arizona (Simons, Li & Associates, 1985, Kresan, 1988), have implemented similar approaches based on three levels of analysis to delineate erosion hazard areas. The Prudent Line approach may not apply to cohesive soils.

### 4.1.9. Summary

The AMAFCA Guide presents a series of techniques and procedures to analyze lateral and vertical movement of large fluvial channels. The emphasis of the manual is to provide a technical basis for design of flood control projects. Hydrologic, hydraulic, geomorphic, and sediment transport aspects are evaluated.

The general approach to sediment transport is subdivided into three levels with increasing degrees of complexity. Level 1 is based on planform analysis and basic bed material evaluations. Level 2 provides a cumulative assessment of channel adjustment based on detailed study of bed and bank materials, sediment transport properties, and quantification of channel changes and local scour. Level 3 involves application of mathematical models to simulate the effect of floods on channel geometry.

The main outcome of the methodology is the development of a Prudent Line approach that can be used for delineation and regulation of erosion hazard areas.

## 4.2. Inventory and Analysis of Stream Meander Problems in Minnesota

| | |
|---|---|
| *Document Title:* | Inventory and Analysis of Stream Meander Problems in Minnesota (MacDonald *et al*., 1991) |
| *Agency:* | St. Anthony Falls Hydraulic Laboratory |
| *Authors:* | Thomas E. MacDonald, Gary Parker, and Dave P. Leuthe |
| *Date:* | August 1991 |
| *Study Method Category:* | Geomorphic Equations (using historic data) |

### 4.2.1. Overview

The study was funded by the Legislative Commission on Minnesota Resources, State of Minnesota. The purpose of this quantitative geomorphic study is to identify meandering streams and rivers in the state of Minnesota experiencing bank erosion problems and to analyze the erosion problem both quantitatively and qualitatively. The report focuses on the analysis of 16 stream reaches ranging from very small (Kanaranzi Creek, bankfull width 25 ft) to very large (Minnesota River, bankfull width 290 ft). The names and locations of stream reaches are listed in Table 4.2.

The analysis was conducted using historic aerial photographs and topographic maps as basic data sources. Several parameters, including valley center line and stream center line, were measured for each reach from digitized photographs taken at two different time periods. The average annual shift of the stream was estimated using the computer program MEANDER. The study then attempted to establish a relationship between stream shift and the various stream parameters. Several relations were obtained.

The study includes literature review, geographic, hydrologic and geomorphic information for each stream or river analyzed, description of aerial photographs and maps used for analysis, and results from the stream shift estimation program MEANDER. The last part of the document discusses plotting and multivariate linear regression analysis that were performed to seek relationships between stream parameters and results. The program MEANDER has been used in studies in other states, such as Illinois (Garcia, *et al*.,1996).

### 4.2.2. Detailed Description

This report consists of two parts. In the first part, stream reach descriptions, consisting of tables, ground and aerial photographs and graphics, provide information on each stream reach analyzed and present results for each reach. The second part explains how the data and measurements were gathered and how this information was used to obtain the results.

**Table 4.2.** Streams and location of study reaches.

| Stream | Location |
|---|---|
| Big Fork River | Koochiching County |
| Buffalo Creek | McLeod County |
| Cottonwood River | Brown County |
| Hawk Creek | Renville County |
| Kanaranzi Creek | Rock County |
| Minnesota River A | Nicollet and Big Earth Counties |
| Minnesota River B | Scott County |
| Mississippi River A | Aitkin County |
| Mississippi River B | Aitkin County |
| Nemadji River | Carlton County |
| Rice Creek | Anoka County |
| Root River | Houston County |
| Rum River | Isanti County |
| Wild Rice River A | Norman County |
| Yellow Medicine River | Yellow Medicine County |
| Zumbro River | Wabasha County |

#### *4.2.2.1. Data Collection and Preparation*

Selection of stream reaches was conducted through the Minnesota Department of Natural Resources. Channel shift was measured over a chosen time period to demonstrate that sufficient shift had occurred for meaningful measurement. For most reaches, this time period is approximately 20 years.

A base map for each reach was created by photographically enlarging a portion of a USGS 7.5-minute topographic map. The aerial photographic maps were then reproduced to the same scale. Stream and valley centerlines were digitized and smoothed to create coordinate data sets. Hydrologic and hydraulic information collected includes two-year storm discharge, bankfull width, stream depth, and channel slope. In addition, bed materials were analyzed to develop grain size distributions for each site.

#### *4.2.2.2. Shift Measurement*

The study a used a Lagrangian reference system to measure stream shift. With the Lagrangian reference, attention is focused on the area surrounding the stream centerline. Centerline movement is measured in the direction normal to the stream bank or, alternatively, the stream centerline.

The first step in the shift measurement process was to equally space and smooth Cartesian x-y coordinates for the stream centerline at the beginning and end of the time period, as well as for the valley centerline. A piecewise spline function was fitted to each centerline. Then, the angular alignment of the stream centerline and the stream curvature were computed for each coordinate. The next step consisted of measuring the normal distance between each point in the initial centerline and the centerline at a later time. The normal shift at each coordinate was then broken down into downvalley and crossvalley components. In the last step, each component was integrated over the entire reach to yield an average annual shift rate.

#### *4.2.2.3. Results Summary*

Many useful results are obtained through the shift measurement process. These include the stream sinuosity, average sinuosity change per year, average normal shift per year, average transverse shift per year, average longitudinal shift per year, and shift ratio. The average normal shift is the most basic and useful information because it indicates how much and how fast the stream banks were eroded during the period studied. Therefore, the normal shift could be used as a basis for predicting future shift.

The floodplain area reworked by the stream per unit stream length per year was computed by integrating the area between the stream centerline at the beginning and end of the time period. This information allows floodplain managers to predict how much land surrounding the stream reach would be affected by meandering.

#### *4.2.2.4. Relationships Between Stream Parameters and Measured Results*

Relationships were sought among stream parameters (slope, sinuosity, 2-year discharge, bankfull width and depth) as well as between independent stream parameters and the dependent shift parameters. It was found that the average normal shift rate is strongly correlated to stream depth and discharge. In both cases, the correlation coefficient is higher than 0.73. Similar strong correlations were found between areas reworked by the stream, and depth and discharge.

### *4.2.3. Applicability*

The report offers a systematic approach to characterizing stream shifts. The computer program MEANDER is available from St. Anthony Falls Hydraulic Laboratory. It is able to compute the average shift rate for a time period provided that stream reach data are available for the beginning and end of the study period.

The relationships produced by regression analysis might be applicable to other stream reaches with similar hydrologic and geomorphic conditions. The accuracy of using such relationships to predict stream shift was not reported.

### *4.2.4. Limitations*

The study focused on the shift of stream centerlines over time; however, bank movements were not studied in depth. The shift rules only apply to the reaches where they were developed. This observation is particularly important for smaller streams, which often change rapidly in space. Likewise, the given shift rates apply best for the period covered by the study, although they may be used for short-term predictions. Rapid changes in land use occurring in many watersheds may limit the applicability of the methodology.

The study is based on descriptive information; it was not aimed at revealing causes of stream shift and erosion from either a geomorphic or an engineering point of view.

### *4.2.5. Relevant References*

Garcia, M.H., L. Bittner and Y. Niño (1996), *Mathematical Modeling of Meandering Streams in Illinois: A Tool for Stream Management and Engineering*, 2nd edition, University of Illinois at Urbana-Champaign.

Hasegawa, K. (1989), "Universal bank erosion coefficient for meandering rivers," ASCE Journal of Hydraulic Engineering, vol. 115, No. 6.

Parker, G. (1982), *Stability of the Channel of the Minnesota River near State Bridge No 93, Minnesota.* St. Anthony Falls Hydraulic Laboratory, University of Minnesota

Parker, G. (1983), "Theory of meander bend deformation," River Meandering, Proceedings of the Conference Rivers '83, New Orleans, Louisiana.

### 4.2.6. Mappability

A stream centerline shift graph was prepared for each reach and presented in the report. It is easy to overlap it with a base map to produce a map to show the meander history and to predict stream shift in the near future. However, there is not sufficient information provided in the report to produce bank erosion maps.

There are two possible directions to enhance the methodology for the purpose of mapping riverine erosion hazard areas. The model MEANDER could be used to delineate the stream banks instead of the centerline. The historic migration progress of the stream banks can be traced and the prediction can be made based on the historic trend. Another option is to use hydraulic models to simulate interactions between the stream bank and the flow (Hasegawa, 1989) and use the results to estimate the width of the erosion band. This procedure may provide more accurate results, but significant amount of additional work is needed.

### 4.2.7. Cost

No cost information was reported.

### 4.2.8. Regulatory Potential

Although the study focused on the shifts of stream centerline, the method, with additional effort, can be further developed to meet the needs of measuring and estimating stream bank movements.

The State of Minnesota is not regulating riverine erosion; therefore, the information obtained from the study has not been used for the regulation purposes.

### 4.2.9. Summary

Sixteen stream reaches in Minnesota were analyzed for stream shift and meander properties. Aerial photographs for a minimum of two different times, approximately 20 years apart, and topographic maps were used to produce x-y coordinate data files for valley centerlines and stream centerlines. The computer program MEANDER was used to measure various components of stream shift. The most useful parameters computed were the average normal shift and the rate of floodplain area rework by the stream reach. The results of the computer analysis were used in a regression analysis to determine relations between stream shift properties and stream parameters. The most useful relations include average normal shift versus depth, average normal shift versus discharge, rate of area rework versus depth, and rate of area rework versus discharge.

The methodology may be further developed to meet regulatory needs.

## 4.3. Probabilistic Spatial Assessment of River Channel Instability

| | |
|---|---|
| *Document Title:* | A Probabilistic Approach to the Special Assessment of River Channel Instability (Graf, 1984) |
| *Agency:* | Arizona State University |
| *Author:* | William L. Graf |
| *Date:* | 1984 |
| *Study Method Category:* | Mathematical method (using historic data) |

### 4.3.1. Overview

The paper reported a study funded by the Phoenix District of the U.S. Army Corps of Engineers (Graf, 1984). The purpose of the study was to provide an approach to predict the behavior of arid region rivers. The study was stimulated by the author's observation that economic analyses for flood mitigation in arid and semi-arid regions fail to take into account destructive channel migration and erosion. The approach presented in the paper combined geographic, geomorphic, hydrologic and statistical techniques to predict future channel locations. A case study of Rillito Creek near Tucson, Arizona, for a period from 1871 to 1978 provided a demonstration of the probabilistic method of erosion damage assessments and mapping.

The study began with an analysis of past channel locations using historic aerial photographs, maps, and engineering surveys. Cell maps were developed from the above information, and the probability function of each cell for a given historic period was defined, allowing the erosion probability of a given cell to be calculated. This probability is directly proportional to the magnitude of annual floods during this historic period and inversely proportional to the upstream and lateral distances from the cell to the channel. The overall probability of erosion was derived from a series of historic probability parameters. These values were then mapped to create a spatial representation of the erosion hazard. The final product is a map showing long-term erosion probability along the stream.

A practical planning implication of a probabilistic approach for prediction of channel migration and erosion is that it permits the economic assessment of potential losses under "no project" condition. In the case study, the method was used to run a simulation for a 50-year period. It is estimated that, given the land value in 1984, the erosion along the creek over the period represents an economic loss over $2 million, which is five times greater than the potential inundation losses.

### 4.3.2. Detailed Description

The paper consists of four major parts: methodology, case study, discussion of limitations, and conclusions.

#### 4.3.2.1. Methodology

The following steps are involved in development of an erosion probability map.

*Step 1. Develop a cellular map for each historic period.* The base map was divided into square cells, 100 meters on the side, each designated as "channel" or "nonchannel" for any particular period.

*Step 2. Develop a probability function that relates the erosion probability for a cell to its location and hydrologic condition.* The fluvial geomorphic literature suggested that location with respect to the active channel and the magnitude and frequencies of floods during the period in question are two most important factors in deciding the probability of a cell being eroded (Gregory, 1977). The following three-parameter erosion function was used

$$\log_{10} P_{ij} = \log_{10} a_0 + b_1 \log_{10} d_l + b_2 \log_{10} d_u + b_3 \left[ \log_{10} \sum_{k=1}^{n} r \right] \tag{4.1}$$

where $a_0$, $b_1$, $b_2$, and $b_3$ are empirically derived coefficients, $P_{i,j}$, is the probability of erosion for a given cell located at coordinates ($i$, $j$), $d_l$ is the distance laterally across the floodplain to the nearest active channel cell, $d_u$ is distance upstream to the nearest active channel cell, $r$ is the return period of the peak annual flood that occurred in year $k$, and $n$ is the number of years in the period of interest.

Using this function, the value of the probability of erosion for each cell in the period was calculated.

*Step 3. Develop a transition matrix.* The transition matrix, in which columns are based on the lateral distance from a cell to the channel and rows are based on the upstream distance along the floodplain from a cell to the channel, summarizes the statistical characteristics of all non-channel cells for a particular time period. Each period of analysis, covering a few years, produces a transition matrix. Values of erosion probability for a selected cell vary from period to period. For example, assume that an element, $a_{11}$, in the matrix represents all cells located 100 meters downstream and 100 meters laterally from a channel at beginning of the period. If there are 59 of such cells and 30 where eventually eroded, 30/59 = 0.51 is the probability that cells with those distance characteristics would be ultimately eroded. If the sum of the return intervals of the annual floods during the period in question is 132 for the period, the ordered set for cells 100 meters downstream and 100 meters laterally from the channel is (0.51, 100, 100, 132).

*Step 4. Estimate values of coefficient $a_0$, $b_1$, $b_2$ and $b_3$ of Eqn. 4.1.* Each period of analysis can produce a transition matrix containing several ordered sets consisting of $P_{i,j}$, $d_l$, $d_u$, and the summation of $r$ values. The ordered sets from several periods provide the data to determine values for these parameters using regression methods.

*Step 5. Predict erosion.* Assuming that the observed fraction of eroded cells is a reasonable indicator of the probability of future erosion for similarly situated cells, Eqn. 4.1 can be used for any initial conditions to predict erosion probability. Calculation of erosion probability can be made for a variety of time spans by manipulating the values for the sum of the annual flood return intervals. The function can generate a new transition matrix for future changes. The number of cells for each location type (*e.g.* 200 meters of lateral distance from the active channel) can be multiplied by the appropriate probability to predict the number of cells likely to be eroded over a given time period. The probabilities for the cells can also be mapped to present the spatial variability.

#### 4.3.2.2. Case Study

The method was applied to Rillito Creek, located on the northern edge of Tucson, Arizona. Rillito Creek flows 18.4 kilometers through an alluvium-filled fault-block valley to its junction with the Santa Cruz River. At its mouth the Rillito drains an area of 2,378 square kilometers (918 square miles). The annual rainfall over most of the basin is 20 - 40 centimeters (8 - 16 inches).

The locations of the channel were defined based on 25 historic documentary records during the period of 1871 to 1978. A review of these records shows that an unstable period extended from 1871 to about 1937. Lower Rillito Creek has consistently been more unstable than the upper and middle reaches. All reaches have shown decreasing instability over the 107-year period.

Transition matrices were developed which provided empirical values of the constants in Eqn. 4.1. Three matrices depicted changes for the periods of 1871-1912, 1912-1918, and 1918-1937. Seven matrices describe the more stable periods of 1937-1941, 1941-1949, 1949-1954, 1954-1960, 1960-1967, 1967-1972, and 1972-1978. Prediction results indicate that the probability of erosion of all cells declines when distance from the channel increases. During the unstable period (1912-1937), this decline was less abrupt than in the more stable period (1937-1978). In the earlier period, distance from a cell laterally to a stream channel was as important as its distance upstream to a channel; in the later period, however, the importance of lateral distance declined more rapidly than the distance upstream to the nearest channel cell.

As a test of the accuracy, Eqn. 4.1 with constants defined empirically for the 1937-1972 period was used to predict the 1978 map using the 1972 map as the starting condition. The resulting erosion probability map identified hazardous zones of instability and other more stable areas. During the test period, erosion was confined to cells that were mapped with the highest probability of erosion in the 1978 map except for six cells, which had been apparently influenced by gravel mining activities.

### 4.3.3. Applicability

The paper provides an approach to predict channel erosion by estimating probability of erosion for each cell. The approach depends on historic records; therefore, it is applicable to areas where sufficient historic records are available.

When long-term predictions are needed, the probabilistic method is based on simulations utilizing random numbers as opposed to given probabilities to generate a series of flood events. For example, if the prediction is for a 50-year period, the calculation uses a single 50-year event, two 25-year events, and so forth. The order of these events is randomly generated. Therefore, the exact course of the events in changing channel locations is not a primary product of the simulation. The most stable result is the number of cells lost rather than the specific location identity of those cells.

### 4.3.4. Limitations

Although the Rillito Creek example indicates that probabilistic approach to erosion damage assessment is possible, there are a number of concerns.

First, the author indicated that the method proposed in this paper was experimental and it required further testing in other areas. However, no additional testing has been undertaken for other watersheds. Second, the method was designated to accommodate the continually eroding conditions along Rillito Creek. When a cell adjacent to the existing channel is eroded, no concomitant deposition is predicted for the opposite bank. Third, the length of the historic channel record is critical in establishing a series of probabilities for erosion of cells. If the records are too short, the result will be dominated by short-term behavior of the system. The most important concern is that the method is based on established trends of the channel system and assumes the continuation of those trends. Although similar assumptions of system stationarity are common in engineering and hydrologic deterministic models, stationarity may not be assumed for erosion problems.

### 4.3.5. Relevant References


Gregory, K.J. (1977), *River Channel Changes,* John Wiley, New York.

Graf, W. L. (1981), "Channel instability in a braided, sand bed river," Water Resources Research, vol. 17, No. 4, p.1087-1094.

Graf, W.L. (1983), "Flood-related channel changes in an arid-region river," Earth Surface Process and Landforms, vol. 8, p.125-139.


### 4.3.6. Mappability

Several erosion probability maps of Rillito Creek, either for historic periods or for prediction, are included. Using different colors, the maps depict the erosion risk of each cell by its erosion probability. A probability map can be created for each channel studied.

### 4.3.7. Cost

Cost information was not reported.

### 4.3.8. Regulatory Potential

The probabilistic erosion maps could be used for regulatory purposes. For example, use of the land cells with higher erosion risk could be restricted.

### 4.3.9. Summary

The most important advantages of the cell map are that it can be developed by a Geographic Information System and that it can be used to reflect channel migration and erosion through empirical functions summarizing the past observed behavior of the channel. Geographic analysis of the likelihood that a given cell of land will experience erosion is based on the fundamental concept of distance decay away from a neighboring channel and the magnitude and frequency of flood events. Based on the assumption that channel systems possess stationarity, functions derived from historic records were used to extent past experience to predict probable future behavior. The probabilistic analysis that relies on grid cell maps of the near-channel landscape can be used to supplement more traditional engineering modeling approaches.

## 4.4. Geomorphology and Hydrology of the Santa Cruz River, Southeastern Arizona

| | |
|---|---|
| *Document Title:* | Channel Change on the Santa Cruz River, Pima County, Arizona 1936-86 (Parker, 1995) |
| *Agency:* | U.S. Geological Survey |
| *Author:* | John T. C. Parker |
| *Date:* | 1995 |
| *Study Method Category:* | Geomorphic analysis (using historic data) |

### 4.4.1. Overview

This study conducted by the U.S. Geological Survey (USGS) evaluated channel changes on the Santa Cruz River in Pima County, Arizona. The investigation covered geology, geomorphology, and hydrology of the river and was a project of the USGS in cooperation with the Pima County Department of Flood Control and Transportation District.

### 4.4.2. Detailed Description

This investigation focused on the major geomorphic and hydrologic processes affecting channel morphology in the Santa Cruz River. This investigation also examined the climate and human activities that have affected the location, magnitude, and timing of such changes.

The methods used in this investigation include the following:

- Documentation of channel changes;
- Examination of factors that control the temporal and spatial patterns of the channel change, including the effect of human activities; and
- Evaluation of available modeling techniques for channel changes.

The primary methods used in this study were interpretation and analysis of aerial photographs supplemented by field observations and published and unpublished geomorphic, topographic, geotechnical, and historic data. The study area is the 70-mile reach of the Santa Cruz River through Pima County. At the downstream end of the study, the river basin has an area of 3,641 square miles. The Santa Cruz River is ephemeral from the upstream end of the study area to the sewage treatment plant in northwest Tucson. Six study reaches along the 70-mile-long main stem of the river in Pima County were defined on the basis of morphology, historic stability, and channel changing processes.

The coverage and quality of the aerial photographs used in this study varied from one location to another. A base map was developed from an aerial photograph taken in 1936 to document lateral channel change. The two reference systems used for longitudinal river position were axial distance, the distance along a straight line through the axis of a river reach, and river distance, the distance along the meandering thalweg of the channel. The use of axial distance provides a fixed reference for measuring changes in channel width or position, whereas river distance changes over time as channels lengthen or shorten.

The Santa Cruz River shows a tremendous amount of physical variation through the 70-mile study area. From 1936 to 1986, an increase in the top width of the channel and a decrease in river length characterized channel changes. Most of the channel straightening was the result of human intervention. The increase in channel width would have been greater if not for channelization and bank protection work. Most of the channel widening resulted from the large floods of 1977 and 1983. In the Cortaro and Marana reaches, most of the channel changes involved lateral shifts in channel position.

Lateral channel changes occurred by three basic mechanisms: meander migration, avulsion and meander cut off, and channel widening. Meander migration is the spatially continuous movement of the channel across its floodplain by the initiation of meanders and subsequent lateral extension. Meander migration tends to be the dominant mechanism of change during low to moderate discharge. Avulsion and meander cut off occur when overbank flow incises a flow path into the floodplain, causing large, abrupt shifts in channel position. In general, channel widening results from high flows that erode banks made of cohesionless soils.

Vertical and lateral channel-change mechanisms operate in concert with bank-retreat mechanisms to produce widening of arroyos in incised reaches. Most of the reaches through Tucson qualify as incised reaches. Most of the arroyo widening occurs when the channel is deeply incised into poorly resistant sand and silt. The most rapid rates of arroyo widening have occurred in connection with the migration of confined meanders. Unlike channel widening, arroyo widening is not readily reversed. Nonetheless, this type of widening was reversed on the most deeply incised parts of the San Xavier reach of the Santa Cruz River.

Hydrologic and climatic factors, such as the magnitude, duration, and intensity of precipitation events, and the frequency of flood events generally control the timing and magnitude of channel changes on the river. Changes in channel geometry caused by successive floods or changes in roughness caused by vegetation growth also contribute to the temporal variability of channel changes. Spatial variability of channel change in the Santa Cruz River, such as the location of channel change and its magnitude in response to a given discharge, is largely controlled by topographic, geologic and human-introduced factors. These factors include sediment sources, bank materials, vegetation density, pre-existing topography, control size and quantity of bed load, resistance to erosion, valley and channel slope, and channel geometry.

The flood history of the Santa Cruz River in this century shows three distinct periods: 1915 to 1929, 1930 to 1959, and 1960 to 1986. The large floods in 1915 to 1929 and 1960 to 1986 caused substantial channel changes throughout the study area. Some reaches, however, were characterized by considerable lateral instability throughout the study period, including 1930 to 1959 when annual floods were generally moderate.

The floods of 1977 and 1983 were the two largest floods of record on the Santa Cruz River. The 1983 flood was the single largest episode of channel change to occur on the Santa Cruz River since at least 1915. That flood produced an enormous magnitude of channel and arroyo widening and lateral shifts in channel position throughout the study area.

Available models for prediction of channel change generally do not address lateral changes, and those that do limit the types of channel change mechanism that can be modeled. The application of probabilistic models of channel changes is not appropriate on the Santa Cruz River because of the change in resistance to erosion with time.

In conclusion, the general stability of various reaches can be evaluated by recognition of major channel-changing mechanisms operating in a reach and identification of the local topographic, geologic, and cultural controls on channel changes.

### 4.4.3. Applicability

The methods used in this study have identified mechanisms of channel change on the Santa Cruz River, timing and magnitude of the channel change with respect to floods, and physical conditions associated with channel instability. A relation exists between hydrologic regimen and the rate and magnitude of channel change. This relationship is modified by resisting forces and hydraulic conditions such as channel morphology. The author suggests that further analysis of the historic database would increase understanding of the river system. However, it would not produce the quantitative information necessary to predict channel change in response to floods.

### 4.4.4. Limitations

There are a few limitations with the method used in this study related to the coverage, quality and resolution of photographs and the time interval between photograph series. Unless there is evidence that such photographs have been taken before and after flooding, it is difficult to determine the extent of erosion and channel change due to a given magnitude and volume of discharge. Also, the author suggests that additional research needed includes analysis and evaluation of the following factors: the nature of bank material, in particular their cohesive properties; mechanical processes, such as cracking and piping; stream bed material composition; interactions between streamflow and soil–hydrologic processes in channel banks; and formation of armored channels and point bars in rapidly varying flow.

### 4.4.5. Relevant References


Baker, V.R. (1977), "Stream-channel response to floods, with examples from central Texas," Geological Society of American Bulletin, v. 88, p. 1057-1071.

Fan, S. S., ed. (1988), *Twelve Selected Computer Stream Sedimentation Models Developed in the United States*, Washington D.C., Federal Energy Regulatory Commission report.

Guber, A. L. (1988), *Channel Changes of the Xavier Reach of the Santa Cruz River, Tucson, Arizona, 1971-1988*, unpublished Master's thesis, University of Arizona, Tucson, Arizona.

Hays, M. E. (1984), *Analysis of Historic Channel Change as a Method for Evaluating Flood Hazard in the Semiarid Southwest*, Master's thesis, University of Arizona, Tucson.

Klimek, K. (1974), "The retreat of alluvial river banks in the Wisloka Valley (South Poland)," Geographia Polonica, v. 28, p. 59-75.

Kresan, P.L. (1988), "The Tucson, Arizona, Flood of October 1983- Implications for Land Management Along Alluvial River Channels," in Baker, V.R., R.C. Kochel, and P.C. Patton, eds., *Flood Geomorphology*, John Wiley & Sons, New York, New York.

Parker, J. T. C. (1995) *Channel Change on the Santa Cruz River, Pima County, Arizona, 1936-86*, U.S. Geological Survey Water-Supply Paper 2429.

Sabol, G.V., C.F. Nordin, and E.V. Richardson (1989), *Scour at Bridge Structures and Channel Aggradation and Degradation Field Measurements*, Arizona Department of Transportation Research Project.

Slezak-Pearthree, M., and V.R. Baker (1987), *Channel Change Along the Rillito Creek System of Southeastern, Arizona, 1941 through 1983*, Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Special Paper 6.

Webb, R.H., and J.I. Betancourt (1992), *Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona*, U.S. Geological Survey, Water supply Paper 2379.

### 4.4.6. Mappability

The rates of lateral channel migration through bank erosion, meander propagation, and channel avulsion can be measured from sequential aerial photographs. Limitations include the quality and resolution of the photographs and the length of time between photographic series. Unless photographs have been taken immediately before and after a major flood, it is difficult to know just how much erosion and channel migration is due to a given magnitude and volume of discharge. It can also be difficult to distinguish the changes that have occurred from natural processes from those related to human activity. The methods used in this study were relatively coarse and, according to the author, accurate to no more than 10 meters on the average, although this accuracy varied considerably depending on the location, photograph quality, and availability of registration points. Greater accuracy can be achieved, but at greater cost. The most important information that can be obtained from mapping channel movements is the extent of geological controls on channel positions and relative rates of erosion. By overlaying channel position through time with surficial geology and geomorphology, the effect of different quaternary units and landforms (*e.g.* terraces, paleochannels) can be clearly seen, and the units most susceptible to erosion can be determined. The author emphasized the use of geologic-geomorphic mapping here because he thinks that, especially in the arid and semi-arid regions, it is the most significant control on the location of channel change. The rate at which such change takes place is governed by the magnitude and frequency of floods, which in dry climates is extremely difficult to forecast; however, by understanding geological controls, at least the location of greatest hazards can be delineated.

### 4.4.7. Cost

No cost information was provided in the document, since the author was a student employee with limited experience when he did this project. An experienced geologist or hydrologist may take a few months to map channel change in a reach of about 100 miles.

### 4.4.8. Regulatory Potential

If the limits of significant channel erosion and migration can be determined on the basis of geologic controls, such controls can be used to delineate areas of most significant hazard.

### 4.4.9. Summary

The primary methods used by the author in this study were the interpretation and analysis of aerial photographs supplemented by interpretation of field observations and geomorphic, topographic, and historic data. Although an appropriate model for predicting channel change on the Santa Cruz River has not been identified, the stability of reaches relative to one another and in time can be evaluated through recognition of the local controls and the major channel-changing mechanisms operating in a reach. Much of the channel change that has occurred during the study period has been human-induced.

## 4.5. San Diego County Alluvial Studies

| | |
|---|---|
| *Document Title:* | San Diego County Alluvial Studies |
| *Agency:* | San Diego County |
| *Author:* | Howard Chang, San Diego State University |
| *Date:* | 1984 |
| *Study Method Category:* | Mathematical modeling |

### 4.5.1. Overview

The County of San Diego, California, was the subject of a number of studies aimed at investigating the effects of erosion in floodplain management of alluvial channels. A substantial portion of this work was accomplished through the work of Dr. Howard Chang, of San Diego State University, using several versions of his model, FLUVIAL. In its latest version, this finite-difference model computes hydraulic profiles, sediment transport, and streambed geometry changes for a given flooding event. Streams that were analyzed include the San Luis Rey, San Diego, and San Dieguito Rivers and Moosa Canyon Creek.

The results of hydraulic modeling were used as a starting point to estimate potential channel changes as a result of the 100-year event. The results were complemented with geomorphic and engineering information to arrive at definition of erosion hazard areas. The County developed floodplain management procedures that incorporate effects of erosion and sedimentation in the form of setback restrictions and a Resource Protection Ordinance.

### 4.5.2. Detailed Description

#### 4.5.2.1. Computer Modeling

The FLUVIAL model was initially developed in 1972 and has undergone several enhancements through the years. The latest version is called FLUVIAL-12 and is capable of simulating water and sediment routing through natural and artificial channels of general configuration for a given flow period. The model has been tested and calibrated with several streams in semi-arid and humid environments. Although intended for perennial streams, with additional effort, the model can simulate ephemeral streams (Chang 1988a,b).

FLUVIAL-12 simulates changes in channel geometry resulting from aggradation and degradation processes. These processes cause changes in width and alignment as well as variations in the bed topography. Limiting conditions can be formulated to model the effect of physical constraints such as bedrock outcrops, grade control structures, and bank resistance. Typical applications include general erosion and deposition studies, bridge scour evaluations, sediment transport analyses, gravel mining impact assessment, and design of bank protection and grade control structures.

The foundation for modeling river changes lies on the tendency of natural streams to reach a state of dynamic equilibrium involving, water, sediment, and channel resistance and geometry. The equilibrium conditions are characterized by uniform sediment discharge along the channel and uniform stream power expenditure $\gamma QS$, where $\gamma$ is the unit weight of the water-sediment mixture,

$Q$ the discharge, and $S$ the energy gradient. The stream adjusts the power expenditure by scouring the bed and reducing the width or filling the bed and increasing the width. FLUVIAL-12 computes changes in bed geometry by implementation of these principles. The main components of FLUVIAL-12 are:

*Water Routing:* Uses the continuity and momentum equations to determine temporal and spatial variations of stage, discharge, energy, and other hydraulic variables. This module includes evaluation of both longitudinal and transverse flows.

*Sediment Routing*: This module computes sediment transport capacity and actual sediment discharge and solves the sediment continuity equation. Six formulas are provided as options for sediment capacity computation: Engelund-Hansen, Yang's unit stream power, Graf, Ackers-White, Meyer-Peter & Muller, and Parker's formula for gravel.

*Channel Geometry Changes:* Uses the erosion or deposition data computed by the sediment routing module to predict how the section geometry is affected. From the energy gradient, the module computes the direction of width adjustment. The rate of width adjustment is computed based on sediment rate, bank stability properties, and bank erodibility. After the width is adjusted, the remainder of the total correction is applied to the channel bed and distributed according to the tractive force.

*Channel Migration:* Curvature-induced scour and deposition are computed from the flow curvature along the stream. Transverse sediment transport is used to predict changes in the bed topography at a given cross section.

FLUVIAL-12 can simulate a river system for an indefinite period, as long as a hydrograph is available. The computation depends on the assumption of a stable portion of the stream that can provide suitable boundary conditions.

#### *4.5.2.2. Definition of Hazard Areas*

The County of San Diego used the modeling results of FLUVIAL-12 to define erosion and sedimentation hazard areas. The following are the general steps to accomplish this objective:

1. Gather information to develop an input data set for FLUVIAL-12. Obtain the hydrograph for the 100-year event and model the channel reach starting with the existing configuration. Define the 100-year floodplain limits for the final configuration of the channel.

2. Use photographs, maps, history of past channel changes, and geomorphic and engineering investigations to evaluate the results of hydraulic modeling and to identify erosion and sedimentation hazards. Use engineering judgement to develop a "safety factor" for these hazard areas (Chang, 1998).

3. Delineate hazard areas on floodplain maps and establish setback requirements.

### *4.5.3. Applicability*

The procedure adopted by San Diego County is a fully developed example of erosion-hazard area delineation. In principle, the methodology can be transferred to other regions. A major advantage is the incorporation of physically based models of most of the major factors influencing channel change.

### 4.5.4. Limitations

The methodology calls for analysis of erosion and sedimentation produced by the 100-year event. Even though the 100-year event is likely responsible for substantial modification of the channel geometry, the approach does not include the potential effects of other floods which may change the channel and invalidate the starting condition used to model the 100-year event. Most likely, a study revision should be undertaken every time the channel suffers major alterations (Chang, 1998).

The methodology does not incorporate procedures to analyze the rate of erosion. FLUVIAL-12 does not limit the simulation time; however, it does need to have a defined flow record for the entire duration of the simulation.

FLUVIAL-12 is a complex movable-bed model that requires specialized skills to run and interpret its results. Careful attention is needed to ensure that field conditions match the assumptions in the model. Modeling of alluvial channels using FLUVIAL-12 can be expensive. These skills and resources may not be available to some jurisdictions.

Specific procedures need to be defined to evaluate the results of modeling and use them to delineate hazard areas.

### 4.5.5. Relevant References


Chang, H. H. (1982), "Mathematical model for erodible channels," Journal of the Hydraulics Division, American Society of Civil Engineers, 108(HY5), p. 678-689.

Chang, H. H. (1984), "Modeling of river channel changes," ASCE Journal of Hydraulic Engineering, vol. 110, No. 2, p.157-172.

Chang, H. H. (1984), "Water and sediment routing through curved channels," Journal of the Hydraulics Division, American Society of Civil Engineers, 101(HY4), p. 644-658.

Chang, H. H., and D. Stow (1991), "Computer simulation of river channel changes induced by sand mining," Proceedings of the International Conference on Computer Applications in Water Resources, July 3-6, Taipei, Taiwan, vol.1, p. 226-234.

Chang, H. H., and J. C. Hill (1977), "Minimum stream power for rivers and deltas," Journal of the Hydraulics Division, American Society of Civil Engineers, 103(HY12), p. 1375-1389.

Cooper Engineering Associates (1987), *Flood Plain Management Study for Moosa Canyon Creek*, prepared for County of San Diego Department of Public Works, July.

National Research Council (1983), *An Evaluation of Flood-Level Prediction Using Alluvial River Models*, National Academy Press, Washington, D.C.


### 4.5.6. Mappability

San Diego County has produced floodplain maps that show erosion hazard areas. The procedure to actually define the extent of hazard areas is mostly based on engineering judgement used to complement the results of hydraulic modeling. The methodology can be used to prepare erosion hazard maps provided that a consistent set of procedures and guidelines is available to derive the extent of these areas.

### 4.5.7. Cost

No information on cost is presented. Although there are large cost differences according to the physical setting, Dr. Chang estimates that the cost is in the order of several thousand dollars per mile. The cost per mile decreases for large studies.

### 4.5.8. Regulatory Potential

San Diego County developed procedures for management of alluvial streams. The County also developed a floodplain mapping procedure and a Resource Protection Ordinance. There are three management options:

1. Based on past events and existing information, the stream is identified as a "special erosion-sedimentation" area.

2. An erosion/sedimentation study is conducted including alluvial hydraulic modeling of the 100-year flood and additional geomorphic and engineering investigations. Flood elevations for the 100-year event are computed for the final configuration of the channel. Setbacks are defined based on the results of this study.

3. In cases of sand and gravel mining where there are substantial bed and width changes, an equilibrium invert is used for hydraulic modeling.

The Resource Protection Ordinance mandates that all proposed development be located beyond the setbacks for the erosion-sedimentation hazard area as shown in County floodplain maps. Development is only allowed if documentation is presented to demonstrate that adequate protection can be provided in a manner compatible with the natural characteristics of the stream.

### 4.5.9. Summary

San Diego County has developed floodplain management procedures for alluvial channels. The procedures are based on hydraulic modeling using FLUVIAL-12 complemented with geomorphic and engineering studies to define erosion and sedimentation hazards. The methodology evaluates the effects of the 100-year event on the channel geometry. Development in hazard areas is restricted by setbacks that become part of floodplain maps.

## 4.6. City of Austin Technical Procedures for Watershed Erosion Assessments

| | |
|---|---|
| *Document Title:* | Technical Procedures for Watershed Erosion Assessments (City of Austin, 1997) |
| *Agency:* | Drainage Utility Department, Austin, Texas |
| *Author:* | Raymond Chan & Associates, Austin, Texas |
| *Date:* | 1997 |
| *Study Method Category:* | Engineering and geomorphic analyses |

### *4.6.1. Overview*

This document was prepared by Raymond Chan & Associates for the Drainage Utility Department of the City of Austin, Texas. The report summarizes the procedures to conduct 17 watershed erosion assessments within the City's jurisdiction. An individual report was prepared for each watershed study. The studies were performed in 1997 and included only watersheds greater than 640 acres.

The procedures seek to characterize the changes in channel geometry, identify potential erosion problems, and estimate sediment yield as a result of channel erosion. Major tasks to accomplish these objectives include:

- Stream inventory,
- Erosion problem identification,
- Characterization of urbanization effects,
- Prioritization of property protection and channel restoration,
- Development of an Erosion Hazard Indicator,
- Nick point identification and management strategies,
- Identification of meander migration, and
- Estimation of channel enlargement and sediment yield.

### *4.6.2. Detailed Description*

#### *4.6.2.1. Introductory Material*

An initial discussion on stream equilibrium concepts describes land use changes and the response they generate in channels and watersheds. For example, aggradation can be the result of deforestation in favor of agriculture. Afforestation as replacement of meadowlands often results in channel erosion and enlargement due to both suppression of thick grass turf and supply of debris that can cause log jams. In general, development introduces an initial increase in sediment loading that translates into aggradation due to reduced channel capacity. After development, the sediment supply decreases but flows increase in rate and volume due to larger impervious surfaces. Although the most noticeable effect is enlargement of the channel, most of the studies cited in the document evidence the wide range of morphological responses depending on watershed and stream characteristics. The most important factors are:

- Basin area,
- Temporal variability, rate, and volume of discharge,
- Quantity, particle size, and transport rate of the sediment,
- Resistance of bed and bank materials,
- Type and spatial distribution of riparian vegetation,
- Longitudinal valley gradient,
- Magnitude, timing, and distribution of urbanization influence in the watershed, and
- Scale of features in the fluvial system.

A typical feature is the formation of an inset channel within the enlarged channel. The inset channel conveys the low flows. The Technical Procedures document uses numerous references to examine fluvial responses to urbanization and stream channel evolution. A large portion is devoted to the concept of channel equilibrium and its four possible states:

- *Neutral*: no channel form alterations under small disturbances,
- *Stable*: temporary alteration followed by return to original state upon cessation of small disturbance,
- *Unstable*: permanent alteration following a small disturbance without achieving a new stable behavior, and
- *Metastable*: no alteration following a small disturbance but general system alteration towards a new equilibrium state as a consequence of a major disturbance.

A fluvial system may move from one state of equilibrium to another either smoothly or catastrophically. The transition and new state depend on the characteristics of the stream and the spatial and temporal distribution of the disturbance. Most engineering analyses use "regime theory," which assumes that the system is in a state of metastable equilibrium. That is, the river reacts to major flooding events, but its form is dictated mostly by events with a return period between 1.5 and 2 years (bankfull discharge). The document cites literature documenting the shift of dominant discharges to the 2- to 3-month event (mid-bankfull discharge) when the watershed undergoes urbanization.

The Technical Procedures document ends its introductory section with a description of watersheds in the City of Austin and the studies that were conducted in them, mostly using the Rapid Geomorphic Assessment (RGA) protocol. The document concludes that the stream channel morphology within the City of Austin appears to be consistent with regime theory.

#### *4.6.2.2. Impervious Cover Computation*

The University of Texas performed this computation using a grid layout to determine drainage area and impervious cover. The calculation was done for each reach at geomorphic survey sections. Little detail is provided on the GIS-based model that was applied to accomplish this task. Impervious cover is estimated for both existing and future conditions.

#### *4.6.2.3. Watershed "Vital Statistics"*

Basic characteristics are gathered to provide a general assessment of the watershed. Sources of information include USGS topographic maps, the Travis County soil survey, development data from the Bureau of Economic Geology, maps to identify parks, and drainage improvement plans from the City's Drainage Utility.

The results are presented in a watershed report that details drainage area, existing and future impervious cover, summary of watershed development, stream length and slope, major tributaries, soil description, list of parks, unique watershed features, and existing and upcoming infrastructure projects.

#### 4.6.2.4. Urbanization Effects

The regional regression equations developed by the USGS are used to estimate existing and future peak discharges for the 2- and 10-year events. These equations require using the impervious fractions previously computed. The flows are computed for every reach and every geomorphic survey cross section. The percent increase in the peak flows can be used as an indicator of management needs for the watershed.

#### 4.6.2.5. Stream Inventory

*Erosion Priority Rating*

The purpose of this task is to identify and prioritize erosion problems. A field survey of the stream is conducted to select reaches, measure geomorphic parameters, assess erosion problems, determine probable causes, assign priorities, and formulate mitigation options. Streams are investigated if the drainage area is at least one square mile. A stream inventory form was developed for this purpose.

Items to be noted include buildings, parking lots, bridges and public facilities, retaining walls, trees, utility poles and utility crossings, fences, steep banks within parks, and significant loss of land. Priorities were assigned as:

Priority 1 - A primary structure, road, or public facility currently threatened and requiring immediate attention.

Priority 2 - Other items such as retaining walls, fences, trees and woodlands currently threatened. This also includes areas that are facing substantial land loss due to erosion.

Priority 3 - Items not currently threatened but that may be in danger in the future due to erosion.

A detailed geotechnical investigation is performed later on Priority 1 areas. The information gathered includes assessment of vegetation, substrate material, bank soil strata, cross section measurements, indicators of erosion potential, slope stability, and structure stability.

*Identification of Erosion Causes*

Photographs are used to document the conditions of the creek. The objective is to collect this information at various points in time to observe changes in bottom width, bank slopes, vegetation, baseflow conditions, and channel substrate. This information can be used to assess maintenance needs in the watershed. Causes of erosion include:

- Effects of development (widening, downcutting, aggradation, slope failure, planform change, channel straightening due to increased velocity)
- Pipelines along and crossing the stream
- Manholes
- Storm sewer outfalls (pipes and channels)
- Rock berms causing scour holes, bank widening, and upstream aggradation
- Severe bends
- Erodible soils
- Past channelization projects
- Culverts without energy dissipators

- In-channel disturbances

*Inset Channel Geometry*

Periodic measurements of inset channel width and depth are taken at the bankfull level in riffle sections. These measurements are used in geomorphic analyses. Bankfull indicators include exposed roots, moss lines, exposed alluvium, and vegetation type and condition.

*Reach Classification*

The stream is subdivided into reaches defined according to the following criteria:

- In straight channels, length is at least 20 bankfull widths with the bankfull width given by the 1.2-year event. In meandering channels, the length is greater than two meander wavelengths,
- A 10 percent increase either in the flow rate of the basin imperviousness, or
- Effective drainage area greater than one square mile.

These reaches are also termed response segments and are used to examine ongoing geomorphic processes.

The document stresses the point that morphologic classifications are not appropriate in cases where development is causing channel adjustment because the form-process relationship is being disrupted. No classification system has been devised for urban streams. Therefore, it is more appropriate to classify channels according to the erosion susceptibility of boundary materials. For the City of Austin, it was determined that the channels respond in one of three basic patterns:

- Valley formation: banks and bed are both susceptible to scour,
- Channel widening: banks are more susceptible to scour, and
- Channel downcutting: bed is more susceptible to scour.

The susceptibility to scour is computed as the sum of stickiness, plasticity, and firmness indexes as produced by standard soil consistency tests.

Reaches are classified according to three standard types: alluvial channel, rock-bed channel, and rock-controlled channel. Structural channels are viewed as a fourth type. These designations are assigned based on a combination of examination of maps and photographs and the field survey. Reaches can be classified further using a system developed by Knighton (1987) which describes the boundary material composition of substratum, substrate, and least resistant bank. These materials can be rock, undisturbed overburden, alluvium, or armor. This classification system is used in determining the enlargement ratio.

*Geomorphic Assessment of Reaches*

The document cites three adjustment scenarios:

- Initial phase: Roughness and depth adjust rapidly to changing conditions. Affected features are microforms with relaxation times of the order of $10^0$ year.

- Second phase: Width is modified until depth and roughness are adjusted. Affected features are mesoforms with relaxation periods between of the order of $10^1$ to $10^2$ years.

- Third phase: Longitudinal slope is adjusted and reaches equilibrium with width, depth, and roughness. This is a macroform feature with relaxation time of the order of $10^2$ to $10^3$ years.

The Technical Procedures document indicates that true representation of any fluvial system should take into account micro, meso, and macroscale features. However, the fine spatial and temporal variability of microforms makes measurement and monitoring impractical. On the other extreme, macroform dimensions and time scales are too large to be of practical management value. Consequently, geomorphic assessments are to be based on mesoforms with a general understanding of the other scales involved.

Relaxation periods for disturbances applied on mesoforms are defined as 10 to 55 years for alluvial and rock-bed channels; however, no guidance is provided to select a value. No relaxation period was defined for rock-controlled channels, but 55 years is suggested for use in computations.

Each reach is analyzed through Rapid Geomorphic Assessment (RGA) to determine its stability conditions. A RGA form is used to check for the presence of geomorphic processes indicative of aggradation, degradation, widening, and planform adjustment. Scores for these processes are used to arrive at a Stability Index (SI) that describes the reach as stable, transitional, or in adjustment. The results of these analyses can be summarized in a color-coded map showing the stability classification for each reach. However, the SI does not indicate the intensity of geomorphic activity, whether the processes are still active, or the sequence in which they occurred. These issues need to be resolved with additional historic or anecdotal data.

In addition to the RGA form, the fluvial geomorphology field reconnaissance form records a large amount of information:

- General site data,
- Photographic records,
- Bank material composition for several stratigraphic units (soil consistency, particle size, soil class, and plasticity index),
- Environmental integrity (channel alteration, sediment deposition, embeddedness of coarse material in fine material, bank condition, riparian vegetation),
- Sketch of planform geometry,
- Field erosion process classification (shear dominated, falling-stage dominated, and/or controlled by other nonfluvial processes like expansion-contraction, chemical weathering, rainfall impact, and animal trampling and burrowing),
- Rosgen (1994, 1996) classification (entrenchment ratio, width/depth ratio, sinuosity, substrate, substratum, slope), and
- Manning's rating curve.

#### *4.6.2.6. Enlargement Potential*

The theory to estimate channel enlargement was proposed by Morisawa and LaFlure (1979) and modified to produced the Austin Enlargement Curve. The basic assumptions are:

- Change in impervious land cover in the watershed is a suitable surrogate for instream erosion potential changes,
- Scour adequately represents instream erosion potential,

- Channel enlargement varies inversely with drainage area and channel boundary resistance, and

- For the purposes of assessing response to changes, channels can be classified in three categories: rock controlled, rock bed controlled, and alluvial.

Morisawa and LaFlure (1979) developed a curve in which enlargement is a function of area with imperviousness greater than 5 percent. This curve was modified by providing different curves for each of the three channel categories as observed for the City of Austin. This approach does not include the effect of past channel maintenance activities. Another curve termed "channel relaxation curve" is used in the computation, but the document does not mention its origin. The procedure to estimate channel enlargement is the following:

1. Using regional regression equations, compute the bankfull discharge for existing conditions.

2. Determine bankfull depth as an average of field-observed values and those computed using Manning's formula. Calculate flow area $A_{BFL\ EXT}$.

3. Using land use maps and other information, determine the average age of development impacting the stream ($t_i$).

4. Define the relaxation period ($t_r$) corresponding to the channel type. Compute the ratio $t_i / t_r$.

5. Compute existing and future watershed impervious cover. Review the Stability Index SI and study any existing photographs to check whether the development pattern and impervious cover conclusions are sensible.

6. Determine the ultimate enlargement ratio for existing conditions $R_{E\ EXT\ ULT}$ from the Morisawa-LaFlure curves modified for the City of Austin. Use $t_i / t_r$ in the "channel relaxation curve" to determine $R_{E\ EXT} / R_{E\ EXT\ ULT}$, where $R_{E\ EXT}$ is the existing enlargement ratio. Compute $R_{E\ EXT}$.

7. Compute the pre-development bankfull channel area as $A_{BFL\ PRE} = A_{BFL\ EXT} / R_{E\ EXT}$.

8. Obtain $R_{E\ FUT\ ULT}$ from the modified Morisawa-LaFlure curves using the future impervious cover. Compute future bankfull channel area from $A_{BFL\ FUT\ ULT} = A_{BFL\ PRE} \times R_{E\ FUT\ ULT}$.

9. Compute the difference between $A_{BFL\ FUT\ ULT}$ and $A_{BFL\ EXT}$. This difference will provide an estimate of sediment yield.

10. Determine the appropriate enlargement process. The channel may be widening, downcutting, or both. Downcutting may be constrained by grade-control structures such as culverts. Widening may be restricted by resistant channel boundaries.

11. Analyze the possibility of further bank failure due to enlargement and the ensuing increase in top width. For example, near vertical or unvegetated slopes are unstable, and widening may cause catastrophic failure and increase sediment yield. The increase in the top width can be viewed as an erosion hazard indicator.

12. Compute sediment volume yield as channel length times the total bank loss. This estimate will be useful only as a planning tool due to variability along the channel reach. Use a suitable density (*e.g.*, 120 pounds per cubic foot) to compute the weight of sediment yield.

13. Determine the new cross section. This requires assessment of bank failure mechanisms and estimation of final bank slopes. Another consideration is the distribution of widening between the two banks according to the relative resistance of bank materials.

14. Formulate management options depending on all of the observed conditions. For example, if the watershed is near ultimate development and the creek has nearly achieved its final configuration, only local erosion problems may need to be addressed.

#### *4.6.2.7. Nick Point and Meander Management*

Nick points and meander issues will be identified in the stream inventory phase to complement the stream stability analysis. Nick point migration indicates downcutting of the stream bed that may result in bank instability, which in turn causes channel widening and increased sediment load. Similarly, meander migration involves erosion and may affect structures located on the banks.

Nick points can occur naturally or be the result of structures such as pipeline crossings and bridges. Migration of nick points may range from a few inches to hundreds of feet per year, depending on the resistance properties of the bed material. The migration rate is usually an indicator of the associated problem because it indicates the rate at which the channel is reconfiguring itself in response to outside impacts. However, the severity of any migration rate is often dictated by the structures in danger. For example, a few inches of annual migration may have serious consequences on the geotechnical stability of the stream banks.

Characterization of nick points involves field documentation of location, height, substrate and substratum description, features affecting nick point movement, and distance to grade control structures that may stop migration. Mitigation measures for nick point problems usually involve the introduction of a control. The two major options are burial with material to avoid exposure of the bed and introduction of hard outcrops (rock or concrete) to interrupt bedding planes of soft-hard materials.

Meander severity is treated according to the methods in Hickin and Nanson (1984). Erosion proceeds in the outer bend of meanders whereas deposition takes place in the inner bend. Most of this process takes place in the downstream third of the meander length. Therefore, meanders move both laterally normal to the valley slope and down slope parallel to the valley. Hickin and Nanson (1984) determined that the rate of channel migration is directly proportional to stream power and channel width and inversely proportional to bend radius, bed material shear resistance, and bank height. Further, the migration rate is maximum when the ratio of bend radius to channel width $r/W_{BFL}$ is between 2 and 3. This conclusion was derived from streams in prairielands but was extrapolated to the Austin area.

The procedure in the document consists of identifying channels with a sinuosity of 1.2 or greater and then determining the $r/W_{BFL}$ ratio. If the ratio falls within the fast-migration range, this factor is taken into consideration when developing management options.

#### *4.6.2.8. Prioritization of Erosion Problems*

The Technical Procedures document proposes a prioritization scheme based on scores assigned to the threatened resources and the potential problems. Resource values vary from a maximum of 100 for a major road to 35 for a yard. Little information is provided on how the scores are actually estimated; however, the process is systematic and leads to ranking of reaches based on the significance of erosion and affected structures. The procedure is implemented by means of spreadsheets.

#### *4.6.2.9. Stream Management Recommendations*

The Technical Procedures document devotes one chapter to the development of restoration measures at the channel and watershed levels. These measures can involve floodplain management, channel geometry modifications, vegetation restoration, flow modification, and substrate manipulation. The Technical Procedures document outlines an 11-step procedure to identify and design appropriate restoration measures.

### *4.6.3. Applicability*

Most of the techniques described in the Technical Procedures document are directly applicable to the riverine erosion investigations. The document offers a systematic procedure based on geomorphic and engineering principles to analyze erosion problems. A major contribution of the methodology is its emphasis in examining the temporal variations of channel evolution as a function of continuing development. Although mapping the extent of hazard areas is not one of its objectives, the Technical Procedures document suggests that channel enlargement computations combined with geotechnical stability considerations can be used to delineate erosion hazard areas.

The methodology was developed specifically for streams in the Austin area but, in principle, can be modified for other regions.

### *4.6.4. Limitations*

The methodology depends on the development of site-specific channel enlargement curves, which may be costly to obtain. However, a carefully designed research program may provide sufficient information to typify stream systems into regionally valid categories. Such an approach would lessen the burden when conducting studies at a national scale. The limitations of such regional studies must be taken into account when conducting site-specific analyses.

Delineation of hazard areas requires development of new procedures for geotechnical bank stability analysis. The Technical Procedures document alludes to the need for these procedures, but a national methodology requires explicit definition of methods. These can be easily defined from a variety of sources.

The methodology only computes total channel enlargement and does not distribute it among the two banks and the stream bed. This limitation may be alleviated in cases where erosion takes place either at the banks or at the bottom. Nonetheless, a procedure needs to be devised to handle all situations.

### *4.6.5. Relevant References*


Hickin, E.J., and G.C. Nanson (1984), "Lateral migration rates of river bends," ASCE Journal of Hydraulic Engineering, vol. 110, No. 11, p.1557-1567.

Knighton, A. D. (1987), “Downstream River Channel Adjustments,” in *River Channels: Environment and Process*, Institute of British Geographers special publication, K. Richards (ed.), Basil Blackwell, Inc., New York.

Morisawa, M., and LaFlure (1979), "Hydraulic Geometry, Stream Equilibrium and Urbanization," in *Adjustments of the Fluvial System,* D. D. Rhodes and G.P. Williams (eds.), Proceedings of the 10th annual Geomorphology Symposium Series, Binghamton, New York, Kendall Hunt Dubuque, Iowa.

Renwick, W.H. (1992), "Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape," in *Geomorphic Systems*, J.D Phillips and W. H. Renwick (eds.), Proceedings of the 23rd annual Geomorphology Symposium Series, Binghamton, New York, Elsevier, Amsterdam.

Rhoads, B. L. (1994), "Fluvial Geomorphology," Progress in Physical Geography, 18(4), p. 588-608.

Rosgen, D. L. (1994), "A classification of natural rivers," Catena, 22, pp. 169-199.

Rosgen, D. L. (1996), *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, Colorado.

Simons, Li & Associates, Inc. (1985), *Design Manual for Engineering Analysis of Fluvial Systems*, prepared for Arizona Department of Water Resources.

Thorne, C.R., and M.K. Tovey (1981), "Stability of composite river banks," Earth Surface Processes and Landforms, 6, pp. 469-484.

Thorne, C.R., and M.R. Welford (1994), "The equilibrium concept in geomorphology," Annals of the Association of American Geographers, v. 84, No. 4, p. 666-696.

Thorne, C.R., and J. Lewin (1982), "Bank processes, bed material movement, and planform development," in *Adjustments of the Fluvial System,* D. D. Rhodes and G.P. Williams (eds.), Proceedings of the 10th annual Geomorphology Symposium Series, Binghamton, New York, Kendall Hunt Dubuque, Iowa.

### 4.6.6. Mappability

The results of this methodology produce maps for indicators of erosion and localized erosion features such as nick points. The color-coded maps show channels in adjustment, transition, or stable conditions. This kind of information is useful for watershed and stream management but not for delineation of riverine erosion hazard areas. The maps need to be enhanced to show the result of channel enlargement computations.

### 4.6.7. Cost

No information on cost is presented in the guideline document. Mr. Tom Hegemier of Raymond Chan & Associates estimates an average cost of $2,000 per mile.

### 4.6.8. Regulatory Potential

The methodology could potentially be enhanced to allow regulation based on delineation of hazard areas.

### 4.6.9. Summary

The Technical Procedures document proposes a systematic methodology aimed mainly at characterization of erosive state of a stream. Geomorphic and engineering methods are outlined to classify channels and determine if they are adjusting through high geomorphic activity, in transition to a new equilibrium form, or stable. The basic tool is a set of curves to estimate channel enlargement. The document presents techniques to analyze localized features such as nick points and meanders.

While in its present form the methodology is extremely useful as a watershed and stream management tool, refinements are needed to allow delineation of hazard areas.

## 4.7. River Stability Studies for Virgin River, Santa Clara River, and Fort Pierce Wash, Utah

| | |
|---|---|
| *Document Title:* | River Stability Study, Virgin River, Santa Clara River and Ft. Pierce Wash, Vicinity of St. George, Utah (CH2M Hill and J.E. Fuller/Hydrology & Geomorphology, 1996) |
| *Agency:* | City of St. George, Utah |
| *Authors:* | CH2MHill and JE Fuller/Hydrology & Geomorphology, Inc. |
| *Date:* | 1996 |
| *Study Method Category:* | Geomorphic analysis |

### 4.7.1. Overview

This report describes the results of an investigation of river stability for three major watercourses: the Virgin River, the Santa Clara River and the Fort Pierce Wash, in the vicinity of St. George, Utah. The objective of the study was to develop a floodplain management plan to help the City of St. George better manage flood and erosion hazards associated with development in floodplains located within the city limits. As a result of the study, erosion hazard boundary corridors along each of three rivers have been established. The report describes the methodologies and assumptions used to develop the erosion hazard boundaries. The erosion hazard boundary corridors are presented on aerial maps.

The basic approach used in the study is geomorphic analysis, entailing the following tasks: data collection, field reconnaissance, historic evaluation, and geomorphic evaluation. Hydraulic and sediment transport analysis and modeling were not included.

### 4.7.2. Detailed Description

Historic evaluation and geomorphic evaluation are essential parts of the study. Evaluation of historic river channel changes and understanding of the nature of past river behavior provide a basis for predicting the type of channel changes that could occur in the future. Geomorphic evaluation allows predicting where future aggradation, degradation, and lateral channel migration are likely to occur. Similar methodologies for historic and geomorphic evaluation were applied to all three streams. In the following sections, the methodologies are described in detail for the Virgin River and in brief summaries for the other two streams.

#### 4.7.2.1. Historical Evaluation, Virgin River

The Virgin River is one of the major tributaries of the lower Colorado River. The drainage basin of the Virgin River covers about 3,800 square miles of southern Utah and northern Arizona. Its perennial flow and fertile floodplain have supported agricultural activities since prehistoric times.

The historical evaluation of the Virgin River was based on following types of data:

- Historic descriptions from pioneer diaries (1853 to 1902)
- Historic aerial maps and ground photographs (1902 to 1995)
- Topographic maps and cadastral survey maps (1870 to 1992)
- Hydrological and climatic data
- Published engineering reports

Review of historic description shows that the appearance and character of the Virgin River have substantially changed. The river observed by the pioneers was narrower, had grassy banks and was lined by tall trees and swampy grassland. The river seen in the earliest photographs (1902) is wide and braided with a barren active floodplain and vertical cut banks.

A total of nine aerial photographs, dating back to 1938, and a cadastral survey map of 1870 were compared to identify the type and extent of changes on the active river channel and floodplain. Map overlays were prepared from each set of historic aerial photographs to compare the locations of the active channel and floodplain. Measurements made from the overlays indicate that the active channel of the Virgin River decreased in width by about 62 percent from 1938 to 1993 (684 to 257 feet), and the maximum active floodplain width decreased from 5,100 to 2,200 feet. The largest measured lateral migration distance due to bank erosion was more than 900 feet.

Hydrologic and climatic information was analyzed. There were 12 floods with discharges greater than 10,000 cubic feet per second (approximately a 5-year flood) recorded for the Virgin River at Virgin, Utah, with the largest recorded natural flood in December 1966. Comparison of the 1960 and 1966 aerial photographs indicated that the active channel of the Virgin River shifted significantly within the floodplain and that bank erosion reached up to about 800 feet in some places. Another large flood, the January 1989 Quail Creek flood, occurred due to a reservoir failure. Channel movement was not as significant as other historic natural floods due to the flood's short duration. The paleoflood hydrologic study revealed that there were at least 12 floods larger than the 1966 event and that there have been at least two floods larger than the Quail Creek Flood since about 900 AD.

From the historical evaluations, the following important conclusions were obtained:

- The Virgin River has been subject to large, erosive floods for at least the past 1,000 years. These erosive floods have caused the active channel to frequently shift locations within the geologic floodplain.

- Channel movement and/or bank erosion of 800 to 2,000 feet was not uncommon during the 7 to 14 year period between dates of aerial photographs.

- During the past 35 years, the Virgin River has become narrower and deeper, and the active floodplain has become densely vegetated.

#### *4.7.2.2. Geomorphic Evaluation, Virgin River*

The geomorphic evaluation estimates where future aggradation, degradation, and lateral channel migration are likely to occur. Several river stability assessment methodologies were used including river-classification based techniques, interpretation of historic river response, USACE allowable velocity and hydraulic geometry procedures, Federal Highway Administration guidance, and sediment continuity relationships. As empirically based methodologies, they are more appropriate for predicting the direction of expected channel change than the exact magnitude of future channel changes. The authors believe that "methodologies that allow precise determination of future (long-term) river behavior simply do not exist." However, the authors also believe that "by application of the geomorphic principles and methodologies, combined with the interpretation of the historic information, a reasonable assessment of the potential for future erosion can be made." The erosion corridor was defined based on past river behavior and the existing river channel conditions. Engineering judgement was used in developing approximate future erosion hazard corridor limits.

The study summarized variables that affect river behavior into eight categories: hydrology, flow, flood characteristics, riverbed and bank sediment, climate, time scale, channel vegetation and watershed characteristics. Sources for data for these categories used for the geomorphic evaluation include:

- Historic records on channel change,
- Aerial photographs and maps,
- HEC-2 output from the effective FEMA Flood Insurance Study, and
- Engineering and scientific reports.

A visual survey was conducted, and observations on above variables were recorded. The longitudinal profile and channel bed elevation data were analyzed. Results indicate that long-term scour of up to 12 feet has occurred since the 1960s and that net long-term scour has probably been occurring in the study reach since at least 1862. Channel degradation on this scale tends to reduce bank stability and increase the potential for lateral erosion.

Stability of channel reaches was evaluated using two classification systems for the Virgin River study reach: the Federal Highway Administration (FHWA, 1991; Brice, 1983) system and the Rosgen system, both described in detail below.

*Federal Highway Administration classification system:* The method (FHWA, 1991) was developed primarily for the evaluation of river stability near bridge structures and uses readily identified river characteristics to predict stability. The system assigns a relative erosion potential classification based on the 12 river characteristics below:

- River Size: The potential for and scale of lateral erosion increase with river size.
- Flow Habit: Perennial rivers tend to be more erosive than ephemeral rivers, except in arid regions where flash floods and unstable bank materials cause significant lateral erosion.
- Bed Materials: The Virgin River has a sandy gravel bed and stratified sand and gravel bank materials susceptible to scour.
- Valley Setting: Channel reaches with low relief (less than 100 feet) typically have more erosion-prone banks.
- Floodplains: Channels with wide floodplains (more than 10 times channel width) typically experience more lateral channel movement than channel with narrow floodplains (2 to 10 times channel width).
- Natural Levees: Rivers with natural levees tend to have low rates of lateral migration.
- Apparent Incision: Rivers with vertical cut banks are generally unstable.
- Channel Boundaries and Vegetation: Alluvial rivers are more susceptible to lateral erosion than non-alluvial rivers. The Virgin River is an alluvial river except for a small portion. Banks with less than 30 percent woody vegetation and banks with cohesive soils are generally less susceptible to scour. The Virgin River does not have these characteristics.
- Sinuosity: The Virgin River has a sinuosity less than 1.5 and probably is not subject to meander geometry relationships.
- Degree of Braiding: Braided rivers are laterally unstable. The Virgin River study reach was generally braided form 1938 to 1967 and retains some characteristics of a braided river at high flows today.
- Degree of Anabranching: The study reach is not anabranched, as defined by FHWA.

- Variability of Width and Development of Bars: Rivers with relatively uniform width and narrow, regular point bars tend to have slow lateral migration rates. The study reach has irregular channel widths and wide irregular bars; therefore, it is subject to rapid migration.

Under this classification system, the Virgin River study reach scores high in all of the categories that indicate lateral instability. It indicates that the river reach has high potential for rapid erosion and lateral channel movement.

*Rosgen Classification System*. The Rosgen system (Rosgen, 1985, 1994, 1996) was developed from data from the intermountain region of the western United States and has many adherents among state and Federal agencies in Utah. The system classifies river reaches into different types based on its slope, channel type, bed materials, entrenchment, erodibility and type of sediment.

The Rosgen bank erosion matrix (Rosgen, 1996) was used to evaluate bank erosion potential. The bank erosion matrix assigns measurable parameters describing bank conditions. These parameters include bank height/bankfull height, root depth/bank height, root density, bank angle in degree, and surface protection. Points are assigned to each parameter, which are then are summed and adjusted for bank material composition and stratification. A high total score indicates high erosion potential. The banks of the Virgin River in the study reach scored in the range of very high to extreme categories of bank erosion potential.

The study evaluated the potential for bed erosion by comparing the permissible velocity, established by USACE (1995) for design of non-scouring flood control channels, with the average channel velocities determined from Flood Insurance Studies. The results showed that floods with 10-year or greater return periods would exceed the permissible velocities. The USACE criteria relating flow depth and velocity to the movement of bed materials and erosion of cohesive bank materials (USACE, 1990) indicate that the Virgin River will erode its bed and banks at flow rates substantially less than the 10-year flood velocities and depths. The criteria developed by Thorne and Osman (1988) as well as by Rosgen (1996) were used to evaluate bank stability. Results indicated that the vertical-cut banks along the Virgin River are unstable. Finally, the channel migration rates during the period of record were determined by comparing channel locations in sequential aerial photographs. The results show the potential for very rapid bank migration within the study reach.

Sediment data were obtained from several engineering reports (SCS, 1990; Biowest, 1995) and USGS measurements at the Hurricane, Utah, station. These sediment data tend to support the theory that much of the geomorphic work on the Virgin River is accomplished during floods, instead of during bankfull discharges and low flows.

Based on conclusions of historic and geomorphic studies and engineering judgement, an erosion hazard corridor was defined.

#### *4.7.2.3. Conclusion*

From the above analysis, the study concluded that the Virgin River is subject to extreme bank erosion, lateral channel movement, and channel changes in bed elevation. Bank erosion with accompanying lateral migration of up to 2,000 feet over the past 120 years was identified using historic maps and aerial photographs. Human modifications in the floodplain of the Virgin River and attempts to control erosion have generally been unsuccessful during the 140-year period of settlement. No trend toward increase of the river stability was identified. For all these reasons, a wide erosion hazard corridor was established.

#### *4.7.2.4. Santa Clara River*

Santa Clara River is a tributary of the Virgin River. Its drainage basin covers about 545 square miles of mountainous terrain north of the City of St. George, Utah. The river has perennial flow; its floodplain has been exploited for agriculture. Although floods and flood-related channel changes have occurred during the last 140 years, the lateral position of the channel within its floodplain has been very stable. Only in recent years has flood-related channel instability caused problems for landowners.

The same historic and geomorphic analyses used on the Virgin River were applied to the Santa Clara River. Evaluation of the historic channel changes of the Santa Clara River reaches demonstrated the following conclusions:

- The Santa Clara River experienced a period of channel bed degradation during the late 1800s that caused the main channel to become incised. However, the channel pattern apparently did not change significantly. The channel was relatively stable from 1938 to 1994. During this period the watershed experienced an extended drought, the record flood, and many other large floods.

- Recent channel instability is concurrent with a period of human disturbances of the floodplain and channel. Undisturbed reaches have been stable since 1938. Recent channel instability is due to relatively small-scale bank failures, but generally the bank has not eroded beyond the limits of the incised channel.

- Geomorphic evaluation consisted of field visual survey, hydraulic data analysis (from FEMA Flood Insurance Studies), channel longitudinal profile development and analysis, and river stability evaluation using the FHWA and Rosgen classification systems.

- The study reach has been relatively stable, except where bank vegetation has been disturbed. Historic channel degradation has over-steepened banks in portions of the study reach.

- Hazard of bank erosion and lateral channel movement is high where bank vegetation has been removed and is moderate elsewhere.

- Long-term scour has lowered the channel bed elevation by as much as 12 feet since 1850 and has increased the potential for bank erosion and lateral channel movement.

- Overall, the study reach is subject to lateral erosion and degradation where bank vegetation is disturbed.

Based on these conclusions, the results of the historic analysis and engineering judgement, an erosion hazard corridor for the Santa Clara River was defined.

#### *4.7.2.5. Fort Pierce Wash*

The Fort Pierce Wash drainage basin covers about 1,600 square miles of southern Utah and northern Arizona. Its watershed consists primarily of poorly vegetated, arid, high desert areas with dry washes in hilly, bedrock terrain. The study reach has ephemeral flow; recently, near-perennial discharge has begun to flow in the wash. The discharge comes from irrigation return flow, mining tailwater and other sources related with urbanization of the St. George area.

Historical evaluation and geomorphic analysis were applied to evaluate stability of the study reach. Channel changes that occurred along Fort Pierce Wash during the historic period are summarized as follows:

- The wash has undergone significant modifications of its channel and floodplain in the past 30 years. The active channel in the disturbed reach has changed from a wide, braided river to a narrow, confined channel choked by dense growth. The disturbed reach narrowed by more than one order of magnitude. Lateral channel movement has not been a significant hazard along Fort Pierce Wash since 1938, partly because that none of the floods recorded in the past 90 years for the study reach exceeded the 20-year recurrence interval.

- Human activities on the floodplain, mainly sand and gravel mining and urban development, have strong impacts on channel changes. Mining has moved material from channels and floodplain, and two mining pits have intercepted the main channel in two places. Development has encroached on the floodplain.

- The geomorphic evaluation indicated that human impacts have had the greatest effect on channel stability in the study reach. Lateral channel stability has not been a problem in the past and is not expected to cause significant problems in the future, except for areas near the sand and gravel mining reach.

An erosion hazard corridor was developed along the study reach.

#### *4.7.2.6. Recommended Management Plans*

Based the on above analysis, the study recommended floodplain management plans for each river. The general recommendations for management of all reaches include the following elements:

- Adopt the erosion hazard corridor.

- Amend the existing flood control ordinances and policies to include river management policies. These policies would support preservation of the natural river systems, promote land uses that are compatible with a natural river system, and limit construction of structural improvements within the erosion hazard corridor. Exceptions would be given to measures that protect existing structures needed for public safety or where the channel threatens to move outside of the established erosion hazard corridor.

- Regulate all new developments within the corridor by requiring a special use permit.

- Establish a no-build zone close to the banks. Habitable structures should be set back a minimum distance from the top of the bank.

Specific recommendations are made for each of the studied rivers.

### *4.7.3. Applicability*

The report described a typical river stability study in arid areas. The study analyzed historic records to interpret river behavior in the past and used geomorphic analysis based on field observation and historic data to predict the erosion potentials for the future. Two river stability classification systems, one developed for nationwide use and another based on regional features, were used to evaluate the stability of study reaches. This methodology is applicable to other rivers.

Based on the analysis, erosion hazard corridors were defined for all studied river reaches. The corridors were developed based on the following factors:

- Judgement
- Historic bank movement distances measures on maps and photographs
- Meander geometry relationships
- Regime/hydraulic geometry relationships to identify unstable/stable reaches
- Geometric mapping of soil units
- Presence of permanent improvements, such as bank protection, bridges, and pipeline crossings, that would be protected and repaired.

Although the above elements do not generate a specific distance to use as setback from banks, they provide a sound base to support proper engineering judgement to delineate erosion corridors. The maps in the report illustrate these corridors.

The study recommended management plans for each river studied. The common elements of the management plans are applicable to other rivers with similar natural and human-introduced characteristics.

### *4.7.4. Limitations*

It is clear that using the procedures described in the report to determine erosion corridors requires specialized knowledge and that the quality of the work would largely rely on the project engineer's experience and judgement.

### *4.7.5. Relevant References*

Biowest, Inc. (1995), *Virgin River Geomorphic and Hydrologic Studies Related to Channel Forming Flows,* Reported prepared for Utah Division of Wildlife Resources, Salt Lake City, Utah.

Federal Highway Administration (1991), *HEC-20: Stream Stability at Highway Structures*, Washington, D.C.

Rosgen, D. (1985), "A Stream Classification System," in *Riparian Ecosystems and Their Management – Reconciling Conflicting Uses*, Proceedings of the First North American Riparian Conference, April 16-18, 1985. Tucson, Arizona.

Rosgen, D. L. (1996), *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, Colorado.

Soil Conservation Service (1990), *Virgin River - Utah, Cooperative Study*, prepared in cooperation with Utah Division of Natural Resources.

Thorne, C. and A. Osman (1988), "Riverbank Stability Analysis. II: Applications," ASCE Journal of Hydraulic Engineering, vol. 114, No. 2, p. 151-172.

U.S. Army Corps of Engineers. (1990), *Stability Assessment for Flood Control Channels* (Draft).

U.S. Army Corps of Engineers (1995), *Hydrologic Design of Flood Control Channels*, EM1110-2-1601.

### 4.7.6. Mappability

The study mapped historic river channel locations for the Virgin River from 1874 to 1993, and erosion hazard corridor boundaries along the studied reach for each of three rivers.

### 4.7.7. Cost

No cost information is reported. Mr. Jon Fuller, a member of the PWG, estimates that the cost is approximately $1,000 per mile for the geomorphic analysis.

### 4.7.8. Regulatory Potential

The results of the study can be used for floodplain management as well as regulation. The study recommended necessary revisions to ordinances of the City of St. George to incorporate floodplain management policies that would reduce human-induced damages to the river systems. Specifically, the study recommended requiring a special use permit to regulate all new development within the erosion hazard corridor. To obtain a permit, the developers within a corridor must meet following requirements:

- Meet NFIP requirements for development within a floodplain.

- Provide an engineering and geomorphic study prepared by a professional engineer licensed to practice in the State of Utah and certifying that the proposed development will not be affected by erosion over a 100-year planning period.

- Demonstrate that proposed bank stabilization, if any, will not deleteriously affect reaches or development upstream or downstream.

- Demonstrate the stability of proposed bank stabilization, if any. Local scour, long-term degradation, channel movement, and bank erosion must be explicitly addressed in the bank protection design.

- Hold the City harmless from any and all claims resulting from erosion or any other flood-related damage to development within the erosion hazard corridor.

- Provide for perpetual maintenance of the bank stabilization at no cost to the City or any other public agency.

- Provide a maintenance and access easement adjacent to any bank stabilization project.

- Obtain necessary floodplain, wetlands (404), and water quality (401) permits or approvals for any construction activities at no cost to the City.

### 4.7.9. Summary

The report describes historic and recent channel changes on the Virgin River, Santa Clara River, and Fort Pierce Wash in the City of St. George, Utah. The document describes methodologies used to predict future river behavior and erosion. These methodologies rely heavily on interpretation of historic channel behavior but also include consideration of engineering and geomorphic techniques for evaluating channel stability. The historic, geomorphic, and engineering analyses were used to support flood control and erosion management for the City of St. George.

## 4.8. Hydrologic and Geomorphic Studies of the Platte River Basin, Nebraska

| | |
|---|---|
| *Document Title*: | Relation of Channel-Width Maintenance to Sediment Transport and River Morphology: Platte River, South-Central Nebraska (Karlinger *et al*., 1983) |
| *Agency*: | U.S. Geological Survey |
| *Authors*: | Michael R. Karlinger, Thomas R. Eschner, Richard F. Hadley, and James E. Kircher |
| *Date*: | 1983 |
| *Study Method Category:* | Geomorphic analysis |

### 4.8.1. Overview

This study was undertaken as a result of the need to maintain a specific channel width along the Platte River, south-central Nebraska, for migratory-bird habitat. The study reach extends from Ashland, Nebraska, to just upstream of the confluence with the North Platte River, near Keystone, Nebraska. Three different methods were developed to estimate the water discharge necessary to maintain the current channel width. The methods include an empirical estimation based on combining a sediment-water discharge relation with a steady state flow duration curve, investigation of macroforms and channel geometry as an aid in predicting the current channel width, and use of Parker's equations (Parker, 1977).

The report reviews, in detail, the channel geometry, sediment characteristics, and vegetation effects before applying the three methods.

### 4.8.2. Detailed Description

The history of channel change was investigated through observations of changes in the channel pattern, width, depth, slope, and bed forms. Information was collected from aerial photographs, USGS maps, topographic surveys, and field inspections. The data were analyzed and plotted to represent changing conditions over time.

The channel's sediment characteristics were also analyzed. Both bed sediment and bank sediment samples were collected and analyzed to determine trends in sediment size. The stream distances versus the median sediment size were plotted to obtain a representation of the sediment characteristics for the entire river section. The effect of changes in vegetation on channel width and sediment transport was also considered.

Once the channel conditions were investigated, three methods were applied to obtain the discharge necessary to maintain the channel width.

*Method One*

The first method involves determining a predominant discharge for which a specific amount of sediment will be transported, thus ensuring that the channel width remains the same. The first step is to determine a relationship between sediment transport rate and water discharge, and a flow-duration curve for the site of interest. Sediment transport is computed using the Modified Einstein Method, and a power regression equation is determined to relate sediment transport rate to water discharge. This relationship can be used with the flow duration curve to assign probabilities of exceedence to sediment transport. This sediment duration curve is then used to compute the expected sediment transport rate. The water discharge associated with the maximum contribution to the expected sediment transport rate is assumed to be the "effective discharge" responsible for carrying most of the sediment load. This discharge must be maintained if the channel shape is to remain unaltered. This discharge transports most of the sediment by virtue of both its magnitude and the frequency of occurrence. Therefore, the "effective discharge" is that for which the product of discharge times probability of occurrence is maximum.

*Method Two*

The second method involves determining a relationship between discharge and macroform characteristics. The premise is that macroforms can be colonized by vegetation and alter the flow section; therefore, the flow regime should be able to transport these macroforms downstream if the channel is to remain unaltered.

Macroforms are large bed forms that are submerged only during high flows and are proportional to the channel's dimensions. In this study, the following equation was used to determine the flow necessary to move a macroform downstream.

$$Q = \left[ \frac{h_s}{2at_{\lambda_L}} \frac{L_f}{\sin \alpha} \right]^{1/n} \tag{4.2}$$

where $h_s$ is the depth of scour, $L_f$ the macroform length, $\alpha$ the angle formed by the intersection of the channel bankline with the crestline of the macroform, and $a$ and $n$ are regression coefficients. The time required to move a unit width of macroform a distance $\lambda_L$ is termed $t_{\lambda_L}$.

This discharge has a lower limit equal to the flow that causes a minimum water depth over the macroforms necessary for incipient sediment motion. In the Platte River, this depth was estimated as 20 cm.

*Method Three*

The third method involves the application of Parker's equations (Parker, 1977), which specify conditions for balance of sediment transport and deposition to attain equilibrium. There are three regime equations. The first one relates grain size to particle fall velocity and channel slope. The second and third equations relate water and sediment discharge to variables describing particle size and channel features including grain size, channel slope, and channel width.

Parker's equations assume that 1) channel reaches are straight; 2) bed and bank materials are noncohesive; and 3) sediment grain sizes are uniform throughout the reach. Because the third condition does not hold for the Platte River, average sediment size was inferred from field measurements. Several parameters (channel width, discharge, depth, and slope) were measured at five locations along the river reach. The data were then inserted into the equations to determine the sediment size. The observed width versus sediment size was plotted for the five locations, thereby enabling the user to apply Parker's equations for any site within the reach.

### 4.8.3. Applicability

The first and third methods are applicable for the purposes of the REHA study. The concept of a predominant discharge, described in the first method, could be used by communities as a monitoring technique. A change in the resulting function could indicate changes in channel morphology. In addition, the calculation of widths based on a given discharge from the first and third methods could be approximately mapped to illustrate erosion hazard areas associated with the various discharges.

The second method is not applicable for the study of REHAs beyond usage as an indicator of channel stability.

### 4.8.4. Limitations

There are several limitations associated with each method. None of the three methods consider channel meandering. The methods are generally only applicable to straight channel reaches.

Although not an insurmountable limitation, it should be noted that to use the first method data must be available to establish the sediment versus water-discharge relation and the flow-duration curve for each site of interest. Sediment transport equations yield greatly varying results depending on the parameter values used and the equation selected. In consequence, large variations can be expected in any derived quantities.

In addition to the fact that the second method has minimal application to the REHA study, the report indicates that the derivation of Eqn. 4.2. may suffer from some statistical inconsistencies.

There are several limitations associated with the use of the third method. In addition to being applicable only to straight channel reaches, Parker's equations are limited by the assumption that the bed and bank materials are non-cohesive. Parker also indicates that appropriate particle sizes are among the smaller sizes. The report indicates that the dependence of the design sediment size on the channel slope is assumed negligible for the calibration curve and the curve is based on maximum widths due to constraining vegetation. Special consideration needs to be made when using the calibration curve for other sites.

### 4.8.5. Relevant References

Parker, G. (1977), *Self-Formed Straight Rivers with Stable Banks and Mobile Bed in Non-Cohesive Alluvium. Part I: The Sand-Silt River*, Department of Civil Engineering, University of Alberta, Alberta, Canada.

Andrews, E. D. (1980), "Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming," Journal of Hydrology, v. 46.

### 4.8.6. Mappability

The first and third methods presented in this study could serve as bases for assessing the effects of channel changes and can be used to approximately map channel changes to illustrate erosion hazard areas.

### 4.8.7. Cost

No cost information was provided.

### 4.8.8. Regulatory Potential

The methodology, in particular methods 1 and 3, could potentially be enhanced to be used as a tool for regulatory purposes.

### 4.8.9. Summary

This study of the physical characteristics of the Platte River channel provides a basis for understanding the channel-forming processes in the stream. These characteristics and understanding are used to estimate discharge and channel width relationships. This study consists of a qualitative assessment of geomorphic and channel conditions on the Platte River with some quantitative assessments involving measurements and analysis of the bed and bank materials. The three methods described can be used to determine the discharge necessary to maintain a specific channel width. The first and third methods may be applicable to the REHA study in estimating channel widths for given discharges. However, the methods have several limitations and their applicability to other sites needs to be further investigated.

## 4.9. Streambank Erosion Along Two Rivers in Iowa

| | |
|---|---|
| *Document Title:* | Streambank Erosion Along Two Rivers in Iowa (Odgaard, 1987) |
| *Agency:* | Iowa Institute of Hydraulic Research, University of Iowa |
| *Author:* | A. Jacob Odgaard |
| *Date:* | 1987 |
| *Study Method Category:* | Historic analysis and geomorphic equations |

### 4.9.1. Overview

This research paper is one of the early studies conducted in the United States to relate the rate of bank erosion to river characteristics. The U.S. Geological Survey supported the research. The objective of the study is twofold: to evaluate the contribution of bank erosion to the sediment load and, more importantly, to identify and quantify specific channel characteristics correlated to bank erosion.

The study was based on Ikeda's theory of river meanders, which assumes that the rate of bank retreat is proportional to the difference between the near-bank depth-averaged mean velocity and the reach-averaged mean velocity at bankfull discharge (Ikeda *et al.* 1981). The analytical framework for this study is an algebraic relation between the migration rate and channel characteristics based on Ikeda's theory and a meander flow model developed by the author.

The study first evaluated the rates and the processes of bank erosion for reaches of two streams in Iowa: the East Nishnabotna River and the Des Moines River. The streams are alluvial with point bars and their widths vary from relatively constant along the length (equiwidth) to wide bends. The evaluation was made using historic records (aerial photographs, maps, and stream records), field measurements, and soil analyses. The erosion rates were then correlated to channel characteristics such as width, depth, curvature, arc angle of channel centerline, channel slope, friction factor, and bank vegetation. The correlation was studied using the migration model, which simulates the velocity distribution in the bends and the location of the erosion occurrence. The final step of the study was to estimate the total sediment influx to the river from cutbank erosion.

### 4.9.2. Detailed Description

The paper consists of three major parts: the migration model, two case studies of the East Nishnabotna and Des Moines Rivers, and conclusions.

#### 4.9.2.1. Migration Model

A meander flow model describes the meander bends as constant-radius curves whose migration is a combination of downvalley translation and lateral expansion. Two basic assumptions behind this model are the following:

- The rate of bank retreat is proportional to the difference between the near-bank, depth-averaged mean velocity and the reach-averaged mean velocity at bankfull discharge, and

- The velocity distribution in bends, or lag in velocity's response to curvature change, determines the distance from the crossover point to the first erosion occurrence on the outer bank.

The migration rate and the bank erosion were related using the following relationship:

$$v/u = e\, u_b'/u \qquad (4.3)$$

in which $v$ is the linear rate of bank retreat, $u$ is the reach-average mean velocity, $e$ is an erosion constant, and $u_b'$ is the difference between the near-bank depth-averaged mean velocity and the reach-averaged mean velocity $u$ at bankfull discharge. An equation for the near-bank depth-averaged mean velocity was obtained by solving the continuity and momentum equations and an equation for lateral stability of the streambed (Odgaard, 1986). The solution is for steady, subcritical, turbulent flow in constant radius segments. The coefficient $e$ is the equivalent of the scour factor (Parker, 1983).

The migration model predicts the "zero point for $v$," which is the point of first outer bank erosion occurrence. The location of this point along the bend depends on the radius-width ratio, bend angle, and upstream channel geometry. The model predicts that sine-generated bends with large radius-width ratio migrate by having both downstream translation and lateral expansion; and the same prediction applies to bends with smaller radius-width ratios if the bend angle is large. For sine-generated bends with relative small radius-width ratios and small bend angles, the migration is driven by downstream translation only.

The average rate of erosion along the eroding part of the bank was assumed to be approximately half of the maximum linear rate of bank retreat. The areal rate of erosion per bend was obtained by multiplying the average linear rate of bank retreat by the bend angle and the radius of curvature referring to the channel centerline. The volumetric rate was obtained by multiplying the areal rate and the height of the cutbank. Summation over all bends along a river yields the total volumetric rate of cutbank erosion.

The method was applied to the East Nishnabotna River and the Des Moines River.

#### *4.9.2.2. East Nishnabotna River*

The East Nishnabotna River is located in southwestern Iowa where it drains about 960 square miles of the Missouri River basin. The East Nishnabotna basin consists of loess deposit with about 30 percent clay content and a thickness of about 18 feet. The erosion study covers a 40.6-mile reach of the river between Atlantic and Red Oak. Flow and sediment data for channel sections were obtained from the USGS Water Resources data for Iowa (1961-1986), and photographs for channel segments were obtained from the Agricultural Stabilization and Conservation Service of the U.S. Department of Agriculture. Two field investigations, one made at near bankfull stage and another at extreme low flow, were conducted to survey the cross sections. Soil samples were collected during the field investigations.

The 40.6-mile reach was subdivided into 136 straight and constant radius segments; from them, 72 were selected as study bends. All 72 bends experienced bank erosion during the period of analysis. Historic bank retreat was determined by superimposing sequential photographs using the technique described by Brice (1982). The data analysis also included defining the location of erosion occurrence relative to the crossover points and determining the channel's bankfull width, cutback height, curvature, bend angle and bed level variations over the period of record. The channel characteristics were then used as an input to the migration model to predict bank erosion retreat, erosion velocity, and location of the first outer bank erosion point.

The study compared erosion velocities measured in the East Nishnabotna River along the cutbanks with the erosion velocities predicted by the migration model. The results showed the observations of erosion velocity followed the same general trend of model predictions. However, there was significant scatter between the observed first outer bank erosion point and the one that the model predicted.

The study then estimated the average bend retreat rate, $v$. While the actual value of $v$ varies from bend to bend, the average bend was migrating at a rate of 25.6 feet per year. The areal loss from outside banks along the lower half of the study reach was estimated, based on historic measurements, to be 13.7 acres per year, or about 0.6 acre per mile per year. Along the upper half of the reach, the loss was 5.0 acres per year, or about 0.28 acre per mile per year.

#### *4.9.2.3. Des Moines River*

The Des Moines River flows to the southeast across central Iowa to its confluence with the Mississippi River in the southeastern corner of the state. The study covered the lower 143 miles of the river, downstream from the Red Rock reservoir. The valley length of this reach is approximately 115 miles and adjacent drainage area is 2,200 square miles. The floodplain consists of alluvial deposits with silt and clay on top of a mixture of sand and gravel. A total of 45 bends were identified comprising 45 percent of the 143-mile reach. The study reach was divided into three subreaches with about equal number of bends in each. Erosion data were obtained from a study conducted by the U.S. Army of Corps of Engineers (USACE, 1979), in which areal losses were determined from historic aerial photographs taken between 1938 to 1976.

The analysis of the historic data showed that over the 37-year period, a total of 2,996 acres were lost along cutbanks. The annual loss rate, 0.56 acre per mile, is almost the same as the East Nishnabotna reach (0.60 acre per mile). The bank retreat for average bends in three reaches varied from 7.8 to 12.1 ft per year. The amount of volume loss and the amount of sediment influx to the water were also estimated.

The meander flow model was used to predict the erosion retreat using the measured channel characteristics as the input. The values for three reaches were then plotted to compare with the measurements from the historic data. The plot showed a good correlation between the measured and predicted values.

#### *4.9.2.4. Conclusion*

The above analyses showed that there were several similarities between the study reaches of the two rivers, although they are different in channel size and discharge patterns. The East Nishnabotna River has natural flow, and the Des Moines River has controlled releases from the Red Rock reservoir. Both reaches were experiencing cutbank erosion in bends at a rate of 13 to 26 feet per year. The erosion constant, which is a measure of the erodibility of the bank materials, is about the same for these two reaches. The study also found that the erosion velocities were generally higher by a factor of about 2 or more in banks flanked by matures trees.

The analyses indicated that the theoretically developed relation between erosion velocity and channel characteristics, as described in the meander flow model, is valid.

The author concluded that the similarity between the two rivers in terms of erosion rates and pattern suggested that the findings were typical for the region, including Iowa and possibly neighboring states, because of a notable uniformity in the region's floodplain features.

### 4.9.3. Applicability

The study provided a relatively simple approach to predict channel erosion from channel characteristics by application of a meander flow model. The model is applicable to other river reaches in the region to estimate annual erosion rate; however, additional procedures must be developed to develop riverine erosion maps.

### 4.9.4. Limitations

Although the two examples of the East Nishnabotna and Des Moines Rivers indicated that applying the meander flow model to the erosion damage assessments is possible, there are two main concerns.

First, the model was only tested in two rivers. From figures included in the paper, it appears that the model was able to predict the erosion velocity with reasonable accuracy; however, the prediction of the first erosion point was not satisfactory. The paper did not present more comparisons of observed or measured data with the prediction.

Second, the study did not generate any maps to identify the erosion hazard area, although the estimated first occurrence of erosion could be used as an indicator of high erosion hazard areas on maps. The applicability of using the modeling results to develop erosion maps needs to be further explored.

### 4.9.5. Relevant References


Brice, J. C. (1982), *Stream Channel Stability Assessment, Report FHWA/RD-82-021.* Federal Highway Administration, Washington, D.C.

Ikeda, S.G., G. Parker, and K. Sawai (1981), "Bend theory of river meanders; 1: Linear Development," Journal of Fluid Mechanics, v. 112, p. 363-377.

Odgaard, A. J. (1984), *Bank Erosion Contribution to Stream Sediment Load,* Iowa Institute of Hydraulic Research Report 280, University of Iowa, Iowa City.

Odgaard, A. J. (1986), "Meander-flow Model, 1, Development," ASCE Journal of Hydraulic Engineering, vol. 112 , p. 1117-1136.

Parker, G. (1983), "Theory of Meander Bend Deformation," in *River Meandering: Proceedings of the Conference Rivers '83,* American Society of Civil Engineers, New York.

U.S. Army Corps of Engineers, Rock Island District (1979), *Des Moines River Bank Erosion Study, Iowa and Missouri Stage 2, Final Feasibility Report*.


### 4.9.6. Mappability

Procedures must be developed to convert model predictions into the boundaries of erosion hazard zones.

### 4.9.7. Cost

Cost information was not reported.

### 4.9.8. Regulatory Potential

The approach, including the meander flow model, procedures to collect and analyze historically recorded data, and comparison of the measured/recorded and predicted bank erosion to test the model, has a potential to provide technical support for regulating riverine erosion hazard areas.

### 4.9.9. Summary

The processes of bank erosion and retreat rates were evaluated for reaches of two alluvial streams in Iowa. The evaluation was made using historic records (aerial photographs, maps and stream flow records), field measurements, and soil analyses. The model simulates the erosion velocity in the river bends and the location of erosion occurrence. The total sediment influx was also estimated for the studied channel reaches.

The migration model and the methodology to use the model to predict erosion location has the potential to be used as a tool to identify the erosion hazard areas. However, the model needs to be further tested and mapping procedures must be developed before the methodology can be applied for the purposes of riverine erosion hazard mapping.

## 4.10. Channel Migration Studies in King County, Washington

| | |
|---|---|
| *Document Title:* | Tolt and Raging Rivers Channel Migration Study, King County, Washington (Shannon & Wilson, 1991)<br>Green River Channel Migration Study (King County Surface Water Management Division, 1993)<br>Channel Migration in the Three-Forks Area of the Snoqualmie River (King County Surface Water Management Division, 1996) |
| *Agency:* | King County Department of Natural Resources, Surface Water Management Division |
| *Authors:* | Shannon & Wilson, Inc.<br>Susan Perkins, King County Surface Water Management Division. |
| *Date:* | See dates next to document titles |
| *Study Method Category:* | Geomorphic and engineering analysis (using historic and field observed data) |

### *4.10.1. Overview*

These three studies were performed for flooding sources in King County, Washington, with known erosion hazards. The basic premise of the studies is that future river migration rates and types of channel migration in each river will, on average, be similar to past behavior under the same water and sediment discharge regime. The methods used in the study are primarily geomorphic and engineering analysis based on historic data, detailed study of bed and bank materials, and quantification of channel changes analysis. The studies provide detailed analysis and mapping of erosion hazard areas.

### *4.10.2. Detailed Description*

The methodology consists of compiling historic aerial photographs, surveys, and available maps for the period of study. The periods of study include 1942–1993, 1898–1992, and 1936–1991 for the Snoqualmie, Green River, and Tolt and Raging Rivers studies, respectively.

#### *4.10.2.1. Study Procedures*

Each of the studies was conducted individually. In general, the studies used the following procedures:

- *Investigating channel characteristics of study areas*. The investigation consists of field surveys and review of historic maps, aerial orthophotographs, and aerial photographs. Features examined during the field survey included geologic materials, river bank height and composition, levees and revetments, vegetation type and age, presence of eroding banks, abandoned channels, deposition zones and descriptions of river and floodplain morphology. Sediment sampling was also conducted. Erosion zones were identified as a result of the investigation.

- *Determining historic channel migration rates*. The average historic channel migration rate for each reach was determined by first comparing the channel locations on maps or aerial photographs at different time periods, then calculating the average migration rate for each channel reach where erosion had occurred.

- *Estimating potential for erosion and enlargement of floodplain channels*. The enlargement potential was estimated by calculating the boundary shear stress that flowing water would exert on each channel during a 100-year flood. Factors affecting channel migration rates were analyzed.

- *Determining hazard area from future channel migration*. The prediction of the probable limit of future migration was determined based on an assumption that future rates and types of channel migration will, on average, be similar to the past behavior under that same water and sediment discharge regime. The basic elements of the prediction are as follows. The appropriate historic period to use for prediction was determined based upon whether hydrologic changes had significantly influenced channel migration. Next, the probable outer limits of future channel migration were determined based on historic meander belt width and measured bend amplitudes for each reach, ignoring existing or potential revetments and levees.

- *Developing mitigated channel migration hazard map*. The outer limits of future migration were modified to account for constraints. Major roads and subdivisions were recognized as likely to be protected from erosion hazards; constraints were added into the natural limits of the channel migration to produce a Mitigated Channel Migration Hazard Map. The mitigated hazard area was then subdivided into areas of severe and moderate hazard, using calculated historic channel migration rates.

The above general procedures were followed in the all three studies; however, each study was somewhat different, depending upon study area characteristics.

#### *4.10.2.2. Study Area Characteristics*

The Snoqualmie study investigates 12 miles of the upper reach of the river, including its three forks, with a contributing drainage area of 358 square miles. The Tolt and Raging Rivers are tributaries to the Snoqualmie River; the study encompasses a 5.9-mile reach of the Tolt River with a drainage area of 101 square miles and an 8.1-mile reach of the Raging River with a drainage area of 33 square miles. The Green River study investigates 20 miles of river, including the Howard Hanson dam. All of the studied rivers are experiencing rapid migration. Human activities, such as gravel mining and logging, are prevalent in many of the study areas. Some of the areas also have flood control structures, levees, and/or bank protection. The studies provide documentation on the hydrologic and geologic conditions of the areas, such as the largest floods of record, bank composition, and sediment size.

#### *4.10.2.3. Estimation of Channel Migration*

For each study, the rivers were divided into distinct reaches based on different rates and types of channel migration and corresponding differences in river morphology. The report provides a description of the morphology of each reach.

Average historic channel migration rates were calculated for each reach. The procedure for calculating migration rates involved dividing the reach into 100 or 200 feet intervals (depending on the size of the reach). For each station where erosion occurred, the distance between the channel edges was measured from successive maps. The results are tabulated as migration rates occurring for specified time periods. Some of the periods are selected based on changes in the flow regime or bank protection. For example in the Green River study, migration rates are calculated for the pre-dam era (circa 1900-1940) and the post-dam era (1960-1992). For the Snoqualmie study, calculations included 1942-1961 (the pre-bank armoring period) compared to 1961-1993 (the post-bank armoring period). Other comparative calculations were made to illustrate the effects of major channel-altering events such as large floods or channel avulsions.

The reports also discuss the factors affecting channel migration rates. Patterns of shear stress and channel stability, changes in gradient, bed elevation, bank materials, vegetation, flood control structures, bank armoring, levees, and channel straightening were all examined to determine the factors affecting the channel migration rates over time. The Snoqualmie study also considered changes in channel sinuosity and bend geometry.

#### *4.10.2.4. Estimation and Mapping of Future Channel Migration*

*Tolt and Raging Rivers:* Both short-term (10 years) and long-term (100 years) erosion hazards were mapped for the Tolt River. To map the 10-year hazard, the study assumed that bank erosion would occur only in the following locations: currently eroding areas, outer banks of bends, "more probable" avulsion sites, and sites likely to erode as a result of upstream channel shifting. The calculated average migration rate over each reach was selected from periods of record at least 10 years in length, which include one or more severe floods. In this study, two records met this qualification, and the higher of the two migration rates was selected. The selected migration rate was then multiplied by the time period, and the resulting width was mapped. The widths were mapped from the existing channel location assuming the channel would migrate laterally. The 100-year hazard was divided into areas of high and moderate hazards. The high-hazard zones were calculated by multiplying the calculated average migration rates for the entire period of record by 50 years. The resulting widths were mapped assuming the channel would migrate in both directions from the existing channel. The moderate hazard zones were calculated by multiplying the calculated average migration rates for the entire period of record by 100 years. The resulting widths were mapped assuming the channel would migrate in either direction from the existing channel.

Avulsions were also considered in the Tolt and Raging River study. The likelihood of an avulsion occurrence is categorized as either "more probable" or "less probable." "More probable" is defined as an existing creek or side channel that diverges from the main channel of the river in a downstream direction. "Less probable" is assigned when one or more conditions would have to change for an avulsion to occur. Avulsions were mapped for the Tolt River based on either rates of growth of avulsion for reaches where avulsion data were available or the highest shifting and widening rate. An avulsion on the Tolt River was assumed to start as a 30-foot wide channel, erode at the higher avulsion rate for 10 years, and then drop back to the normal channel migration rate for the remainder of the prediction period. For the Raging River, where avulsions were less significant, an avulsion was assumed to start as a 30-foot wide channel, then erode at the normal migration rate for the remainder of the prediction period.

*Green and Snoqualmie Rivers*: Several additional items were considered in the mapping for these two rivers. First, based on hydrologic changes, the appropriate historic period was selected. For example, in the Green River study, there was evidence to suggest that some of the reaches had changed significantly as a result of the diversion of the White River and construction of Howard Hanson Dam. Therefore, when making migration predictions, more recent migration behavior was used instead of the entire period of record. Second, two geomorphological channel characteristics were used to estimate the outer boundary of the erosion hazard area: the meander belt width and the bend amplitude. The meander belt width is used to estimate the maximum valley width occupied by all the mapped channels for the relevant time period. The bend amplitude is used to map the median amplitude of the bends that grew in each reach during the relevant time period. The hazard zone was then extended from the existing channel the greater of the two distances (the meander belt width or the bend amplitude). If the extension reached a valley wall or high terrace, the hazard area was extended in the opposite direction. As indicated on the maps provided with the report, the resulting hazard area encompassed all former river channels in both studies. Third, another map was produced, which scaled back the erosion hazard area to reflect the effects of existing roads, levees, and bank protection.

An underlying assumption for the Green River and Snoqualmie studies was that the river would shift into all high avulsion potential channels and then migrate laterally according to the migration rates calculated for the reach. High avulsion potential is defined as creeks and well-defined former channels that are flooded deeply and frequently (at least once every two or three years), diverge from the main channel in a downstream direction, and are (or could become) directly connected to the river.

Lastly, the erosion hazard area was further divided into severe and moderate hazard areas by using a procedure similar to the one used in the Tolt and Raging River study. For the severe hazard area, it was assumed that during a 100-year period the river would migrate for 50 years in each direction from its present position. The calculated migration rate multiplied by 50 years results in the widths that were mapped. The moderate hazard area is defined as the land between the outer boundary of the severe hazard area and the outer boundary of the mitigated channel migration hazard area.

### *4.10.3. Applicability*

These studies are applicable to the REHA study. The final products of the studies are maps delineating erosion hazard zones. The maps provide a general erosion hazard area and further divide the area into zones of different degrees of hazards. Although the studies are all in the same county, they encompass a variety of basin sizes, flood control structures, and land-use conditions.

### *4.10.4. Limitations*

Many assumptions and selections seem subjective. For example, studies do not provide justification for the time periods and methodology used to define the moderate and severe hazard area zones that would be necessary for the purposes of the REHA study. The selection of barriers to migrating channels is somewhat subjective. No stability analysis was done to determine how effective these structures would be in preventing channel migration.

The channel migration estimates are based on historic data; therefore, years of photographs and documentation of the migrating channel must be available to perform the type of analysis used in the studies.

There are some errors associated with the mapping. For example, if the area used to calculate the migration rates is too small, the depicted widths may be inaccurate.

The studies do not consider the effects of landslides due to undercutting of valley walls.

The basis of using historic trends for a prediction is the assumption of stationarity. Although the assumption may be applicable to study areas that are not significantly impacted by the human activities, this is not always valid for most cases.

### *4.10.5. Relevant References*


Dunne, T., W.E. Dietrich, and D. Nimick (1976), "The Yakima River Between the Selah and Union Gaps", in Jones and Jones, 1976, *Hydrology: Seattle*, Report to the City of Yakima Department of Parks and Recreation, Appendix A.

Dunne, T., and W.E. Dietrich (1978), "A River of Green", in Jones & Jones, 1978, *Hydrology, Sedimentation, Channel Migration, and Flood Diking Along the Green River: Seattle,* Report to the City of Yakima Department of Parks and Recreation, Appendix A.

### 4.10.6. Mappability

The studies provide numerous maps. The maps depict historic channel locations, locations of geologic and man-made channel constraints, unconstrained channel migration hazards, and mitigated channel migration hazards.

### 4.10.7. Cost

No cost information was included in the report. King County and Ms. Susan Perkins, a consultant to the County, estimated that it cost between $3,000 to $6,000 per river mile to complete the channel migration hazard studies. The cost per mile would be less for large projects. The estimate includes digitizing maps into GIS format.

### 4.10.8. Regulatory Potential

Currently, a formal regulatory policy is in place adopted by the County Council as part of the King County Flood Hazard Reduction Plan in November 1993. The King County Surface Water Management Division recommended the adoption of the policy to prevent future development in channel migration hazard areas through land use regulation. The hazard maps produced by the studies were transmitted to the King County Department of Development and Environmental Services to use in regulating development under the Sensitive Areas Code. King County has also implemented a 100-foot buffer zone for class 1 streams in accordance with the King County Sensitive Areas Ordinance.

### 4.10.9. Summary

The three studies performed for King County are based on engineering and geomorphic analysis. The methodology applied includes compiling historic data, conducting field investigations, researching and analyzing channel characteristics, calculating channel mitigation rates, and mapping erosion hazard areas.

The studies are appropriate for the purposes of the REHA study. However, some of the limitations such as defining and providing justification for the severe and moderate erosion hazard designations need to be resolved.

The main result of the studies is the production of maps depicting erosion hazard areas, which are being used for regulatory purposes.

## 4.11. Bank Erosion Field Survey Report of the Upper Mississippi River and Illinois Waterway

| | |
|---|---|
| *Document Title:* | Bank Erosion Field Survey Report of the Upper Mississippi River and Illinois Waterway -- Interim Report for the Upper Mississippi River – Illinois Waterway System Navigation Study (Illinois State Water Survey,1997) |
| *Agency:* | USACE, Illinois State Water Survey (ISWS), and Iowa Institute of Hydraulic Research (IIHR) |
| *Authors:* | Nani Bhowmik and David Soong, ISWS; Tatsuaki Nakato, IIHR; Mike Spoor, USACE, Huntington District, Jeff Anderson, Anderson Environmental Services, and Dan Johnson, USACE, Rock Island District |
| *Date:* | November 1997 |
| *Study Method Category:* | Geomorphic and engineering analysis based on historic data |

### *4.11.1. Overview*

This report summarizes findings from several phases of the Upper Mississippi River/ Illinois Waterway (UMR/IWW) bank erosion study, which is a part of the UMR/IWW system navigation study. The USACE Districts of Rock Island, St. Louis, and St. Paul led the study under the authority of Section 216 of the Flood Control Act of 1970. The objective of the study is to examine the feasibility of navigation improvements for a 50-year planning horizon from 2000 through 2050.

Tasks completed to the date of publication of the report include a literature review, an aerial reconnaissance survey, and field surveys to qualitatively assess the relative significance of commercial navigation on bank erosion. The research team consists of the ISWS, the University of Iowa's IIHR, and the USACE's Rock Island, St. Paul, St. Louis, and Huntington Districts. The principal authors for this report are ISWS and IIHR.

Field surveys were conducted in the Fall of 1995. The surveys covered 854 miles in the UMR and the IWW. The study team selected 72 erosion sites (29 sites on the IWW and 43 sites on the UMR) for detailed study.

The report summarized approaches and findings of the field survey. The surveys evidenced that approximately 115 bank miles on the IWW and 240 bank miles on the UMR are severely eroded. These figures amount to approximately 20 percent of the total bank length of the IWW and 14 percent of the UMR that are actively eroding. The severely eroded reaches are marked on navigation charts.

The next phase of the study was to develop a model to assess the risk of bank erosion based on site-specific field data for existing and future conditions in the UMR/IWW.

### 4.11.2. Detailed Description

The objective of the field survey is twofold:

- Documenting bank conditions along both sides of the surveyed rivers on their navigation charts and identifying major erosion sites; and
- Selecting representative sites, collecting data on each site, and developing explanations as to the causes and failure mechanisms of erosion at each site.

#### 4.11.2.1. Data Collection and Parameter Classification

The study developed a systematic approach to selecting the study sites. First, the sites were initially selected based on aerial oblique videotape, photographs, and information from operation and maintenance personnel of the USACE. The final selection of the sites was done during field reconnaissance. The sites were classified as "detailed study" and "observation" sites. The location of each site was selected from maps and was located using a Global Positioning System (GPS) during the field trip. Each site was then mapped on the navigation chart. Standard procedures were used to collect bank data. The field data were then entered into a database for each river.

Field parameters were classified according to site location, site attributes, and erosion attributes. The study adapted a near-shore bank failure model in bank assessment. The model characterizes a typical bank section using three features: scarp, berm, and bench. Soils were classified based on the Unified Soil Classification System.

#### 4.11.2.2. Characterization of Bank Erosion and Failure Mechanisms

The report described, in general terms, the characteristics of the riverbank and near-bank benches: soil, slopes, depositional features, failure and erosion mechanisms. Stage histograms were developed for selected sites for relating erosion patterns, bank slopes and other features to hydrologic conditions described by stage-duration data.

#### 4.11.2.3. The Illinois Waterway

The field survey was conducted by the ISWS, the IIHR, and the USACE.

Detailed field data were collected at a total of 29 study sites and 3 observation sites. Data collected at all sites include bank sections, core samples of bank materials, and measurements of at least one cross section. A total of 80 bank sections from 29 eroded sites were measured. All sites were grouped into six bank types based on their physical features (slope and height of scarp, slope and shape of bench, soil type, vegetation cover, near-bank and underwater materials, and ordinary high water level) and erosion potential, which is defined as "the most likely erosion processes." However, the grouping is somewhat subjective; the report did not develop quantitative criteria for all physical features. Some qualitative descriptions, such as "gently sloping," were used for the classification. Under this system, types 1 and 2 indicate high potential for erosion, types 3 and 4 indicate moderate potential for erosion, and types 5 and 6 indicate active but less severe erosion. Hydrologic conditions prior to the field survey were provided to compare with the conditions prior to two previous surveys in 1984-1985 (Warren, 1987) and 1988 (Hagerty, 1988).

The report described each site in detail; a site map showing the locations of bank erosion was prepared for each study site.

During the field data collection, the survey team identified the probable causes of erosion at all of the bank sections investigated. The study found that 27 percent of bank sections showed erosion occurring only at high stages, while 63 percent of the bank sections had erosion within the normal range of stage fluctuation — between the ordinary high water marks and normal pool stage. This observation indicates that erosion cannot be completely attributed to large floods; the rework and transport processes, as caused by waves and currents, are significant at stages between the normal pool and the high water marks.

The study identified major erosion causes. About 74 percent of the bank sections showed evidence of seepage effects, 28 percent showed evidence of waves and seepage impacts, and 24 percent showed impacts of traffic-induced disturbance.

Analysis of the erosion mechanisms at all measured bank sections indicated that about 10 percent of locations are in types 1 and 2 (high erosion potential), 21 percent in types 3 and 4 (moderate erosion potential), and 17 percent in types 5 and 6 (low erosion potential). The remaining bank sections showed some deviation from these defined types or a combination of different types.

#### *4.11.2.4. The Upper Mississippi River*

The field survey was conducted by the ISWS, IIHR, and the USACE.

A total of 43 sites distributed along the river through Minnesota, Wisconsin, Iowa, Illinois, and Missouri were selected as major study sites. The sites were classified into six types according to observed bank erosion features: soil type and deposition, slope of scarp, formation of terraces, and bank failure features. The classification method and criteria for the classification are different from those used in the IWW survey.

A detailed site description and site map showing the location of erosion bank were prepared for each site. Based on individual geomorphologic and hydraulic characteristics, traffic-wave induced erosion potential was estimated for each study site.

The report provided a descriptive summary of findings of the field survey. Much of the summary is descriptive. The study did not estimate bank retreat due to erosion; however, it described the field observations of impacts of the Great Flood of 1993 at most of the study sites. The study concluded that flood effects appear to be more significant than other erosion mechanisms. Stage recession after floods is greater in the upper ends of pools, and gradients and exposed bank heights for emergent seepage are larger in upper ends of pools.

On the basis of the field study, approximately 14 percent of the Mississippi River banks were estimated to be actively eroding as of 1995.

### *4.11.3. Applicability*

The document reported the findings of field surveys of the UMR/IWW System Navigation Study. It did not present or discuss any systematically defined methodology; in fact, the two parts of the study (IWW and UMR) are different in many aspects, most significantly, in the selection of site parameters and the classification of erosion mechanism. Both methods may be applicable to some locations, but it is difficult to make a general evaluation for overall applicability to other locations.

### 4.11.4. Limitations

The report provided detailed bank erosion information of UMP and IWW in 1995; these results and findings are site-specific and not transferable.

### 4.11.5. Relevant References


Bhowmik, N.G. and R. J. Schicht. *Bank Erosion of the Illinois River*, Report of Investigation 92, Illinois State Water Survey, 1980

Bhowmik, N.G., M. Demissie, and C.-Y. Guo. *Waves Generated by River Traffic and Wind on the Illinois and Mississippi Rivers.* Illinois State Water Survey Contract Report 293, 1982

Hagerty, D. J. *Illinois Waterway Bank Evaluation.* Unpublished report, submitted to the U.S. Army Corps of Engineers, Rock Island District. 1989

Spoor, M.F. and D.J. Hagerty. *Bank Failure and Erosion on the Illinois Waterway.* Proceedings, International Symposium on Sediment Transport and Modeling, ASCE, New Your, 600-605, 1989

Warren, R.E. *The Impact of Bank Erosion on Prehistoric Culture Resources in the Lower Illinois River Valley.* Technical Report 87-211-10, Illinois State Museum Society, Springfield, IL, 1987


### 4.11.6. Mappability

There are two types of maps developed from the field surveys. The site map developed for each study site shows erosional banks identified during the site investigation. Overall results of the field survey are presented in *Charts of the Illinois Waterway* and *Upper Mississippi River Navigation Charts*. In these navigation charts, banks are classified into eight categories and color-coded accordingly. The categories are the following: scarp approximately 4 feet or higher, scarp approximately less than 4 feet, moderate to minor erosion with occasional vegetation, mostly sand bench with vegetation growing on upper bank, alternate erosion and disposal, dredge material disposal, stable, and riprap/rock outcrop/bank protection/seawall.

Only erosion sections along the riverbanks were mapped; the lateral span of erosion at a location was not shown on either site maps or navigation charts.

### 4.11.7. Cost

No cost information was reported. Additional information provided by the ISWS indicated that the total costs for the IWW survey were about $190,000; the average cost per mile was about $660.

### 4.11.8. Regulatory Potential

The study is designed to investigate impacts of navigation on bank erosion; the report mainly contains descriptions of the field surveys and findings. Although some information may be used for riverine erosion evaluation, its overall usefulness for regulation purposes is limited.

### 4.11.9. Summary

As a part of the UMR/IWW System Navigation Study, a field investigation of the current state of bank erosion on the UMR and the IWW was conducted. The purpose of the study was to estimate the relative significance of navigation impacts in the context of riverbank erosion processes.

For the selected sites on the IWW, the research team observed multiple erosion processes at most of the selected bank sections. The most frequently identified erosion mechanisms are seepage, stage fluctuations, flood flows, navigation traffic, wave action and eddies, and disturbed flow.

Bank failure and erosion conditions on the UMR also showed significant flood impacts. Analyses of surficial soil samples showed that the banks were mantled by primarily sand and gravel in the upper reach of the river, silt and sand in the middle reach, and clay and silt in the lower reach. Most of the bank failure and erosion sites showed that flood damage is the dominant erosion cause.

Based on results of field survey, the study team recommended developing correlations between apparent navigation-induced erosion and physical parameters, including proximity to narrow channel reaches and locks, mooring and fleeting activities, soil and sediment characteristics, and land use. The risk assessment study will develop models to assess the risk of bank erosion, which is identified as directly related to the increase in commercial navigation and recreation traffic in the rivers.

## 4.12. Arizona Standards for Lateral Migration and Channel Degradation

| | |
|---|---|
| *Document Title:* | State Standards for Watercourse System Sediment Balance (Arizona Department of Water Resources, Flood Warning, and Dam Safety Section, 1996) |
| *Agency:* | Arizona Department of Water Resources, Flood Warning, and Dam Safety Section |
| *Authors:* | Simons, Li & Associates |
| *Date:* | September 1996 |
| *Study Method Category:* | Geomorphic and engineering analysis based on historic data |

### 4.12.1. Overview

The Standards document presents the following three guidelines to characterize erosion hazard areas:

Guideline 1: Lateral migration setback allowance for riverine floodplains in Arizona,

Guideline 2: Channel degradation estimation for alluvial channels in Arizona, and

Guideline 3: Evaluation of river stability impacts associated with sand and gravel mining.

Guidelines 1 and 2 are the most relevant for the purposes of evaluating riverine erosion hazard areas. Guideline 1 provides procedures for estimating the setback distance along streams within which erosion is expected. Guideline 2 presents procedures applicable to estimate degradation in natural channels. The Guidelines present three levels of methodologies with increasing degree of detail in the analyses. Level 1 offers a preliminary assessment, Level 2 requires additional effort and provides refined estimates, and Level 3 allows for detailed analyses generally needed only for special circumstances.

### 4.12.2. Detailed Description

#### 4.12.2.1. Guideline 1 — Lateral Migration Setback Allowance for Riverine Floodplains in Arizona

This Guideline provides techniques to estimate the setback where development must be restricted along a stream to minimize the potential damages caused by erosion of the streambanks. Three levels of analysis are available with increasing degrees of complexity.

*Level 1*

This level requires as basic data the drainage area to the point of interest and the peak 100-year discharge. The method is applicable to basins with an area less than 30 square miles. The setbacks are given by

$$\text{Setback} = (Q_{100})^{0.5} \qquad \text{for straight or mildly-curved channels } (r_c > 5T) \qquad (4.4)$$

$$\text{Setback} = 2.5\,(Q_{100})^{0.5} \qquad \text{for channels with curvature such that } r_c \le 5T \qquad (4.5)$$

where $Q_{100}$ is the 100-year peak discharge in cubic feet per second, $r_c$ is the radius of curvature measured at the centerline of the stream, and $T$ is the top width of the channel. The minimum setback is 20 feet for a straight channel and 50 feet for a curved channel. The setback is measured in feet outward from the 100-year floodway or the top of the channel bank, whichever is greater. In channel bends, the setback is applied to the outer bend.

*Level 2*

The Standards suggest that this level can be used to demonstrate stability of the banks during the 100-year flood and to justify a smaller setback than that produced by Level 1 computations. Three methods are provided: Allowable Velocity Analysis, Tractive Stress Analysis, and Tractive Power Analysis.

In the *Allowable Velocity Analysis* the velocity of the 100-year peak flow within the stream is compared to a maximum velocity below which erosion does not occur. The source of this maximum allowable velocity is a chart developed by the Soil Conservation Service (now the Natural Resources Conservation Service). Two curves in the chart show the variation of the maximum permissible velocity as a function of grain size as indicated by the diameter for which 75 percent of the material is finer ($D_{75}$). One curve applies for sediment-laden water (more than 20,000 parts per million) and the other for clear water (less than 1,000 parts per million). The conditions in Arizona require the curve for sediment-laden water. The velocity thus found is then multiplied by correction factors to account for channel alignment, bank slope, and flow depth.

The *Tractive Stress Analysis* is subdivided into two cases: Case 1 applies when the $D_{75}$ of the sediment is between 0.25 and 5.0 inches. Case 2 applies when $D_{75}$ is less than or equal to 0.25 inches. For Case 1, a formula is provided to compute the tractive stress for an infinitely wide channel as a function of $D_{75}$, Manning's $n$, the energy slope, and the flow depth. This basic stress is multiplied by a correction factor to obtain the value for trapezoidal channels of finite width. The value obtained is compared with the maximum allowable tractive stress that measures the grain's propensity to be eroded by the flowing water. The allowable stress is a function of the channel side slopes, the angle of repose of the material, and $D_{75}$. For Case 2, the procedure is similar, but a graphical solution, instead of formulas, is used to arrive at the values for the tractive and allowable stresses.

Tractive power is defined as the product of the mean flow velocity times the tractive stress. The *Tractive Power Analysis* can account for processes like cementation that reduce the erodibility of the soil. A soil sample is collected to conduct an unconfined compression test. The resulting unconfined compression strength is reduced by a factor of safety equal to or greater than 2. The procedure provides a chart zoned according to combinations of the compression strength and the tractive stress. A line marks the boundary between erosive and nonerosive conditions. Using the compression strength from the test and the computed tractive power, the flow conditions can be classified as erosive or nonerosive.

*Level 3*

This is the most complex level of analysis and involves the use of mathematical models to simulate hydraulics and sediment transport and the resulting erosion or deposition. The analysis involves an evaluation of historic data, field data collection and geomorphic evaluations, and hydraulic and sediment transport modeling.

#### 4.12.2.2. *Guideline 2 — Channel Degradation Estimation for Alluvial Channels in Arizona*

This Guideline describes procedures that may be used to predict channel degradation in streams and unlined channels. The total degradation impacts the depth to which structures must be buried. As with Guideline 1, three levels of analysis are presented.

*Level 1*

This level requires knowledge of the 100-year peak discharge. The total scour depth $d_s$ is computed as the sum of general degradation $d_{gs}$ and long-term degradation $d_{lts}$. General degradation $d_{gs}$ is given by

$$d_{gs} = 0.157\,(Q_{100})^{0.4} \qquad \text{for straight channels} \tag{4.6}$$

$$d_{gs} = 0.219\,(Q_{100})^{0.4} \qquad \text{for channels with curvature} \tag{4.7}$$

The Guideline states that Eqn. 4.7 should not be used unless "significant curvature is evident in the channel reach"; however no information is provided to decide whether the channel has a curvature.

Long-term degradation $d_{lts}$ is computed as

$$d_{lts} = 0.219\,(Q_{100})^{0.4} \tag{4.8}$$

This equation should only be used in the absence of downstream channel controls. The minimum total scour depth is 3 feet. The total scour is applied to the lowest point in the cross section.

*Level 2*

The Guideline indicates that this level can be used to demonstrate the ability of the channel to resist degradation and to justify lesser degradation depths, which lead to less burial requirements. Four alternatives are available to conduct Level 2 analyses: Erodibility Evaluations, Armoring Potential Evaluation, Channel Profile History Comparison, and Grade Stabilization Measures Adequacy Analysis.

*Erodibility Evaluations* can be conducted using any of the three methods provided under Level 2 of Guideline 1: Allowable Velocity, Tractive Force, and Tractive Power.

*Armoring Potential Evaluations* and incipient motion analyses can be performed to evaluate channel stability. Incipient motion occurs when the hydrodynamic forces equal the gravity and friction forces and movement of the grain is imminent. If a particle reaches the incipient motion threshold, all other finer particles are assumed to have been lifted. The Guideline uses the Shields diagram to evaluate the state of incipient motion. For the turbulent flow range, the critical particle diameter $D_c$ is given by

$$D_c = \frac{\tau_p}{0.047(\gamma_s - \gamma)} \tag{4.9}$$

where $\tau_p$ is the boundary shear stress acting on the grain, and $\gamma_s$ and $\gamma$ are the specific weights of sediment and water respectively. The boundary shear stress is

$$\tau_p = \frac{1}{8} f \rho V^2 \tag{4.10}$$

where $f$ is a friction factor (a function of Manning's $n$), $\rho$ is the density of water, and $V$ is the flow velocity. A chart is provided to correct this shear stress for channel curvature.

The armoring potential is estimated by comparing the critical diameter in Eqn. 4.9 with the diameter for which 90 percent of the material is finer ($D_{90}$). Armoring can occur if $D_c < D_{90}$. After determination of the fraction of the material with sizes equal to or larger than $D_c$, the depth of scour necessary to establish an armor layer $\Delta Z_a$ is given by (USBR, 1984)

$$\Delta Z_a = y_a \left[ \frac{1}{P_c} - 1 \right] \tag{4.11}$$

where $P_c$ is the fraction of the material coarser than $D_c$, and $y_a$ is the thickness of the armor layer, usually taken as a multiple of $D_c$. Field observations indicate that at least two layers of armoring particles are needed for a stable armor.

If sufficient data are available, a *Channel Profile History Comparison* can be conducted to identify the condition of various areas in the channel. The approach should be used to demonstrate stability or aggradation rather than degradation. The analysis should include an evaluation of expected future trends.

*Grade Stabilization Measures Adequacy Analysis* should be conducted for measures implemented to reduce potential degradation. The Guideline states that local procedures may be in place for various jurisdictions in Arizona and suggests two documents for all other cases.

*Level 3*

The nature and scope of this level is the same as for Level 3 in Guideline 1.

### 4.12.3. Applicability

The Guidelines provide standardized procedures to analyze channel stability and define erosion setbacks.

### 4.12.4. Limitations

The Guidelines allow for great latitude in the techniques that may be used to define erosion setbacks. The limitations of the approach are those of the analytical tools selected for the analysis. The information provided is insufficient to assess the shortcomings of Level 1 techniques. Therefore, a potential user cannot evaluate the reliability of the predictions. No procedures are available to determine aggradation.

A limitation is the emphasis on the 100-year flood event, which is assumed to be the controlling event. Events of lesser magnitude can also introduce substantial changes in the channel geometry. Except for Level 3 methods, the techniques do not take into account some important geotechnical variables in streambank analysis; for instance, slope stability.

There is indication that the procedure can be extended to other regions; however, the procedures used to derive Level 1 tools are not disclosed.

### 4.12.5. Relevant References

Simons, Li & Associates, Inc. (1985), *Design Manual for Engineering Analysis of Fluvial Systems*, prepared for Arizona Department of Water Resources, Tucson, Arizona.

City of Tucson Department of Transportation (1989), *Standards Manual for Drainage Design and Floodplain Management in Tucson*, Engineering Division, Tucson, Arizona.

### 4.12.6. Mappability

The procedure to map erosion hazard areas through a setback is straightforward and can be accomplished easily.

### 4.12.7. Cost

No cost information was reported.

### 4.12.8. Regulatory Potential

The procedure is already implemented as a regulatory instrument.

### 4.12.9. Summary

The Standards document presents two guidelines to characterize erosion hazard areas:

Guideline 1: Lateral migration setback allowance for riverine floodplains in Arizona.

Guideline 2: Channel degradation estimation for alluvial channels in Arizona.

Guideline 1 provides procedures for estimating the setback distance along streams within which erosion is expected. The resulting setback can be used for mapping of hazard areas. Guideline 2 presents procedures applicable to estimate degradation in natural channels. This guideline is intended to set minimum burial depths.

The Guidelines are structured in three levels of methodologies with increasing degree of complexity. Level 1 offers a preliminary assessment using simple equations, Level 2 requires standard engineering calculations, and Level 3 calls for numerical modeling using specialized computer programs.

The Guidelines are already used for regulatory purposes in Arizona.

# 5. Assessment of Technical Feasibility

## 5.1. Overview

Section 577 of the National Flood Insurance Reform Act of 1994 discusses mapping erosion hazard areas for riverine areas, if technologically feasible. The purpose of this study is to determine whether it is technologically feasible to map REHAs.

Technologically feasible was defined earlier in the report as:

> Methodologies exist that are scientifically sound and implementable under the NFIP. *Scientifically sound* means that the methodologies are based on physical or statistical principles and are supported by the scientific community. "Implementable" means that the approaches can be applied by FEMA as part of a nationwide program under the NFIP and for an acceptable cost.

Scientific soundness and cost acceptability will be covered in this chapter. Applicability as a nationwide program will be covered in Chapter 6.

This chapter is organized into four main topics: Evaluation of Scientific Soundness, the 60-Year Horizon, Cost, and Conclusions on Technological Feasibility. These topics are developed as follows:

- The Evaluation of Scientific Soundness contains summaries of material covered in Chapter 4.
- Section 577 defines hazard areas as those where erosion is likely to result in damage to buildings and infrastructure within a 60-year period. Discussion of the options to address the 60-year period is presented in this chapter.
- Total cost to the NFIP is determined using unit costs developed in the study and applying them to counties prone to riverine erosion.
- The conclusions on technological feasibility are based on the analysis of the 12 selected documents and suggestions and recommendations from the Project Working Group (PWG).

## 5.2. Evaluation of Scientific Soundness

The case studies in the previous chapter indicate that it is possible to conduct riverine erosion studies and establish conclusions regarding the likelihood of future erosion. The case studies also illustrate the fact that erosion studies can follow various methodologies depending on data availability, funding and resource limitations, stream characteristics, and the needs that motivated the study. This observation implies that there is significant flexibility in conducting these studies, although not all methodologies allow delineation of erosion setbacks along streams. In general, the studies seem to fall under three categories: 1) geomorphic analysis; 2) engineering analysis; and 3) mathematical modeling. These categories will be used as a framework to analyze scientific soundness.

### *5.2.1. Field Investigations*

The majority of the case studies required substantial field investigations of watersheds and stream channels. Table 5.1 summarizes the type and scope of the field investigations for each of the studies.

**Table 5.1.** Scope of field investigations for the case studies.

| Case Study Title | Field Investigations |
|---|---|
| AMAFCA Sediment and Erosion Design Guide | Level 1: Geomorphic and other qualitative analyses<br>• Survey of local stability problems<br>• Observations on flow patterns<br>• Identification of aggradation and degradation zones<br>• Sampling of bank and bed materials<br>• Inventory of activities affecting the stream (e.g., urbanization, channelization, dams, and other human activities)<br>Level 2: Basic engineering analysis<br>• Field verification of hydrologic parameters<br>• Cross section and channel profile topographic surveys<br>• Survey of bridges, culverts, and other hydraulic structures<br>• Estimation of roughness coefficients<br>• Sediment sampling<br>• Sediment transport rate measurements<br>• Sampling of bed and bank materials<br>Level 3: Mathematical modeling<br>• Same as in Level 2 but in greater detail |
| Inventory and Analysis of Stream Meander Problems in Minnesota | • Sediment sampling |
| A Probabilistic Approach to the Special Assessment of River Channel Instability | • No field investigation needed |
| Geomorphology And Hydrology of the Santa Cruz River, Southeastern Arizona | • Periodic fluvial geologic surveys<br>• Periodic topographic, geomorphic, and geotechnical surveys<br>• Periodic aerial photographic surveys<br>• Topographic survey of stream profile and cross sections<br>• Stream reconnaissance surveys |
| San Diego County Alluvial Studies | • Field verification of hydrologic parameters<br>• Measurements of hydrographs<br>• Measurements of stage and discharge at cross sections<br>• Cross section and channel profile topographic surveys<br>• Survey of bridges, culverts, and other hydraulic structures<br>• Estimation of roughness coefficients<br>• Sediment sampling<br>• Sediment transport rate measurements<br>• Sampling of bed and bank materials |

**Table 5.1.** Scope of field investigations for the case studies (continued).

| Case Study Title | Field Investigations |
|---|---|
| City of Austin Technical Procedures for Watershed Erosion Assessments | • Sediment sampling<br>• Sampling of bed and bank material<br>• Survey of riparian vegetation<br>• Watershed survey to verify watershed boundaries, geology, urbanization (existing or future projects), and structures at risk<br>• Topographic survey of stream profile and cross sections<br>• Periodic stream reconnaissance surveys to assess aggradation/degradation, widening, planform changes, slope failure, severe bends, nick points, erodibility of soils, bankfull width and depth, channel type, channelization projects, hydraulic structures, presence of utilities, and other disturbances<br>• Geotechnical survey to evaluate slope stability<br>• Survey or roughness coefficients<br>• Discharge measurements |
| River Stability Study, Virgin River, Santa Clara River and Fort Pierce Wash, Vicinity of St. George, Utah | • Visual survey to assess relative river stability; physical characteristics observed are banks and cutting, vegetation on banks, floodplain, bars, bank and bed sediments, bank protection, bridge scour, and tributaries<br>• Suspended sediment measurements<br>• Floodplain land use |
| Hydrologic and Geomorphic Studies of the Platte River Basin, Nebraska | • Sediment sampling<br>• Sampling of bed and bank material<br>• Survey of riparian vegetation<br>• Topographic survey of stream profile and cross sections<br>• Stream reconnaissance surveys to assess channel patterns, scour, and bed forms<br>• Water samples for suspended sediment analysis<br>• Discharge measurements |
| Streambank Erosion Along Two Rivers In Iowa | • Cross section surveys<br>• Sampling of bed sediment<br>• Streamflow observations<br>• Bank vegetation survey for type and distribution |
| Channel Migration Studies in King County, Washington | • Sampling of bed and bank material<br>• Survey of bank heights and bank erosion<br>• Survey of riparian vegetation type and age<br>• Geologic survey<br>• Watershed survey to inventory urbanization, roads, and other infrastructure at risk<br>• Topographic survey of stream profile and cross sections<br>• Stream surveys to assess aggradation/degradation and floodplain morphology<br>• Survey of levees, revetments, dams, and other hydraulic structures |

Table 5.1. Scope of field investigations for the case studies (continued).

| Case Study Title | Field Investigations |
|---|---|
| Bank Erosion Field Survey Report of the Upper Mississippi River and Illinois Waterway | • Field verification of hydrologic parameters<br>• Cross section and channel profile topographic surveys<br>• Survey of bridges, culverts, and other hydraulic structures<br>• Estimation of roughness coefficients<br>• Sediment sampling<br>• Sediment transport rate measurements<br>• Sampling of bed and bank |
| Arizona Standards for Lateral Migration and Channel Degradation | Level 1<br>• No field investigations needed<br>Level 2<br>• Soil samples for grain analysis<br>• Soil samples for unconfined compression test<br>• Water samples for suspended sediment analysis<br>Level 3<br>• Same as Level 3 in AMAFCA Sediment and Erosion Design Guide |

### *5.2.2. Geomorphic Analysis*

This study category involves comprehensive evaluation of stream morphology, watershed characteristics and historic data. The objective is to assemble all of these pieces of information to assess channel stability and predict changes in depth and width.

Of the twelve case studies, nine of them report application of geomorphic methods to some extent. Some of the case studies involve joint application of geomorphic and engineering principles but are included in this section because the approach is predominantly geomorphic. Table 5.2 summarizes the data needs and analysis procedures employed in each study.

The geomorphic procedures in Table 5.2 are all useful in providing a picture of the erosion hazards, although not all of the methodologies had the delineation of erosion setbacks as ultimate goal. Nevertheless, the literature indicates that geomorphic methods can be used to define erosion hazard areas to some degree. One difficulty is the wide variation of time scales associated with the data ranging from geologic to recent events. Information from all of these time scales must be assembled to be able to make predictions a few decades into the future. Another challenge is that past phenomena are the result of varying watershed conditions due both to natural events and to human intervention; for example, urban development, channel modification, and hydraulic structures. The analyst is often confronted with drawing conclusions for the short- to mid term by extrapolating to future conditions that will also be characterized by varying watershed characteristics. Geomorphic analysis requires professionals with a specialized set of skills and experience that may be in short supply.

**Table 5.2.** Data needs and procedures in geomorphic studies.

| Case Study Title | Data Needs | Analysis Procedures |
|---|---|---|
| AMAFCA Sediment and Erosion Design Guide (Level 1) | • Topographic maps (USGS quads, local mapping, control points, etc.)<br>• Historic stream plans and profiles<br>• Field notes and photographs on bank geometry, stability problems, flow patterns<br>• Planimetric maps<br>• Aerial and satellite photographs<br>• Transportation maps<br>• Bridge and culvert as-built plans<br>• Geologic maps<br>• Soils maps<br>• Land use<br>• Rainfall records<br>• Streamflow data (flooding events)<br>• Sedimentation data (bed and bank sediment size, transport rates, aggradation and degradation areas)<br>• Water quality data (sediment concentrations)<br>• Water use data (irrigation, power generation, diversions, etc.)<br>• Watershed development plans (urbanization, channel modifications, dams, and streambed mining) | • Use topographic, soils, land use, and geologic maps to identify instability problems<br>• Use maps to locate braids, bars, tributaries, and channel controls such as rock outcrops<br>• Use soil and land use maps to evaluate vegetative cover and other factors affecting sediment supply<br>• Analyze aerial photographs to assess watershed development and changes in stream patterns: bend migration, bankline failure, and erosion progress<br>• Determine stability of streambanks using photographs and field notes<br>• Use as-built plans and observations to evaluate scour<br>• Analyze impact on instability of existing and planned human activities (streambed mining, channel modifications, urbanization, dam construction)<br>• Identify changes in hydrology and hydraulics using rainfall and streamflow records<br>• Consolidate the analyses above into an overall assessment of stream stability<br>• Combine stream bank field notes and bankline failure observations from aerial photographs to evaluate lateral stability and estimate lateral erosion rates<br>• Evaluate vertical stability from information on bank failure, historic streambed profiles, and long-term trends in stage-discharge relationships<br>• Use simple predictive geomorphic tools (e.g., the Lane Relationship) to evaluate channel response mechanisms |
| Inventory and Analysis of Stream Meander Problems in Minnesota | • Grain size distribution<br>• Historic aerial photographs<br>• Topographic maps<br>• 2-year flood discharge as the bankfull discharge<br>• Stream parameters (slope, bankfull width, and depth) | • Process photographs and maps to obtain digitized valley centerlines and stream centerlines<br>• Clean and smooth lines and run computer program MEANDER to determine the stream's transversal and longitudinal shift, sinuosity change rate, and reworked floodplain area<br>• Develop relationships between the shift parameters from MEANDER and stream parameters: width, depth, flow rate, and slope |
| Geomorphology and Hydrology of the Santa Cruz River, Southeastern Arizona | • Geologic maps and reports<br>• Topographic maps<br>• Historic stream and plans and profiles<br>• Hydrologic data<br>• Climatic data<br>• Seasonal sediment concentration<br>• Aerial and satellite photographs | • Use geologic data to define tectonics, depositional patterns, floodplain landforms and sedimentation<br>• Use hydrologic data to determine runoff volumes and history, frequency, spatial and temporal characteristics of flood events<br>• Use climatic data to define meteorological characteristics of major storms |

**Table 5.2.** Data needs and procedures in geomorphic studies (continued).

| Case Study Title | Data Needs | Analysis Procedures |
|---|---|---|
| Geomorphology and Hydrology of the Santa Cruz River, Southeastern Arizona (continued) | • Field observations on aggradation/degradation, channel widening, planform changes, bank structural condition, and mass wasting<br>• Watershed plans (urbanization, channel modifications, dams, effluent discharge, and streambed mining). | • Analyze field data and maps to summarize channel changes: meander migration, avulsion, meander cutoff, channel widening, mass wasting, slope degradation, vertical channel change, and human-induced changes<br>• Identify effects of geology, topography, hydrology, climate, and human intervention in controlling channel change |
| City of Austin Technical Procedures for Watershed Erosion Assessments | • Watershed boundaries and surface area<br>• Sediment size distribution and transport rate<br>• Soil consistency of bed and bank materials and geotechnical data on slope stability<br>• Type and spatial distribution of riparian vegetation<br>• Watershed boundaries<br>• USGS regression equations<br>• Geologic maps<br>• Soils maps<br>• Magnitude, timing and distribution of urbanization influence in the watershed<br>• Inventory of structures at risk<br>• Longitudinal stream valley gradient<br>• Cross section measurements<br>• Field observations on aggradation/degradation, widening, planform changes, slope failure, severe bends, nick points, and erodibility of soils, channel type, channelization projects, hydraulic structures, presence of utilities, and other disturbances<br>• Measurements of bankfull width and depth<br>• Roughness coefficients<br>• Discharge measurements<br>• Scale of features in the streams | • Use watershed data to estimate impervious areas<br>• Use watershed development information and maps to prepare summary of drainage, development patterns, stream geometry and topology, soils, and inventory of parklands and other watershed features<br>• Use USGS regression equations to estimate 2- and 10-year peak flow events for all reaches<br>• Use field data to prioritize erosion problems and the assets at risk. Use geotechnical data on highest priority sites to assess slope stability<br>• Identify causes of erosion<br>• Classify channels according to 1) erosion susceptibility of bed, banks, or both; 2) bed material (alluvial rock-bed controlled, rock controlled, and structural); 3) the Knighton (1987) system<br>• Use Rapid Geomorphic Assessment (RGA) to compute the Stability Index (SI) describing the channel as stable, transitional, or in adjustment<br>• Determine "channel enlargement curve" after Morisawa and LaFlure (1979)<br>• Use channel enlargement curve to estimate ultimate channel geometry and approximate sediment yield (see Section 4.6.2.6 for a detailed description) |
| River Stability Study, Virgin River, Santa Clara River and Fort Pierce Wash, Vicinity of St. George, Utah<br><br>River Stability Study, Virgin River, Santa Clara River and Fort Pierce Wash, Vicinity of St. | • Historic aerial photographs<br>• Topographic maps<br>• Geologic maps and reports<br>• Archeological data<br>• Historic accounts and diaries<br>• Floodplain maps<br>• Available hydraulic models<br>• Hydrologic and paleohydrology data<br>• Climatic data | • Use historic information to determine stream alignment and characteristics in the past<br>• Produce map overlays from configurations at various points in time<br>• Quantify geometric changes in channel and floodplain geometry to estimate lateral migration<br>• Correlate flood occurrence to channel changes caused by erosion |

**Table 5.2.** Data needs and procedures in geomorphic studies (continued).

| Case Study Title | Data Needs | Analysis Procedures |
|---|---|---|
| George, Utah (continued) | • Suspended sediment data<br>• Flood photographs<br>• Inventory of human activities in the watershed (ditches, diversions, reservoirs, grazing activities)<br>• Bridge construction plans and maintenance records | • Use geomorphic data to classify the stream according to Rosgen (1994) and FHWA's system (FHWA, 1991; Brice, 1983)<br>• Evaluate bank erosion using Rosgen's bank erosion matrix (Rosgen, 1996) and the approach in Thorne and Osman (1988)<br>• Evaluate erosion potential using the maximum permissible velocity<br>• Consolidate all information to define an erosion corridor |
| Hydrologic and Geomorphic Studies of the Platte River Basin, Nebraska (Methods 1 and 3) | Method 1<br>• Flow duration curve<br>• Regression equation relating sediment transport rate to water discharge<br>Method 3<br>• Channel slope, depth, and width<br>• Sediment size distribution and specific gravity | Method 1<br>• Use flow duration curve and regression equation to compute duration curve for sediment transport<br>• Determine "effective discharge" as water discharge associated with maximum contribution to expected sediment transport rate<br>Method 3<br>• Compute particle fall velocity<br>• Use channel slope and particle fall velocity to compute relative smoothness from the first Parker (1997) equation<br>• Use relative smoothness and channel geometric parameters to compute water discharge and sediment transport rate using the remaining two Parker (1977) equations |
| Channel Migration Studies in King County, Washington<br><br>Channel Migration Studies in King County, Washington (continued) | • Properties of bed and bank material<br>• Bank heights and erosion problems<br>• Type, age, and distribution of riparian vegetation<br>• Geologic maps<br>• Watershed development maps<br>• Aerial photographs<br>• Stream profile and cross sections<br>• Flood magnitudes<br>• Data on aggradation/degradation<br>• Floodplain morphologic data<br>• Inventory of levees, revetments, dams, and other hydraulic structures | • Review historic maps and photographs and determine migration rates<br>• Divide streams into geomorphologically uniform reaches<br>• Compute shear stress caused by the 100-year flood and analyze potential channel enlargement<br>• Evaluate effect of hydrologic changes in channel migration potential. Select those periods consistent with current conditions<br>• Use historic data on bend amplitude and meander belt width to estimate outer limits of future channel migration<br>• Adjust the limits using information on likely erosion constraints (*e.g.*, roads, levees, bank protection, and development). Produce a Mitigated Migration Hazard Map<br>• Adjust the map using evidence of frequent avulsion<br>• Use historic data to classify erosion hazard as moderate or severe |
| Bank Erosion Field Survey Report of the Upper Mississippi River | • Aerial oblique videotape<br>• Site photographs<br>• Topographic maps | • Use soils data to classify soils<br>• For all study sites, use bank characteristics and hydrologic data to assess bank erosion and failure mechanisms |

**Table 5.2.** Data needs and procedures in geomorphic studies (continued).

| Case Study Title | Data Needs | Analysis Procedures |
|---|---|---|
| and Illinois Waterway | • Navigation charts<br>• Geometry of banks<br>• Properties of bed and bank materials<br>• Cross sections<br>• Vegetation cover<br>• Historic flood data and water level | • Compare erosion with stage records to define correlation with flood events, traffic waves, and currents<br>• Prepare color-coded erosion location map |
| Arizona Standards for Lateral Migration and Channel Degradation (Level 1) | • 100-year peak discharge<br>• Ratio of channel curvature to top width<br>• 100-year floodway<br>• Top of channel bank location<br>• Drainage area | • Use 100-year discharge in setback regression equation appropriate for curvature-top width ratio<br>• Use 100-year discharge in total scour regression equation appropriate for channel curvature |

### *5.2.3. Engineering Analysis*

This study category involves application of basic engineering principles and is often complemented with geomorphic methods. Some of the tools employed include friction formulas for hydraulic conveyance, flood frequency procedures, hydrologic and hydraulic models, sediment yield, sediment transport, geotechnical analysis of slope stability, and soil property testing. The objective is to analyze flow regimes and their effect on structural stability to predict changes in channel geometry.

Several case studies involve joint application of geomorphic and engineering principles. However, only three are included in this section because the approach is predominantly based on engineering principles. It should be noted that the most effective use of engineering tools is accomplished when preceded or combined with geomorphic analyses; therefore, separation of the two approaches is not always possible or desired. Table 5.3 summarizes the data needs and analysis procedures employed in each of the three case studies.

Application of basic engineering methods affords a series of tools for quantification of erosion rates. The analyst must compile the information available from both geomorphic and engineering tools and use considerable judgement in delineating an erosion hazard area. Of special concern is the inability of many of these simple tools to consider past erosion history. The analyst must carry out this temporal integration by consolidating all of the information available.

**Table 5.3.** Data needs and procedures in basic engineering studies.

| Case Study Title | Data Needs | Analysis Procedures |
|---|---|---|
| AMAFCA Sediment and Erosion Design Guide (Level 2) | • Flood frequency curves<br>• Flood hydrographs<br>• Rainfall data<br>• Bankfull discharge<br>• Stream profile, alignment, and cross sections<br>• Roughness coefficients<br>• Geometric data on bridges and culverts<br>• Land use maps<br>• Soils maps<br>• Geologic maps<br>• Sediment size distribution in watershed and channel<br>• Mechanical properties of bed and bank materials: size, shape, fall velocity, cohesion, density, and angle of repose<br>• Measurements of sediment transport rates<br>• Reservoir operation and sedimentation data | • Use watershed data and rainfall records to conduct hydrologic modeling (*e.g.*, HEC-HMS) and develop flood frequency curves<br>• Evaluate flood history to identify wet-dry periods<br>• Use hydraulic modeling (*e.g.*, HEC-RAS or Manning's formula) to define velocity, flow depth, top width, and other flow properties of the main channel and overbanks<br>• Analyze characteristics of bed and bank materials: size, fall velocity, and mechanical properties<br>• Use maps of land use and soils, and watershed plans to evaluate sediment yield from the watershed for existing and future conditions. The RUSLE methodology can be applied for this purpose<br>• Use bed and material size distribution to perform incipient motion analyses and analyze bed armoring<br>• Compute or estimate sediment transport and apply sediment continuity to determine aggradation/degradation potential. Various sediment transport formulas can be used (Table 2.4)<br>• Evaluate lateral erosion potential by analyzing slope stability and bank failure mechanisms (*e.g.*, Osman and Thorne, 1988)<br>• Evaluate local scour using formulas in AMAFCA (1994) |
| Streambank Erosion Along Two Rivers In Iowa | • Topographic maps<br>• Aerial photographs<br>• Bed and bank material properties<br>• Type and distribution of vegetation along banks<br>• Streamflow records<br>• Data on areal loss from banks<br>• Roughness coefficients<br>• History of channel planform, width, depth, curvature, slope, and bed forms | • Develop a conceptual model of the stream in which the meanders are approximated as constant-radius curves<br>• Determine the near-bank, depth-averaged mean velocity using equations in Odgaard (1986)<br>• Determine the lateral migration rate using the scour factor in Parker (1983)<br>• Use equations in Odgaard (1987) to compute maximum rate of bank retreat, average areal and volumetric erosion rates, and downvalley migration rates |
| Arizona Standards for Lateral Migration and Channel Degradation (Level 2) | • 100-year peak discharge<br>• Suspended sediment concentration<br>• Channel curvature, bank slope, width, and flow depth<br>• Grain size distribution<br>• Energy slope<br>• Manning's roughness coefficient<br>• Unconfined compression strength | • Use grain size to determine maximum allowable velocity and compare with 100-year discharge velocity<br>• Use grain size distribution, flow depth, energy slope, and roughness coefficient to determine tractive stress. Correct for channel geometry and compare with maximum allowable tractive stress<br>• Compute tractive power and use unconfined compression strength to derive maximum allowable tractive power |

### 5.2.4. Mathematical Modeling

This approach is the most complex level of analysis and requires discretization of the fluvial system into small units where computational models are applied to determine variations of the channel geometry in time. Variable material properties can be assigned to each discretized unit to account for localized conditions. The computations are usually complex and could be statistical or physically based in nature.

Two case studies involve mathematical modeling. The first case study is based on probabilistic analysis; the second is based on simulation of the basic equations for hydraulics and sediment transport. Table 5.4 summarizes the data needs and procedures for the two case studies.

**Table 5.4.** Data needs and procedures in mathematical modeling studies.

| Case Study Title | Data Needs | Analysis Procedures |
|---|---|---|
| A Probabilistic Approach to the Special Assessment of River Channel Instability | • Aerial photographs for several time periods. | • Divide all of the aerial photographs into uniform square cells. Designate those cells occupied by the channel.<br>• Assign "coordinates" to each cell based on lateral and upstream distances to the channel.<br>• For each period of analysis, count the cells that were eroded for each pair of "coordinates" between the photographs defining the beginning and end of the period. Compute the erosion probability as the number of eroded cells divided by the total number of cells for those coordinates.<br>• Repeat the procedure for other time periods.<br>• Use regression techniques to define the erosion probability as a function of lateral and upstream distance to the channel and of the return period of flooding events.<br>• Use the equation to predict future erosion extent.<br>• Develop erosion probability map to identify potential hazards. |
| San Diego County Alluvial Studies | • Initial profile and cross sections of the channel<br>• Channel roughness<br>• Sediment characteristics<br>• Hydrographs<br>• Downstream stage-discharge rating curve<br>• Physical constraints (*e.g.*, rock outcrops, check dams, and nonerodible banks)<br>• History of floods and induced channel change | • Enter initial conditions of channel geometry<br>• Enter hydrograph and simulation time step<br>• Run FLUVIAL-12 and obtain bed profiles at all sections.<br>• Calibrate model to known conditions<br>• Verify with another set of known conditions |

Table 5.4 illustrates two very different approaches to mathematical modeling. They both discretize the area of interest and apply equations to each of the discrete elements; however, the results are quite different. The statistical model predicts the probability of erosion occurrence at various locations along river reaches whereas the physically based model provides the channel geometry and alignment at various points in time. Therefore, the statistical model needs to be interpreted further to define erosion hazard boundaries whereas these hazard areas can be directly obtained from the output of the physically based model.

Data needs, computational algorithms, and output are specific for each model (see Table 2.6) and cannot be generalized. However, mathematical models are usually designed to simulate the evolution of channel morphology under a variety of scenarios. As such, these models are naturally suited for hazard area delineation. On the other hand, the mathematical representation of sediment transport and erosion processes is still imperfect and prone to large errors. In addition to being calibrated and verified, models should be analyzed critically in light of their limitations to understand the nature and magnitude of potential errors.

### *5.2.5. Conclusions*

The case studies indicate that delineation of riverine erosion hazard areas is feasible. There are various geomorphic, engineering, and modeling procedures that can be applied, although the accuracy of such methods could be quite variable. Considerable judgement and experience are needed to draw conclusions that would lead to delineation of a hazard area.

The basic data used by geomorphic and engineering methods are nonstationary in the sense that the response of the fluvial system is the result of time-variable watershed conditions. This characteristic implies that extrapolation directly from historic data may need to correct for past and future variability.

In addition to issues of spatial accuracy, hazard area delineation has a temporal component. This issue is analyzed in the following section.

## 5.3. The 60-Year Horizon

To be useful, the REHA delineated should have an associated time span within which erosion is expected to occur within the delineation. Evidence of erosion in geologic times could be strongly supported with field observations but may be of limited application for floodplain management due to the long time scale involved. Therefore, planners and decision-makers need to know the time frame for which a particular hazard area is valid. For management purposes this time frame should be of the order of magnitude of decades, which is consistent with the useful life of structures in the built environment. For example, a structure's useful life usually extends well beyond the 30 years of a typical mortgage, and there are many structures in the United States older than 100 years.

A time frame of 60 years has been specified in Section 577 of NFIRA as the interval of interest for delineation of riverine erosion hazard areas. This designation likely stems from a similar requirement for assessment of coastal erosion, but there is no apparent scientific basis to choose 60 years. However, the case studies and the opinions of the PWG indicate existing techniques are better suited for shorter time frames; in consequence, larger uncertainties will likely affect erosion predictions for 60-year periods. This difficulty arises from limitations in data accuracy, errors in sediment transport models, and unknowns in future watershed development, hydrologic conditions, and magnitude and sequence of future flooding events.

From the review of the case studies, two approaches emerge to address the erosion time frame:

1. *Extrapolation from site data*: This is the approach applied by those case studies that yield an erosion-prone area as part of the results. As a general procedure, the configuration of the stream at two or more points in time is used to determine average migration rates that can be translated into erosion and deposition rates. Ideally, the rates would be adjusted to account for variable watershed conditions in the historic period. These rates can then be used to predict the stream's location at some time in the future. In the simplest case, migration can be assumed linear in time by selecting a migration rate variable in space but constant for the time period under consideration. A more suitable approach uses a "frequency weighted" erosion rate (*i.e.*, the expected annual erosion rate), which includes the erosion caused by the possible range of flows weighted by their frequency of occurrence. The predicted alignment can be modified to account for localized conditions such as identified geologic controls and existing hydraulic structures. The prediction should also incorporate expected future watershed development.

2. *Mathematical modeling up to a specified time:* Continuous simulation models (*e.g.*, FLUVIAL-12) make use of streamflow hydrographs and time series for watershed characteristics to simulate temporal variations in stream geometry. In theory, the simulation can proceed indefinitely for as long as detailed temporal resolution of input data is available. To predict future conditions, the model requires estimated future time series of the input data, which can be statistically generated or inferred from historic data and expected future trends. In practice, forecasts for input data may be reliable only for a short period in the future. The basic procedure involves using available data to generate time series up to a specified target date and running the model to simulate changes in the stream.

Application of either approach raises the issue of uncertainty surrounding both the time frame and the spatial location of the REHA limits. For the floodplain manager, assessment of erosion risk must include an estimation of the confidence interval of erosion predictions both in time and space. The need for this information is especially critical when restrictions are placed on development and other activities due to erosion hazards.

An analyst experienced in the application of geomorphic and engineering methods can use professional judgement in assigning a confidence interval to a particular REHA delineation. However, when judgement is involved, there is a distinct possibility that two analysts may arrive at different conclusions due to the subjective nature of the analysis process. In addition, there is an acknowledged lack of professionals with the necessary training and expertise in this field to conduct these assessments.

Continuous simulation applying mathematical models offers a more systematic approach that also lends itself to replicability. The historic data can be used to derive statistical distributions for streamflow and for other input parameters that can be considered random variables. Using Monte Carlo simulation techniques, the distributions are sampled to generate several hypothetical future scenarios for which the model is run. With a sufficiently large number of scenarios, the resulting set of erosion areas can be used to derive REHA statistics and confidence intervals (Froehlich, 1997). In addition to the skills needed to run the fluvial model, this approach requires knowledge of stochastic processes and Monte Carlo simulation. For instance, expertise is also required to assign probability distributions to model parameters. After running all of the simulations, considerable effort is needed to process the results from the individual runs and derive output statistics.

Implementation of the approach is expensive because it involves numerous runs, but the procedure is straightforward and lends itself to drawing objective conclusions. Uncertainty is built into the approach as the various probability distributions are sampled to generate run scenarios; therefore, the confidence intervals produced by the Monte Carlo approach can be used for risk-based analysis.

Avulsion presents an additional challenge because of the catastrophic nature of the phenomenon and its unpredictability. It is possible to identify past and potential avulsion sites during stream reconnaissance; however, it is doubtful that the occurrence of avulsion can be predicted reliably even for the near future. The cumulative effect of long-term avulsion is unknown.

## 5.4. Cost

### *5.4.1. Data Source and Assumptions*

A detailed estimation of total REHA analysis and mapping costs is beyond the scope of this study. However, an approximate cost of implementation has been estimated. The purpose of the cost estimation of this study is threefold:

- identifying elements that should be included in the cost estimation;
- establishing a conceptual cost estimation framework; and
- providing approximate NFIP cost for REHA analysis and mapping.

The sources of cost data for this report include information provided by the PWG, costs reported in the case studies (Chapter 4), FEMA reports and other literature, and cost data from previous studies performed by the project team members. The data are not sufficient to make a reliable nationwide cost estimation; however, they can be used to perform an educated guess for total costs.

Several assumptions were made to estimate costs of nationwide REHA mapping. First, the REHA mapping would be based on the existing FIRMs of a community. The hydrologic and hydraulic studies used to develop FIRMs could be used as the base for riverine erosion studies, and the same base map would be used to map REHAs. The costs of the basic hydrologic and hydraulic studies to develop FIRMs and the cost for preparing base maps were excluded from the REHA cost estimation. Only the costs that are solely designated for performing riverine erosion studies and mapping the erosion boundaries are included.

Second, cost data, especially data from case studies, are from different time periods. For the estimate presented herein, all costs are assumed in 1997 dollars; inflation rates were not considered.

Third, although study costs vary with amount of stream miles, there is not enough information to quantify economies of scale. For simplicity, the average unit cost per map panel was used as the base rate. Under this assumption, the average unit cost was first estimated and then multiplied by the number of panels to obtain the total costs.

Procedures of cost estimation are presented in following sections.

### *5.4.2. Affected Areas*

To determine the extent of areas prone to riverine erosion, the Project Team designated levels of erosion as “high,” “intermediate,” or “low” for each county in the entire United States. These initial designations were supplemented with input from the PWG and the literature that was reviewed (listed in the Appendix). Quantitatively, a county's erosion potential was designated as "high" if more than 60 percent of stream miles in the county were subject to riverine erosion. An average percentage of erosion-prone stream miles of 80 percent was used in the cost estimation. "Intermediate" was assigned to counties with erosion prone stream miles from 30 to 60 percent, and an average of 45 percent was assumed. "Low" was assigned to counties with less than 30 percent erosion-prone stream miles, and 15 percent was assumed as an average.

### 5.4.3. Applicability of REHA Study Approaches

Not all erosion prone streams would be studied using technical approaches that belong to the same study category. This is because counties with erosion-prone streams in limited areas would be less motivated to develop REHA maps; while counties that have many erosion-prone streams widely distributed would have more urgent needs and interest in mapping REHAs. In addition, even in counties with severe erosion problems, less populated areas, such as areas mapped as Zone A in FIRMs, are unlikely to be studied and mapped by using detailed, advanced and costly technical approaches such as mathematical modeling. More likely, they would be mapped using a rather simplified, less costly approach.

From these considerations, a fraction of stream miles was designated to be studied by each selected study category: geomorphic, engineering, and mathematical modeling, as defined in Section 1.4.2, for each level of erosion. The same percentage was applied to all counties, regardless of their location.

Using limited available information and considerable judgement, the Project Team estimated the approximate ranges for percentage of stream miles shown in Table 5.5. For example, it was assumed that an area with intermediate levels of erosion could be adequately studied with geomorphic methods applied to between 50 and 80 percent of the stream miles, engineering methods used in 20 to 40 percent of the stream miles, and mathematical modeling needed only for a maximum of 10 percent of the stream miles.

**Table 5.5.** Assumed ranges for percentage of stream miles by study category for each level of erosion.

| Study Category | Level of Erosion | | |
|---|---|---|---|
| | High | Intermediate | Low |
| Geomorphic | 30%–50% | 50%-80% | 70%-100% |
| Engineering | 45%-60% | 20%-40% | 0%-30% |
| Mathematical Modeling | 5%-10% | 0%-10% | 0% |

### 5.4.4. Costs of REHA Study and Mapping

REHA average unit cost is defined as the sum of the study cost, the mapping cost, and the cost of publication and distribution. These components are explained below.

- *Study cost.* Costs for performing analysis to determine riverine erosion boundaries ranged from $2,000-$12,000 per stream mile, depending upon the study category. Average values are $2,000-$3,000 per mile for a study using geomorphic methods, $6,000-$7,000 for using engineering methods and $10,000-$12,000 for using mathematical modeling methods. Those data are from limited case studies as well as from the PWG and the project team; actual study costs per mile may vary in a wider range. The study cost per map panel was computed by multiplying the cost per mile and the average miles per panel. The nationwide average is 2.2 stream miles per panel and is based on analysis of Q3 digital flood data conducted for the cost estimate for the FEMA map modernization report (FEMA, 1997).

- *Mapping cost.* The cost for mapping erosion boundaries, including reviewing study results and transferring them into a digital map, was estimated using data for preparing FIRMs. In a digital mapping format, REHA boundaries would be stored as an additional layer in the FIRMs. The cost of preparing this layer was estimated as $1,000 per panel, one-third of the current mapping cost for a FIRM panel.

- *Publication and distribution cost.* REHA maps would be published and distributed together with FIRMs. Additional costs for publication and distribution are limited and were estimated as $100 per panel.

The average unit cost is estimated using following procedures for a given county:

- Compute the erosion-prone stream miles per panel. Different percentages are used for counties with different levels of erosion, as discussed in Section 5.4.2.

- Estimate the REHA study cost. The fraction of stream miles studied by each study category and the cost per mile for each study category are used to compute the study cost for each study category, using information presented in Section 5.4.3 (Table 5.5) and this section. The study cost per panel is obtained by adding the cost for each study category, then multiplied by the miles per panel.

- The average unit cost is the sum of the study cost, the mapping cost, and the publication and distribution cost.

The average unit cost for mapping REHAs varies with the level of erosion. Table 5.6 shows a summary of costs per panel by level of erosion.

**Table 5.6.** Average unit cost for each level of erosion

| Level of Erosion | Cost per Panel, $ | | | |
|---|---|---|---|---|
| | Study | Mapping | Publication/ Distribution | Total |
| High | 7,400-11,000 | 1,000 | 100 | 8,500-12,100 |
| Intermediate | 2,800-5,400 | 1,000 | 100 | 3,900-6,500 |
| Low | 700-1,400 | 1,000 | 100 | 1,800-2,500 |

### *5.4.5. NFIP Costs*

The cost per county for mapping REHAs was determined by applying the cost per panel to the number of panels in a county. The nationwide cost was obtained by summing all of the county estimates. The approximate cost to the NFIP is in the range of 200 to 300 million dollars.

Section 577 of NFIRA specifies that, if REHA determination is found to be technically feasible, a cost-benefit study is to be conducted. The current study does not include these cost-benefit analyses.

## 5.5. Conclusions on Technical Feasibility

There is evidence that a time frame can be associated with a particular REHA delineation using one or a combination of the three analysis methodologies. However, specialized knowledge and expertise are needed to accomplish this task and evaluate the reliability of the results. Due to inherent inaccuracies in data collection and to the limitations of current models in attempting to represent the complex phenomena associated with fluvial processes, it is likely that various levels of reliability for the results will occur for a 60-year horizon. This difficulty is compounded by the unpredictability of avulsion.

A more reasonable option would be to use a time frame that is long enough so that the stream may have time to change appreciably but short enough so that the uncertainty in forecasts can be reduced. It appears that a shorter time frame, such as 30 years, with periodic revisions meets these conditions. However, as pointed out earlier, the useful life of structures may extend well beyond 30 years. Some progressive communities may prefer to use the "geologic floodplain" for management purposes.

Another option consistent with individual floodplain management needs is to assign a suitable time frame depending on local conditions and data availability. For example, more frequent assessments would be conducted for areas with severe erosion problems. Longer periods can be analyzed as better data become available.

# 6. Implementation

Previous chapters addressed the technical aspects of delineating riverine erosion hazard areas and assessing the time frame for erosion to occur in those areas. The material in those chapters summarizes scientifically sound methodologies for REHA delineation. The approximate cost of conducting these activities was also examined.

This chapter completes the analysis of technical feasibility by providing a description of implementation options for a nationwide program of REHA delineation. Information is also provided on regulations already in place in some jurisdictions that incorporate erosion into floodplain management activities.

## 6.1. Existing Regulations

### *6.1.1. Federal Regulations*

The NFIP regulations contain provisions to handle flood-related erosion to some extent. Section 60.5 of the regulations states that FEMA is to furnish information so that communities with erosion-prone areas can implement floodplain management plans. In cases where they have been identified, erosion hazard areas are designated as Zone E on FIRMs, although there are currently no flood insurance rates for Zone E. The FEMA-supplied information sets forth the minimum requirements of floodplain regulations, but the communities can acquire additional data to complement this information.

If in the process of applying for flood insurance coverage a community has identified erosion-prone areas, the Federal regulations require issuance of construction permits in these areas and a review to establish the safety of proposed projects and the risk of causing additional hazards elsewhere. If these negative aspects are identified, the community must request modification of the project or deployment of mitigation measures. If a Zone E has been designated, in addition to the above requirements, the community is to require setbacks for new development to create a safety buffer consistent with the useful life of the structures and physical setting: geology, hydrology, topography, climate, and other site characteristics. No permanent structures can be placed in the buffer, but the zone can be used for open space purposes.

The regulations state that communities must include erosion hazards in their planning to avoid development in hazard areas, promote open space utilization, and implementation of preventive measures in E zones (setbacks, shore protection, relocation and property acquisition of erosion-prone areas). The planning process should include coordination with other jurisdictions and the State to ensure consistency.

### *6.1.2. Local Regulations*

The Federal regulations are flexible to allow communities freedom to implement additional requirements. One example is the Floodplain and Erosion Hazard Management Ordinance for Pima County, Arizona. The ordinance requires the issuance of floodplain use permits that include review for impacts on riparian vegetation and for building setbacks. The ordinance states different setback criteria for major watercourses and minor washes in the county.

As defined in the Pima County ordinance, major watercourses constitute those streams where the 100-year flood discharge is greater than 2,000 cubic feet per second. In the absence of "unusual conditions," the setback is 100 feet for streams with 100-year peak discharges between 2,000 and 10,000 cubic feet per second and 250 feet when the discharge is greater than 10,000 cubic feet per second. The setback is 500 feet for a few critical sections of certain county streams; for example, the Santa Cruz River and Rillito Creek. These setbacks can be reduced provided that additional analysis is performed to the satisfaction of the County Engineer. Examples of "unusual conditions" include historic meandering of the watercourse, large excavation pits, poorly consolidated banks, natural channel armoring, proximity to bridges or rock outcrops, and changes in flow amount, direction, and velocity in the watercourse. If "unusual conditions" prevail, the setback will be established on an individual case basis and approved by the County Engineer. The analysis must consider potential danger to life and property.

Minor watercourses are streams where the 100-year peak flow is less than 2,000 cubic feet per second. Where no "unusual conditions" exist, the setback for these streams is 50 feet, unless approved bank protection measures have been deployed or additional analysis prove that the setback can be safely reduced. As with major watercourses, "unusual conditions" dictate the need for individual assessment of site-specific conditions.

There are other communities in the United States that manage riverine erosion through adopted regulations or guidance through the local floodplain management program. In addition, under the Community Rating System (CRS), communities can receive credit for regulating erosion hazards. For example, up to 10 points can be awarded for disclosure of hazards other than flooding, including erosion; up to 50 points can be earned if the community maps areas with special flood-related hazards; and up to 100 points can be assigned for regulations keyed to special flood-related hazards.

## 6.2. Options for Implementation

The foregoing section suggests two potential options for implementation of a nationwide REHA delineation program. The first is a federally run program similar and integral to the NFIP. The second is a locally run program with support from the Federal government. The following subsections describe the general vision and features of these options as well as some of their advantages and disadvantages.

### *6.2.1. NFIP Expansion*

The fundamental principle of the first option is to expand the current floodplain regulations to encompass riverine erosion. This option emphasizes authority from the Federal government.

The process would parallel the current determination of floodplains. Qualified study contractors would conduct riverine erosion studies according to approved guidelines. The studies would undergo technical review before being approved by FEMA for inclusion in FIRMs. Actuarial studies would be conducted to account for erosion risks, and E zones would be used to determine insurance rates. Communities would be required to comply with Federal requirements to be eligible for insurance coverage. Additional legislation may need to be passed to regulate activities within REHAs. Similar to flooding studies, the regulations would require that REHAs be restudied periodically, which would lend itself to implementing the appropriate time frame with periodic revisions as discussed previously in Section 5.5.

The main advantage of this option is the fact that there is already a regulatory structure in place to regulate flood-prone areas. The existing framework can be modified to accommodate the new responsibilities of regulating erosion-prone areas. One obvious disadvantage is the additional cost to the Federal government to implement the program. Another disadvantage is the risk of imposing rigid guidelines for REHA delineation in a field that requires flexibility and accessibility to a wide array of analytical options. A related disadvantage is the potential for developing adversarial situations among the Federal government, local jurisdictions, and citizens due to the inherent uncertainty in REHA delineation. One last disadvantage is the apparent shortage of qualified professionals to conduct and review REHA determination studies.

### 6.2.2. Local Implementation

The second option shifts the authority for regulating erosion-prone areas to the local jurisdictions. Implementation would be tailored to suit individual floodplain management needs. The Federal government would provide technical assistance, if required, and disseminate information.

Under this option, the communities would determine the need to undertake REHA delineation studies that would be paid with local funds, although Federal funding may be available in some cases. The sole responsibility of selecting a consultant and approving the work would rest with the community's engineering staff. The Federal government could provide some review functions. The community would use the results of the studies to develop ordinances to manage erosion-prone areas. The main responsibility of the Federal government is to publish erosion hazard areas in FIRMs for informational purposes. For insurance purposes, the Zone E designation could have the same rates as Zone X.

An advantage of this option is that if follows the philosophy of current FEMA initiatives to support progressive communities, such as Cooperating Technical Communities and Project Impact. The delineated REHAs would be distributed digitally as additional layers in the Digital Flood Insurance Rate Maps (DFIRMs) as a tool for communities to use in evaluating exposure to multiple hazards. Another advantage is that the communities would have the flexibility to match their resources and needs with the complexity of the studies. The community would be responsible for defending its local regulations in potentially controversial situations.

Similar to the first option, local implementation may be limited by a lack of skilled professionals to delineate REHAs. This shortcoming presents an additional disadvantage to the communities because they may not have the expertise or resources to evaluate potential consultants. Another disadvantage is that communities may not be politically or financially capable of revising REHA studies as often as required to maximize validity.

Yet another disadvantage is the potential risk of inconsistencies and conflicts across jurisdictional boundaries. One community's lax erosion area regulations may be the cause of increased hazards to neighboring communities. These types of situations currently arise in connection with water quantity, but the authority of the Federal government serves to resolve these conflicts. In the case of erosion, however, the absence of a strong Federal arbiter compounded by the uncertainty associated with erosion hazard characterization could make these interjurisdictional differences more common.

# 7. Conclusions

Riverine erosion is a complex physical process that involves interaction of numerous factors: fluvial hydraulics, geotechnical stability, sediment transport, and watershed characteristics, including hydrology and sediment yield, past and future land use, and vegetation, among others. The study of riverine erosion is multidisciplinary in nature and requires experienced geomorphologists, hydrologists, hydraulic engineers, geotechnical engineers, photointerpreters, planners, and mapping specialists. Some of these professions require advanced degrees in their specialties. Valuable input is also needed from local floodplain managers.

Despite decades of research into the physical processes associated with riverine erosion, knowledge of the subject is still imperfect, and much work remains to be done. Accurate mathematical representation of these processes has not been achieved yet, and available tools produce results surrounded by varying degrees of uncertainty. Nevertheless, there are analytical procedures that can be used to characterize riverine erosion and that, depending on the application, can yield reliable results. For example, because of limitations in data availability and model capabilities, it is extremely difficult to reproduce detailed time variation of stream movement; however, it is entirely feasible to analyze channel history and infer trends in the stream alignment and average migration rates.

The analysis approaches currently in use by professionals in the field can be broadly classified into three categories: geomorphic analysis, basic engineering analysis, and mathematical modeling. Data needs and complexity are increasingly more rigorous from geomorphic analysis to mathematical modeling. Field investigations are a major component of all three approaches. Geomorphic analysis is characterized by evaluation of readily available information to infer relationships among sediment, flow regime, and channel geometry. Basic engineering analysis complements geomorphic analysis and introduces equations to quantify relationships among factors affecting channel configuration. Mathematical modeling couples analytical representations for processes in fluid mechanics and sediment transport to simulate the interaction of several physical phenomena and their impact on channel geometry. Modeling is the most complex approach, and its implementation requires considerable expertise and resources.

The 12 case studies investigated for this report indicate that there are scientifically sound approaches to analyze riverine erosion. Some of the methods are suitable for qualitative assessments of erosion hazards; others establish conditions to be maintained if erosion is to be prevented. A few of the methods in the case studies can be applied to delineate erosion hazard areas, although the accuracy is highly variable.

Two issues impact the significance and usefulness of a REHA: the degree of uncertainty in the spatial location and the time frame for which the REHA is applicable, that is, the time for which it is estimated that erosion will take place within the REHA. These two issues are related in that uncertainty is greater for long time frames. On the other hand, a very short time frame for which uncertainty is much reduced may be useless for floodplain management because of the minimal amount of erosion expected to occur. Section 577 of NFIRA specified a period of 60 years for REHA delineation; however, it appears that a shorter time frame, such as 30 years with periodic revisions, presents a more practical alternative.

A preliminary cost analysis was performed based on limited information obtained as part of the current study and from personal experience within the Project Team and the PWG. Average study values are $2,000-$3,000 per mile for geomorphic methods, $6,000-$7,000 for engineering methods, and $10,000-$12,000 for mathematical modeling methods. If this effort were to be implemented as part of the NFIP, the cost to the Federal government would be between 200 and 300 million dollars. Section 577 of NFIRA specifies that, if REHA determination is found to be technically feasible, a cost-benefit study is to be conducted. The current study does not include these cost-benefit analyses.

A program for nationwide delineation of REHAs can be implemented under two scenarios. The first option is an expansion of the current NFIP regulatory scheme to include erosion. This option emphasizes authority at the Federal government level, and its foremost advantage is that there is already a framework in place for implementation. The main disadvantage is the additional regulatory burden and cost to the Federal government. The second option shifts responsibility to the local jurisdictions to conduct REHA delineation voluntarily. The Federal government would publish REHAs for informational purposes. The main advantage is that the delineations would be conducted according to the individual needs of the community. A disadvantage is the risk of adversarial situations that a community may face from land use restrictions.

# 8. References


Ackers, P., and W. R. White (1973), "Sediment transport: A new approach and analysis," ASCE Journal of the Hydraulics Division, 99 (HY11), p. 2041-2060, November.

Albuquerque Metropolitan Arroyo Flood Control Authority (1983), *Design Guide for Riprap-Lined Flood Control Channels,* Albuquerque, New Mexico.

Albuquerque Metropolitan Arroyo Flood Control Authority (1994), *Sediment and Erosion Design Guide*, Albuquerque, New Mexico.

Alonso, C. V., and S. T. Combs (1986), "Channel width adjustment in straight alluvial streams," Proceedings of the 4th Federal Interagency Sedimentation Conference, U.S. Government Printing Office, Washington, D.C.

Alonso, C.V., D.K. Borah, and S.N. Prasad (1981). "Numerical model for routing graded sediments in alluvial streams," Appendix J, Report Prepared for the U.S. Army Corps of Engineers, Vicksburg District, USDA Sedimentation Laboratory, Oxford, Missssissippi.

American Society of Civil Engineers (1998a), "River width adjustment I: Processes and mechanisms," by the ASCE Task Committee on Hydraulics, Bank Mechanics, and Modeling of River Width Adjustment, ASCE Journal of Hydraulic Engineering, vol. 124, No. 9, September.

American Society of Civil Engineers (1998b), "River width adjustment II: Modeling," by the ASCE Task Committee on Hydraulics, Bank Mechanics, and Modeling of River Width Adjustment, ASCE Journal of Hydraulic Engineering, vol. 124, No. 9, September.

Anderson, A. G. (1967), "On the development of stream meanders," Proceedings of the Twelfth Congress, IAHR, Colorado State University, Fort Collins, Colorado.

Andrews, E. D. (1980), "Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming," Journal of Hydrology, v. 46.

Arizona Department of Water Resources, Flood Warning and Dam Safety (1996), *State Standard for Watercourse System Sediment Balance*, Phoenix, Arizona.

Athaullah, M. (1968), *Prediction of Bed Forms In Erodible Channels*, Ph.D. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Baker, V.R. (1977), "Stream-channel response to floods, with examples from central Texas," Geological Society of American Bulletin, v. 88, p. 1057-1071.

Bhowmik, N.G. and R. J. Schicht. *Bank Erosion of the Illinois River*, Report of Investigation 92, Illinois State Water Survey, 1980.

Bhowmik, N.G., M. Demissie, and C.-Y. Guo. *Waves Generated by River Traffic and Wind on the Illinois and Mississippi Rivers.* Illinois State Water Survey Contract Report 293, 1982.

Biowest, Inc. (1995), *Virgin River Geomorphic and Hydrologic Studies Related to Channel Forming Flows,* Reported prepared for Utah Division of Wildlife Resources, Salt Lake City, Utah.

Blench, T. (1969), Mobile-Bed Fluviology: A Regime Treatment of Canals and Rivers, University of Alberta Press, Edmonton, Canada.

Borah, D. K., and P. K. Bordoloi (1989), "Stream bank erosion and bed evolution model," in *Sediment Transport Modeling*, S. Wang, ed., American Society of Civil Engineers, New York, New York.

Brice, J. C. (1982), *Stream Channel Stability Assessment, Report FHWA/RD-82-021.* Federal Highway Administration, Washington, D.C.

Brice, J. C. (1983), "Planform Properties of Meandering Rivers," in *River Meandering,* Proceedings of the Rivers'83 Conference, American Society of Civil Engineers, new Orleans, Louisiana, October.

Brown, C. B. (1950), "Sediment Transportation," in *Engineering Hydraulics*, H. Rouse, ed., John Wiley & Sons, New York.

Brownlie, W.R. (1983), "Flow depth in sand-bed channels," ASCE Journal of Hydraulic Engineering, vol. 109, No. 7, p. 959-990.

CH2M Hill and J. E. Fuller/Hydrology & Geomorphology, Inc. (1996), *River Stability Study, Virgin River, Santa Clara River, and Ft. Pierce, Washington, Vicinity of St. George, Utah*, prepared for City of St. George, Utah.

Chang, H. H. (1982), "Mathematical model for erodible channels," Journal of the Hydraulics Division, American Society of Civil Engineers, 108(HY5), p. 678-689.

Chang, H. H. (1984), "Modeling of river channel changes," ASCE Journal of Hydraulic Engineering, 110(2), p.157-172.

Chang, H. H. (1984), "Water and sediment routing through curved channels," Journal of the Hydraulics Division, American Society of Civil Engineers, 101(HY4), p. 644-658.

Chang, H. H. (1988a), *Fluvial Processes in River Engineering,* John Wiley & Sons, New York.

Chang, H. H. (1988b), *FLUVIAL-12: Mathematical Model for Erodible Channels – User's Manual,* San Diego, California.

Chang, H. H. (1993), *Test and Calibration Studies of FLUVIAL-12 Mathematical Model for Erodible Channels*, San Diego, California.

Chang, H. H. (1998), Personal communication with Daniel E. Medina of Dewberry & Davis, August 28.

Chang, H. H., and D. Stow (1991), "Computer simulation of river channel changes induced by sand mining," Proceedings of the International Conference on computer Applications in Water Resources, July 3-6, Taipei, Taiwan, vol.1, p. 226-234.

Chang, H. H., and J. C. Hill (1977), "Minimum stream power for rivers and deltas," Journal of the Hydraulics Division, American Society of Civil Engineers, 103(HY12), p. 1375-1389.

City of Albuquerque (1993), *Development Process Manual*, Section 22.2, Hydrology, Volume 2, Design Criteria, prepared by the DPM Drainage Design Criteria Committee.

City of Austin (1997), *Technical Procedures for the Watershed Erosion Assessments*, prepared by Raymond Chan & Associates, Austin, Texas.

City of Tucson Department of Transportation (1989), *Standards Manual for Drainage Design and Floodplain Management in Tucson*, Engineering Division, Tucson, Arizona.

Clark, M. J., D. A. Sear, C. T. Hill, J. Branson, M. D. Newson, R. Pawson, and S. Juggins (1995), "River channel typology for catchment and river management," Report to the National Rivers Authority, University of Southhampton, United Kingdom.

Colby, B. R. (1964), *Discharge of Sands and Mean Velocity Relationships in Sand-Bed Streams*, USGS Professional Paper 462-A.

Cooper Engineering Associates (1987), *Flood Plain Management Study for Moosa Canyon Creek*, prepared for County of San Diego Department of Public Works, July.

Crowell, M., H. Leikin, M. K. Buckley (1999), "Evaluation of Erosion Hazards Study: An Overview", Journal of Coastal Research, Special Issue No. 28.

Culvertson, D. M., L. E. Young, J. C. Brice (1967), *Scour and Fill in Alluvial Channels*, USGS Open-File Report.

Darby, S. E., and C. R. Thorne (1996a), "Development and testing of a riverbank stability analysis," ASCE Journal of Hydraulic Engineering, vol. 122, No. 8, p. 443-455.

Darby S. E., and C. R. Thorne (1996b), "Numerical simulation of widening and bed deformation of straight sand-bed rivers. I: Model development," ASCE Journal of Hydraulic Engineering, vol. 122, No. 4, p. 184-193.

Davis, W. M. 1902, "Base-level, grade, and peneplain"; Geographical Essays, XVIII, p. 381-412, Ginn, Boston.

Davison, A.T. (1993), *The National Flood Insurance Program Coastal Hazards.*

Diplas, P. and G. G. Vigilar (1992), "Hydraulic geometry of threshold channels," ASCE Journal of Hydraulic Engineering, vol. 116, No. 5, p. 597-614.

DuBoys, P. (1879), "Le Rhone et les Rivieres a Lit Affouillable," Annales des Ponts et Chausses, 18, Series 5, p. 141-195.

Dunne, T., and W.E. Dietrich (1978), "A River of Green", in Jones & Jones, 1978, *Hydrology, Sedimentation, Channel Migration, and Flood Diking Along the Green River: Seattle,* Report to the City of Yakima Department of Parks and Recreation, Appendix A.

Dunne, T., W.E. Dietrich, and D. Nimick (1976), "The Yakima River Between the Selah and Union Gaps", in Jones and Jones, 1976, *Hydrology: Seattle*, Report to the City of Yakima Department of Parks and Recreation, Appendix A.

Edgar, D. E., and A. R. Rao (1983), "An empirical analysis of meandering and flow characteristics in laboratory and natural channels," in *River Meandering,* Proceedings of the Rivers'83 Conference, American Society of Civil Engineers, new Orleans, Louisiana, October.

Einstein, H. A. (1950), *The Bed Load Function for Sediment Transportation in Open Channels*, Technical Bulletin 1026, U.S. Department of Agriculture.

Engelund, F., and E. Hansen (1967), *A Monograph on Sediment Transport in Alluvial Streams*, Teknisk Vorlag, Copenhagen, Denmark.

Fan, S. S., ed. (1988), *Twelve Selected Computer Stream Sedimentation Models Developed in the United States*, Washington D.C., Federal Energy Regulatory Commission report.

Federal Emergency Management Agency (1990), *Analysis of Stream Bank and Bluff Stability for Use in the Evaluation of Flood Insurance Claim Eligibility Under the Upton/Jones Amendment*, Office of Risk Assessment, Federal Insurance Administration.

Federal Emergency Management Agency (1991), *Detailed Chronology of Significant National Flood Insurance Program Events*, Federal Insurance Administration.

Federal Emergency Management Agency, (1995), *Upton-Jones Claim Database*, unpublished.

Federal Emergency Management Agency, (1997), *Modernizing FEMA's Flood Hazard Mapping Program: A Progress Report*, November.

Federal Highway Administration (1985), Hydraulic Design of Highway Culverts, U.S. Department of Transportation, Hydraulic Design Series No. 5.

Federal Highway Administration (1991), *HEC-20: Stream Stability at Highway Structures*, Washington, D.C.

Froelich, D. C. (1997), Personal communication with Michael Grimm of FEMA.

Garcia, M.H., L. Bittner and Y. Niño (1996), *Mathematical Modeling of Meandering Streams in Illinois: A Tool for Stream Management and Engineering*, 2nd edition, University of Illinois at Urbana-Champaign.

Gomez, B., and M. Church (1989), "An assessment of bed load sediment transport formulae for gravel bed rivers," Water Resources Research, vol. 25, No. 6, p. 1161-1186.

Graf, W. H. (1971), *Hydraulics of Sediment Transport*, McGraw-Hill Inc., New York, New York.

Graf, W. L. (1981), "Channel instability in a braided, sand bed river", Water Resources Research, vol. 17, No. 4, p.1087-1094.

Graf, W.L. (1983), "Flood-related channel changes in an arid-region river", Earth Surface Process and Landforms, vol. 8, p.125-139.

Graf, W.L. (1984), "A Probabilistic Approach to the Spatial Assessment of River Channel Instability," Water Resources Research, 20 (7), 953-962.

Gregory, K.J. (1977), *River Channel Changes,* John Wiley, New York.

Grimm, M. (1996), "Applied Geomorphology and Floodplain Management," Land and Water, March/April.

Guber, A. L. (1988), *Channel Changes of the Xavier Reach of the Santa Cruz River, Tucson, Arizona, 1971-1988*, unpublished Master's thesis, University of Arizona, Tucson, Arizona.

Hagerty, D. J. *Illinois Waterway Bank Evaluation.* Unpublished report, submitted to the U.S. Army Corps of Engineers, Rock Island District, 1989.

Hasegawa, K. (1989), "Universal bank erosion coefficient for meandering rivers," ASCE Journal of Hydraulic Engineering, vol. 115, No. 6.

Hays, M.E. (1984), *Analysis of Historical Changes as a Method for Evaluating Flood Hazard in the Semi-Arid Southwest*, MS Thesis, University of Arizona, Tucson, Arizona.

Hey, R. D. (1976), "Geometry of river meanders," Nature, No. 262, p. 482-484.

Hey, R. D., and C. R. Thorne (1986), "Stable channels with mobile gravel beds," ASCE Journal of Hydraulic Engineering, vol. 112, No. 6, p. 671-689.

Hickin, E.J., and G.C. Nanson (1984), "Lateral migration rates of river bends," ASCE Journal of Hydraulic Engineering, v. 110, No. 11, p.1557-1567.

Ikeda, S., G. Parker, and Y. Kimura (1988), "Stable width and depth of straight gravel rivers with heterogeneous bed materials," Water Resources Research, 24 (5), p. 713-722.

Ikeda, S., and N. Izumi (1990), "Width and depth of self formed straight gravel rivers with bank vegetation," Water Resources Research, vol. 26, No. 10, p. 2353-2364.

Ikeda, S., G. Parker and K. Sawai (1981), "Bend theory of river meanders; 1: Linear Development," Journal of Fluid Mechanics, v. 112, p. 363-377.

Illinois State Water Survey (1997), *Bank Erosion Field Survey Report of the Upper Mississippi River and Illinois Waterway*, prepared for U.S. Army Corps of Engineers, St. Paul District, Rock Island District, and St. Louis District.

Karlinger M. R., T. R. Eschner, R. Hadley, and J. E. Kircher (1983), *Relation of Channel-Width Maintenance to Sediment Transport and River Morphology: Platte River, South-Central Nebraska, Hydrologic and Geomorphic Studies of the Platte River Basin*, US Geological Survey Professional Paper No. 1277-E.

Kellerhalls, R. and D.I. Bray (1971), "Sampling procedures for coarse fluvial sediments," ASCE Journal of the Hydraulics Division, v. 97, No. HY8, p. 1165-1179.

Keulegan, G.H. (1938), "Laws of turbulent flow in open channels." Journal of Research of the National Bureau of Standards, 21, 707-741.

Klimek, K. (1974), "The retreat of alluvial river banks in the Wisloka Valley (South Poland)," Geographia Polonica, v. 28, p. 59-75.

Knight, D. W., and K. Shiono (1995), "River channel and floodplain hydraulics," in *Floodplain Processes*, M. Anderson, D. Walling, and J. Bates, eds., John Wiley & Sons, Chichester, United Kingdom.

Knighton, A. D. (1987), "Downstream River Channel Adjustments," in *River Channels: Environment and Process*, Institute of British Geographers special publication, K. Richards (ed.), Basil Blackwell, Inc., New York.

Kovacs, A. E., and G. Parker (1994), "A new vectorial bedload formulation and its application to the time evolution of straight rive channels," Journal of Fluid Mechanics, vol. 267, p.153-183.

Kresan, P.L. (1988), "The Tucson, Arizona, Flood of October 1983 - Implications for Land Management Along Alluvial River Channels," in Baker, V.R., R.C. Kochel, and P.C. Patton, eds., *Flood Geomorphology*, John Wiley & Sons, New York, New York.

Lacey, G. (1920), "Stable channels in alluvium," Proceedings of the Institution of Civil Engineers, 229, p. 259-292.

Lane, E. W. (1955), "Design of stable channels," Transactions of the American Society of Civil Engineers, 120, p.1234-1260.

Leopold, L. B., and M. G. Wolman (1960), "River meanders," Geologic Society of America Bulletin, 71, p. 769-794.

Leopold, L. B., M. G. Wolman, and J. P. Miller (1964), *Fluvial Processes in Geomorphology*, Dover, New York.

Li, L., and S. S. Y. Wang (1993), "Numerical modeling of alluvial stream bank erosion," *Advances in Hydro-science and Engineering*, S. S. Y. Wang, ed., University of Mississippi, Oxford, Mississippi.

Lindley, E. S. (1919), "Regime channels," Proceedings of the Punjab Engineering Congress, vol. 7, Punjab, India.

MacDonald, T. E., G. Parker, and D. P. Leuthe (1991), *Inventory and Analysis of Stream Meander Problems in Minnesota*, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Mackin, J. H. (1948), "Concept of the graded river," Geologic Society of America Bulletin, v. 59, p. 463-512.

Meyer-Peter, E., and R. Muller (1948), "Formulas for bed-load transport," Paper No. 2, Proceedings of the 2nd Meeting, IAHR, p. 39-64.

Miller, H.C. (1992), "On the Brink: Coastal Location and Relocation Choices," in *Coastal Erosion, Has Retreat Sounded?*, R.H., Platt, *et al.*, eds., Program on Environment and Behavior Monograph No. 53, Institute of Behavioral Science, University of Colorado.

Molinas, A. (1993), User's Manual for BRI-STARS (Bridge Stream Tube Model for Alluvial River Simulation), National Cooperative Highway Research Program, Project No. HR15-11.

Mollard, J. D., and J. R. Janes (1984), *Airphoto Interpretation and the Canadian Landscape*, Department of Energy, Mines and Resources, Ottawa, Canada, Canadian Government Publishing Centre, Hull, Quebec, Canada.

Morisawa, M., and LaFlure (1979), "Hydraulic Geometry, Stream Equilibrium and Urbanization," in *Adjustments of the Fluvial System,* D. D. Rhodes and G.P. Williams (eds.), Proceedings of the 10th annual Geomorphology Symposium Series, Binghamton, New York, Kendall Hunt Dubuque, Iowa.

Mosselman, E. (1992), *Mathematical Modeling Of Morphological Processes In Rivers With Erodible Cohesive Banks*, Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands.

Mrazik, B.R., and H.A. Kinberg (1989), *National Flood Insurance Program – Twenty Years of Progress Toward Decreasing Nationwide Flood Losses*, National Water Summary 1988-1989 – Floods and Droughts: Institutional and Management Aspects, p. 133-142.

National Research Council (1983), *An Evaluation of Flood-Level Prediction Using Alluvial River Models*, National Academy Press, Washington, D.C.

National Research Council (1996), *Alluvial Fan Flooding*, Committee on Alluvial Fan Flooding, National Academy Press, Washington, D.C.

National Research Council (1999), *Hydrologic Science at the U.S. Geological Survey,* National Academy Press, Washington, D.C.

Odgaard, A. J. (1984), *Bank Erosion Contribution to Stream Sediment Load*, Iowa Institute of Hydraulic Research Report 280, University of Iowa, Iowa City.

Odgaard, A. J. (1986), "Meander-flow Model, 1, Development," ASCE Journal of Hydraulic Engineering, vol. 112 , p. 1117-1136.

Odgaard, A. J. (1987), "Streambank Erosion along Two Rivers in Iowa," Water Resources Research, vol. 23, No. 7, p. 1225-1236.

Osman, A. M. (1985), *Channel Width Response to Changes in Flow Hydraulics and Sediment Load*, Ph.D. Thesis, Colorado State University, Fort Collins, Colorado.

Osman, A. M., and C. R. Thorne (1988), "Riverbank Stability Analysis I: Theory," ASCE Journal of Hydraulic Engineering, vol. 114, No. 2, pp.134-150.

Pacific Southwest Interagency Committee (1968), *Factors affecting sediment yield in the Pacific Southwest areas*, Water Management Subcommittee, Sediment Task Force.

Park, G. (1982). *Stability of the Channel of the Minnesota River near State Bridge No 93, Minnesota.* St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Park, G. (1983) " Theory of meander bend deformation," in *River Meandering*, Proceedings of the Conference Rivers'83, New Orleans, Louisiana.

Parker, G. (1977), *Self-Formed Straight Rivers with Stable Banks and Mobile Bed in Non-Cohesive Alluvium. Part I. The Sand-Silt River*, Department of Civil Engineering, University of Alberta, Alberta, Canada.

Parker, G. (1978), "Self-formed straight rivers with equilibrium banks and mobile bed, Part 1: The sand-silt river," Journal of Fluid Mechanics, vol. 89, No. 1, p. 109-125.

Parker, G. (1979). "Hydraulic geometry of active gravel rivers," ASCE Journal of the Hydraulics Division, vol. 105, p. 1185-1201.

Parker, G., P. C. Klingeman, and D. G. McLean (1982), "Bed load and size distribution in paved gravel-bed streams," ASCE Journal of the Hydraulics Division, 108(HY4), p. 544-571, April.

Parker, G. (1983), "Theory of Meander Bend Deformation," in *River Meandering*, Proceedings of the Conference Rivers'83, American Society of Civil Engineers, New York.

Parker, G. (1983), "Discussion of 'Lateral bed load transport on side slopes' by S. Ikeda." ASCE Journal of Hydraulic Engineering, vol. 109, p. 197-199.

Parker, J.T.C. (1995), *Channel Change on the Santa Cruz River, Pima County, Arizona, 1936-86*, U.S. Geological Survey Water-Supply Paper 2429, Denver, Colorado.

Perkins, S. J. (1993), *Green River Channel Migration Study,* King County Department of Public Works, Surface Water Management Division, Seattle, Washington.

Perkins, S. J. (1996), *Channel Migration in Three Forks Area of the Snoqualmie River,* King County Department of Natural Resources, Surface Water Management Division, Seattle, Washington.

Pemberton, E.L., and J. M. Lara (1984), *Computing Degradation and Local Scour*, Technical Guidelines for Bureau of Reclamation, Engineering Research Center, Denver, Colorado.

Pizzuto, J. E. (1990), "Numerical simulation of gravel river widening," Water Resources Research, vol. 26, p. 1971-1980.

Ponce, V.M. (1978), "Generalized Stability Analysis of Channel Banks," ASCE Journal of the Irrigation and Drainage Division, v. 104, No. 1R4, p. 343-350.

Renwick, W.H. (1992), "Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape," in *Geomorphic Systems*, J.D Phillips and W. H. Renwick (eds.), Proceedings of the 23rd annual Geomorphology Symposium Series, Binghamton, New York, Elsevier, Amsterdam.

Rhoads, B. L. (1994), "Fluvial Geomorphology," Progress in Physical Geography, 18(4), p. 588-608.

Richarson, E.V., L.J. Harrison, and S. R. Davis (1991), *Evaluating Scour at Bridges*, Hydraulic Engineering Circular No. 18, U.S. Department of Transportation, Federal Highway Administration, Turner Fairbanks Highway Research Center, McLean, Virginia.

Rosgen, D. (1985), "A stream Classification System," in *Riparian Ecosystems and Their Management – Reconciling Conflicting Uses*, Proceedings of the First North American Riparian Conference, April 16-18, 1985. Tucson, Arizona.

Rosgen, D. L. (1994), "A classification of natural rivers," Catena, 22, pp. 169-199.

Rosgen, D. L. (1996), *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, Colorado.

Sabol, G.V., C.F. Nordin, and E.V. Richardson (1989), *Scour at Bridge Structures and Channel Aggradation and Degradation Field Measurements*, Arizona Department of Transportation Research Project.

Schumm, S. A., (1969), "River Metamorphosis," ASCE Journal of the Hydraulics Division, 95(HY1), p.255-273, January.

Schumm, S. A., (1971), "Fluvial Geomorphology: Historical Perspective," in *River Mechanics*, H. W. Shen (ed.), Fort Collins, Colorado.

Schumm, S. A., (1977), *The Fluvial System*, John Wiley & Sons, New York.

Shannon & Wilson, Inc. (1991), *Tolt and Raging Rivers Channel Migration Study, King County, Washington*, prepared for King County Surface Water Management Division, King County Department of Public Works, Seattle, Washington.

Shields, A. (1936), "Anwendung Aenlich Keitsmechanik und der Turbulenzfor-schung auf Die Geschiebebewegung," Mitteilungen de Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, Berlin, Germany, (in German).

Simon, A., W. J. Wolfe, and A. Molinas (1991), "Mass wasting algorithms in an alluvial channel model," Proceedings of the 5th Federal Interagency Sedimentation Conference, U.S. Government Printing Office, Washington, D.C.

Simons, D. B., and E. V. Richardson (1961), "Resistance to flow in alluvial channels," ASCE Journal of the Hydraulics Division, 87 (HY3), p. 87-105.

Simons, D. B., and M. Albertson (1963), "Uniform water conveyance channels in alluvial material," Transactions of the American Society of Civil Engineers, vol. 128, No.1, p. 65-167.

Simons, Li, & Associates (1983), *Erosion Study to Determine Boundaries for Adjacent Development – Calabacillas Arroyo, Bernalillo County, New Mexico*, prepared for the Albuquerque Metropolitan Arroyo and Flood Control Authority, Albuquerque, New Mexico.

Simons, Li, & Associates (1984), *River Management Plan for the Rillito River and Major Tributaries*, prepared for Pima County Department of Transportation and Flood Control District, Tucson, Arizona.

Simons, Li & Associates, Inc. (1985), *Design Manual for Engineering Analysis of Fluvial Systems*, prepared for Arizona Department of Water Resources, Tucson, Arizona.

Simons, Li, & Associates (1986), *Santa Cruz Management Plan Technical Report*, prepared for Pima County Department of Transportation and Flood Control District, Tucson, Arizona.

Slezak-Pearthree, M., and V.R. Baker (1987), *Channel change Along the Rillito Creek System of Southeastern, Arizona, 1941 through 1983*, Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Special Paper 6.

Soil Conservation Service (1990), *Virgin River - Utah, Cooperative Study*, prepared in cooperation with Utah Division of Natural Resources.

Spoor, M.F. and D.J. Hagerty (1989), *Bank Failure and Erosion on the Illinois Waterway.* Proceedings, International Symposium on Sediment Transport and Modeling, ASCE, New Your, 600-605.

Strickler, A. (1923), “Beitrage zur frage der geschwindigheitsformel und der rauhigkeitszahlen for strome, kanale und geschlossene leitungen,” Mitteilungen des eidgenossicher amtes fur wasserwirtschaft, Bern, Switzerland, (in German).

Thorne, C. R. (1982), “Processes and mechanisms of river bank erosion,” in *Gravel-Bed Rivers*, R. D. Hey, J. C Bathurst, and C. R. Thorne (eds.), John Wiley & Sons, Chichester, United Kingdom.

Thorne, C. R., and A. M. Osman (1988), “Riverbank stability analysis II: Applications,” ASCE Journal of Hydraulic Engineering, vol. 114, No. 2, p. 151-172.

Thorne, C. R., and N. K. Tovey (1981), “Stability of composite river banks,” Earth Surface Processes and Landforms, vol. 6, p. 469-484.

Thorne, C.R., and J. Lewin (1982), "Bank processes, bed material movement, and planform development," in *Adjustments of the Fluvial System,* D. D. Rhodes and G.P. Williams (eds.), Proceedings of the 10th annual Geomorphology Symposium Series, Binghamton, New York, Kendall Hunt Dubuque, Iowa.

Thorne, C.R., and M.K. Tovey (1981), "Stability of composite river banks," Earth Surface Processes and Landforms, 6, pp. 469-484.

Thorne, C.R., and M.R. Welford (1994), "The equilibrium concept in geomorphology," Annals of the Association of American Geographers, v. 84, No. 4, p. 666-696.

Thornes, J. B. (1977), “Hydraulic geometry and channel changes,” in *River Channel Changes*, K. J. Gregory, ed., John Wiley & Sons, New York, New York, p 91-100.

U.S. Army Corps of Engineers (1994), *Channel Stability Assessment for Flood Control Projects*, EM 1110-2-1418.

U.S. Army Corps of Engineers (1995), *Hydrologic Design of Flood Control Channels*, EM1110-2-1601.

U.S. Army Corps of Engineers,(1979), *Des Moines River Bank Erosion Study, Iowa and Missouri Stage 2, Final Feasibility Report*, Rock Island District

U.S. Bureau of Reclamation (1984), *Computing Degradation and Local Scour,* Technical Guideline for Bureau of Reclamation.

US Army Corps of Engineers (1981), *The Streambank Erosion Control Evaluation and Demonstration Act of 1974*, Final Report to Congress.

Van Rijn, L. C. (1982), “Sediment transport, Part III: Bed forms and alluvial roughness,” ASCE Journal of Hydraulic Engineering, vol. 110, No. 12, p. 1733-1754.

Warren, R.E. (1987), *The Impact of Bank Erosion on Prehistoric Culture Resources in the Lower Illinois River Valley,* Technical Report 87-211-10, Illinois State Museum Society, Springfield, Illinois.

Webb, R.H., and J.I. Betancourt (1992), *Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona*, U.S. Geological Survey, Water supply Paper 2379.

Wiele, S. M. (1992), *A Computational Investigation of Bank Erosion and Midchannel Bar Formation In Gravel-Bed Rivers*, Ph.D. Thesis, University of Minnesota, Minneapolis, Minnesota.

Yang, C. T. (1972), "Unit stream power and sediment transport," ASCE Journal of the Hydraulics Division, 98(HY10), p. 1805-1826.

Yang, C.T. (1973), "Incipient motion and sediment transport." ASCE Journal of Hydraulic Engineering, vol. 110, p. 1783-1797.

Yang, C. T. (1984), "Unit stream power equation for gravel," ASCE Journal of Hydraulic Engineering, vol. 110, p. 1783-1797.

Yang, C. T., A. Molinas, and C. S. Song (1988), "GSTARS – Generalized stream tube model for alluvial river simulation," in *Twelve Selected Computer Stream Sedimentation Models Developed in the United States*, S. Fan (ed.), Federal Energy Regulatory Commission, Washington, D.C.

Yang, C. T., and S. Wan (1991), "Comparison of selected bed-material formulas," ASCE Journal of Hydraulic Engineering, vol. 117, p. 973-989.

Yang, C. T., C. C. S. Song, and M. J. Woldenberg (1981), "Hydraulic geometry and minimum rate of energy dissipation," Water Resources Research, vol. 17, No. 4, p. 1014-1018.

# Appendix

## List of Publications Investigated

Ahmed, A. F. and M. M. Gasser (1992), "Bank erosion study of the nile river at bani mazar," in *Hydraulic Engineering: Saving a Threatened Resource -- In Search of Solutions*.

Alaska Division of Emergency Services (1992), *Mantanuska River Erosion Task Force Interim Report*.

Albuquerque Metropolitan Arroyo Flood Control Authority (1994), *Sediment and Erosion Design Guide*, Albuquerque, New Mexico.

Andrews, E. D. (1979), *Scour and Fill in a Stream Channel, East Fork River, Western Wyoming,* USGS Professional Paper 1117.

Annandale, G. W. and D. L. Parkhill (1995), "Stream bank erosion: application of the erodibility index method," in *Water Resources Engineering*, p. 1570.

Arizona Department of Water Resources, Flood Warning and Dam Safety (1996), *State Standard for Watercourse System Sediment Balance*, Phoenix, Arizona.

Arizona Geological Survey (1992), *Geomorphic Assessment of Flood-Prone Areas on the Southern Piedmont of the Tortolita Mountain, Pima County, Arizona.*

Ayres Associates (1983), *Cottonwood Creek Drainage Basin Planning Study*.

Baker, V.R., R.C. Kochel, and P.C. Patton, eds. (1988), *Flood Geomorphology*, p. 465-489, John Wiley & Sons, New York, New York.

Biedenharn, D. S., P. G. Combs, G. J. Hill, C. F. Pinkard, Jr., and C. B. Pinkston (1989), "relationship between channel migration and radius of curvature on the red river," in *Sediment Transport Modeling*, p. 536.

Binnter, L., Y. Niño, and M. García (1994), "Mathematical models to assess stream dynamics," in *Hydraulic Engineering'94*, p. 391.

Bond, L. A. (1997), *Community Rating System Credit for Mapping and Management of Areas with Uncertain Flow Paths,* Engineering Report to Community Task Force.

Borah, D. K. and M. S. Dashputre (1994), "Field evaluation of the sediment transport model stream with a bank erosion component," *Hydraulic Engineering'94*.

Borah, D. K. and P. K. Bordoloi (1989), "Stream bank erosion and bed evolution model," in *Sediment Transport Modeling*.

Brabets, T. P. (1994), *Scour Assessment at Bridges from Flag Point to Million Dollar Bridge, Copper River Highway, Alaska,* Water Resources Investigations Report 94-9073.

Bryan, B. A. (1989), *Channel Evolution of the Hatchie River near the U. S. Highway 51 Crossing in Lauderdale and Tipton Counties, West Tennessee,* USGS Open-File Report 89-598.

Burkham, D. E. (1972), *Channel Changes of the Gila River in Safford Valley, Arizona 1846-1970*, USGS Professional Paper 655-G.

Chang, H. H. (1984), "Modeling of river channel changes," ASCE Journal of Hydraulic Engineering, vol. 110, No. 2, p.157-172.

CH2M Hill, and R. H. French (1992), *Alluvial Fan Data Collection and Monitoring Study for the Flood Control District of Maricopa County,* Engineering Report to Flood Control District of Maricopa County.

CH2M Hill and J. E. Fuller/Hydrology & Geomorphology, Inc. (1996), *River Stability Study, Virgin River, Santa Clara River, and Ft. Pierce, Washington, vicinity of St. George, Utah,* prepared for City of St. George, Utah.

City of Austin (1997), *Technical Procedures for the Watershed Erosion Assessments*, prepared by Raymond Chan & Associates, Austin, Texas.

Comes, B. M. (1990), "Identification techniques for bank erosion and failure processes," in *Hydraulic Engineering*, p. 193.

Copeland, R, R., and W. A. Thomas (1996), *Sediment Impact Assessments Using the Hydraulic Design Package-SAM*, USACE Waterway Experiment Station, Proceedings of 6th Federal Interagency Sedimentation Conference, vol. 1, p. 370.

Daniel, J. F. (1971), *Channel Movement of Meandering Indiana Streams,* USGS Professional Paper 732-A.

Darby, S. E. and C. R. Thorne (1994), "A physically based model of channel widening," Hydraulic Engineering '94, p. 944.

Darby, S. E. and C. R. Thorne (1994), "Prediction of tension crack location and riverbank erosion hazards along destabilized channels," *Earth Surface Processes and Landforms*, vol. 19, p. 233.

Darby, S. E. and C. R. Thorne (1996), "Numerical simulation of widening and bed deformation of straight sand-bed rivers. I: Model development," ASCE Journal of Hydraulic Engineering, vol. 122, No.4.

Darby, S. E., C. R. Thorne, and A. Simon (1996), "numerical simulation of widening and bed deformation of straight sand-bed rivers. II: Model evaluation," ASCE Journal of Hydraulic Engineering, vol. 122, No. 4, p. 194.

Darby, S. E. and C. R. Thorne (1996), "development and testing of riverbank-stability analysis," ASCE Journal of Hydraulic Engineering, vol. 122, No. 8, p. 443.

Davis, R. J. and K. J. Gregory (1994), "A new distinct mechanism of river bank erosion in a forested catchment," Journal of Hydrology, vol. 157, No. 1, p. 1.

DeLong, L. L. (1986), "Extension of the unsteady one-dimensional open-channel flow equations for flow simulation in meandering channels with floodplains," in *Selected Papers in the Hydrologic Sciences*.

Eschner, T. R., Hadley, R. F., and Crowley, K. D. (1983), *Hydrologic and Morphologic Changes in Channels of the Platte River Basin in Colorado, Wyoming and Nebraska: A Historical Perspective,* Geologic Survey Professional Paper 1277-A.

Faye, R.E., W.P. Carey, J.K. Stamer, and R.L. Kleckner (1980), *Erosion, Sediment Discharge, and Channel Morphology in the Upper Chattahoochee River Basin, Georgia,* USGS Professional Paper 1107.

Federal Emergency Management Agency (1990), *Analysis of Stream Bank and Bluff Stability for Use in the Evaluation of Flood Insurance Claim Eligibility Under The Upton/Jones Amendment*, Washington, D.C.

Federal Interagency Stream Restoration Working Group (1998), *Stream Corridor Restoration Handbook*.

Graf, W. L. (1981), "Channel instability in a braided, sand bed river," Water Resources Research, vol. 17, No. 4, p. 1087.

Graf, W. L. (1983), "Flood-related channel change in an arid-region river," Earth Surface Process and Landforms, vol. 8, p. 125.

Graf, W. L. (1984), "A probabilistic approach to the spatial assessment of river channel instability," Water Resources Research, vol. 20, p. 953.

Grimm, M. (1996), "Applied geomorphology and floodplain management," Land and Water, March/April, p. 32.

Grissinger, E. H., and J. B. Murphey,. (1985), "Channel cross-section changes in Mississippi's Goodwin Creek," Journal of Soil and Water Conservation, January-February. , p. 148-153.

Hagerty, D. J., and M. F. Spoor (1989), "Alluvial Stream Bank Erosion -- A 10-Year Study," in *Sediment Transport Modeling*, p. 594.

Hagerty, D. J., and M. N. French (1988), "An Investigation into Causes of Bank Caving," in *Critical Water Issues and Computer Applications*, p. 254.

Hasegawa, K. (1989), "Universal bank erosion coefficient for meandering rivers," ASCE Journal of Hydraulic Engineering, vol. 155, No. 6, p. 744.

Hey, R. D. (1990), "Environmental river engineering," Journal of the Institute of Water and Environmental Management, vol. 4, p. 358.

Hjalmarson, H. W., and S. P. Kemna (1991), *Flood Hazards of Distributary-Flow Areas in Southwestern Arizona,* USGS Water-Resources Investigations Report 91-4171.

Holtorff, G. (1989), "The Formation of Meandering and Braided Channels," in *Sediment Transport Modeling*, p. 70.

Jacobson, R. B., and K. Oberg (1997), *Geomorphic Changes on the Mississippi River Flood Plain at Miller City, Illinois as a result of the flood of 1993*, USGS Circular 1120-J.

Jay, D. A., and C. A. Simenstad (1996), "Downstream effects of water withdrawal in a small, high-gradient basin: Erosion and deposition on the Skokomish River delta," *Estuaries*, vol. 19, No. 3, p. 501.

Johannesson, H, and G. Parker (1985), *Computer Simulated Migration of Meandering Rivers in Minnesota*, Project Report 242, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Jones, J. A. A. (1989), "Bank erosion: A review of British research," *Hydraulic Engineering*'89, p. 283.

Karlinger, M. R., T. R. Eschner, R. F. Hadley, and J.E. Kircher (1983), "Relation of channel-width maintenance to sediment transport and river morphology: Platte River, South-Central Nebraska," in *Hydrologic and Geomorphic Studies on the Platte River Basin*, p. E1.

King County Surface Water Management Division (1993), *Green River Channel Migration Study*.

King County Surface Water Management Division (1996), *Channel Migration in the Three Forks Area of the Snoqualmie River*.

Kircher, J. E. (1983), *Interpretation of Sediment Data for the South Platte River in Colorado and Nebraska, and the North Platte and Platte Rivers in Nebraska,* Geologic Survey Professional Paper 1277-D.

Kovacs, A. and G. Parker (1994), *Erosion of Steep River Banks and Time Evolution Towards Equilibrium Channel Shape*, in Engineering Mechanics, p. 896.

Kresan, P.L. (1988), "The Tucson, Arizona, flood of October 1983 - Implications for land management along alluvial river channels," in Baker, V.R., R.C. Kochel, and P.C. Patton (eds.), *Flood Geomorphology*, p. 465-489, John Wiley & Sons, New York, New York.

Lagasse, P. F., J. D. Schall, and M. Peterson (1985), "Erosion risk analysis for a southwestern arroyo," Journal of Urban Planning and Development, vol. 111, No. 1.

Lawler, D.M. (1993), "The measurement of river bank erosion and lateral channel change: A review," Earth Surface Processes, vol. 18, p. 777.

Liou, J. (n.d.), *Evaluation of Existing Mathematical Fluvial Models for National Flood Insurance Studies,* 329 p.

Lohnes, R. A. (1991), "A method for estimating land loss associated with stream channel degradation," Engineering Geology, vol. 31, p. 115.

MacDonald, T. E., G. Parker, and D. P. Leuthe (1991), *Inventory and Analysis of Stream Meander Problems in Minnesota*, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

MacMurray, H. L., and M.N.R. Jaeggi (1990), "Modeling erosion of sand and silt bed river," ASCE Journal of Hydraulic Engineering, vol. 116, No. 9.

Madej, M. A., W. E. Weaver, and D. K. Hagans (1994), "Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA," Environmental Management, vol. 18, No. 2, p. 235-250.

March, D. E., S. R. Abt, and C. R. Thorne (1993), "Bank stability analyses versus field observations," in *Hydraulic Engineering'93,* p. 881.

McCaffrey, W. F., J. C. Blodgett, and J. L.Thornton (1988), *Channel Morphology of Cottonwood Creek near Cottonwood, California, from 1940 to 1985,* USGS Water-Resources Investigations Report 87-4251.

Millar, R. G., and M. C. Quick (1994), Equilibrium geometry of channels with cohesive banks, in *Hydraulic Engineering'94,* p. 964.

Neill, C. R., and E. K. Yaremko (1989), "Identifying causes and predicting effects of bank erosion," in *Hydraulic Engineering'89*, p. 101.

Newson, M., and J. Lewin (1991), "Climatic change, river flow extremes and fluvial erosion - scenarios for England and Wales," Progress in Physical Geography, vol. 15, No. 1.

Odgaard, A. J. (1987), "Streambank erosion along two rivers in Iowa," Water Resources Research, vol. 23, p. 1225.

Odgaard, A. J., S. C. Jain, and D. J. Lutzbetak (1989), "Hydraulic mechanisms of riverbank erosion," in *Hydraulic Engineering'89*, p. 112.

Osman, A. M., and C. R. Thorne (1988), “Riverbank stability analysis I: Theory,” ASCE Journal of Hydraulic Engineering, vol. 114, No. 2, pp.134-150.

Osterkamp, W.R., L.J. Lane, and G. R. Foster (1983), *An Analytical Treatment of Channel Morphology Relations,* USGS Professional Paper 1288.

Parsons Brinkerhoff, Quade, & Douglas (1997), *Methodology for Predicting Channel Migration*, Proposal presented to National Cooperative Highway Research Program (NCHRP), Project No. 24-16.

Parker, J. T. C. (1995), *Channel Change and Sediment Transport in Two Desert Streams in Central Arizona, 1991-92*, USGS Water Resources Investigation Report 95-4059.

Parker, J. T. C. (1995), *Channel Change on the Santa Cruz River, Pima County, Arizona, 1936-86*, USGS Water-Supply Paper 2429.

Pemberton, M., J. Bradbury, P. Cullen, and G. Dixon (1995), "Monitoring and management of streambank erosion and natural revegetation on the Lower Gordon River, Tasmanian Wilderness World Heritage Area, Australia," Environmental Management, vol. 19, No. 2, p. 13.

Pizzuto, J. E. (1990), "Numerical simulation of gravel river widening," Water Resources Research, vol. 26, No. 9, p. 1971.

Rhoads, B. L. (1990), "The impact of stream channelizations on the geomorphic stability of an arid-region river," National Geographic Research, vol.6, No. 2, p. 157.

Romero-Díaz, M. A., F. Cabezas and F. López-Bermúdez (1992), "Erosion and fluvial sedimentation in the River Segura basin (Spain)," Catena, vol. 19, p. 379.

Rosgen, D. L. (1994), "A classification of natural rivers," Catena, vol. 22, No. 3, p. 169.

Sevon, W.D. (1989), "Erosion in the Juniata River drainage basin, Pennsylvania," Geomorphology, May, p. 303.

Shan S. F., ed. (1988), *Twelve Selected Computer Stream Sedimentation Models Developed in the United States*, Federal Energy Regulatory Commission Report, vols. 1 & 2.

Shannon and Wilson, Inc (1991), *Tolt and Raging Rivers Channel Migration Study, King County, Washington,* report prepared for King County Surface Water Management Division, Seattle, Washington, April.

Shields, Jr., F. D., A. J. Bowie, and C. M. Cooper (1995), "Control of streambank erosion due to bed degradation with vegetation and structure," Water Resources Bulletin, vol. 31, p. 475.

Shields, Jr., F. D., S. S. Knight and C. M. Cooper (1995), "Rehabilitation of watersheds with incising channels, Water Resources Bulletin," vol. 31, No. 6, p. 971.

Simon, A. (1989), "The discharge of sediment in channelized alluvial streams, Water Resources Bulletin," vol. 25, No. 6, p. 1177.

Simon, A. (1994), *Gradation Processes and Channel Evolution in Modified Tennessee Streams: Process, Response, and Form,* USGS Professional Paper 1470.

Simon, A. and C. R. Hupp (1986), *Channel Widening Characteristics and Bank Slope Development Along a Reach of Cane Creek, West Tennessee,* USGS Water-Supply Paper 2290.

Simon, A., and C. R. Hupp (1992), *Geomorphic and Vegetative Recovery Processes Along Modified Stream Channels of West Tennessee,* U.S.G.S Open Fille Report 91-502.

Simon, A., M. Rinaldi, and G. Hadish (1996), "Channel evolution in the loess area of the Midwestern United States," in Proceedings of the 6th Federal Interagency Sedimentation Conference, vol. 1, p. 386.

Simons, Li & Associates, Inc. (1985), *Design Manual for Engineering Analysis of Fluvial Systems*, prepared for Arizona Department of Water Resources, Tucson, Arizona.

Sinclair, K., and R. C. Ball (1996), "Mechanism for global optimization of river networks from local erosion rules," Physical Review Letters, vol. 76, No. 18, p. 3360.

Somfai, E., and L.M. Sander (1997), "Scaling and river networks: A Landau theory for erosion," Physical Review, vol. 56, No. 1, p. 56.

Spoor, M. F. (1989), "International research on mechanics of river bank erosion -- A summary overview," in *Hydraulic Engineering*, p. 1179.

Sun, T., P. Meakin, T. Jossang and K. Schwarz (1996), "A simulation model for meandering rivers," Water Resources Research, vol. 32, No. 9, p. 2937.

Thorne, C. R., and A. M. Osman (1988), “Riverbank stability analysis II: Applications,” ASCE Journal of Hydraulic Engineering, vol. 114, No. 2, p. 151-172.

Thorne, C.R., and V.R. Baghirathan (1994), "Blueprint for morphologic studies," in *The Variability of Large Alluvial Rivers*, Schumm, Stanley A, ASCE Press, Chapter 20, p. 441.

Thorne, C. R., R.G. Allen, and A. Simon (1996), "Geomorphological river channel reconnaissance for river analysis, engineering and management," Transactions of the Institute of British Geographers, vol. NS 21, p. 469.

Tsay, K. D., and E. M. Laursen (1990), "Predicting stream width and bank retreat," in *Hydraulics/Hydrology of Arid Lands (H2AL)*, p. 447.

Turnipseed, D. P. (1993), *Lateral Movement and Stability of Channel Banks near Two Highway Crossings in the Pascagoula River Basin in Mississippi,* USGS Water Resources Investigation Report 93-4131.

Turnipseed, D. P. and K. Van Wilson, Jr. (1992), *Channel and Bank Stability of Standing Pine Creek at State Highway 488 near Freeny, Leake County, Mississippi,* USGS Open File Report 92-112.

US Army Corps of Engineers (1981), *The Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section32, Public Law 93-251*, Report to the US Congress.

US Army Corps of Engineers (1994), *Channel Stability Assessment for Flood Control Projects,* Engineer Manual EM 1110-2-1418.

US Army Corps of Engineers (1997), *Bank Erosion Field Survey Report of the Upper Mississippi and Illinois Waterway,* USACE St. Paul, Rock Island, and St. Louis Districts.

Van Wilson, Jr., K. and D. P. Turnipseed (1994), *Geomorphic Response to Channel Modifications of Skuna River at the State Highway 9 Crossing at Bruce, Calhoun County, Mississippi,* USGS Water Resources Investigation Report 94-4000.

Whiting, P. J. and W. E. Dietrich (1993), "Experimental studies of bed topography and flow patterns in large-amplitude meanders 1: Observations," Water Resources Research, vol. 29, No. 11, p. 3615.

Whiting, P. J. and W. E. Dietrich (1993), "Experimental studies of bed topography and flow patterns in large-amplitude meanders 2. Meanders," Water Resources Research, vol. 29, No. 11, p. 3605.

Zongxin, C. (1988), "Characteristics of soil erosion on the upper Changjiang river and preventive measures," Natural Exploration, vol. 4, p. 51.