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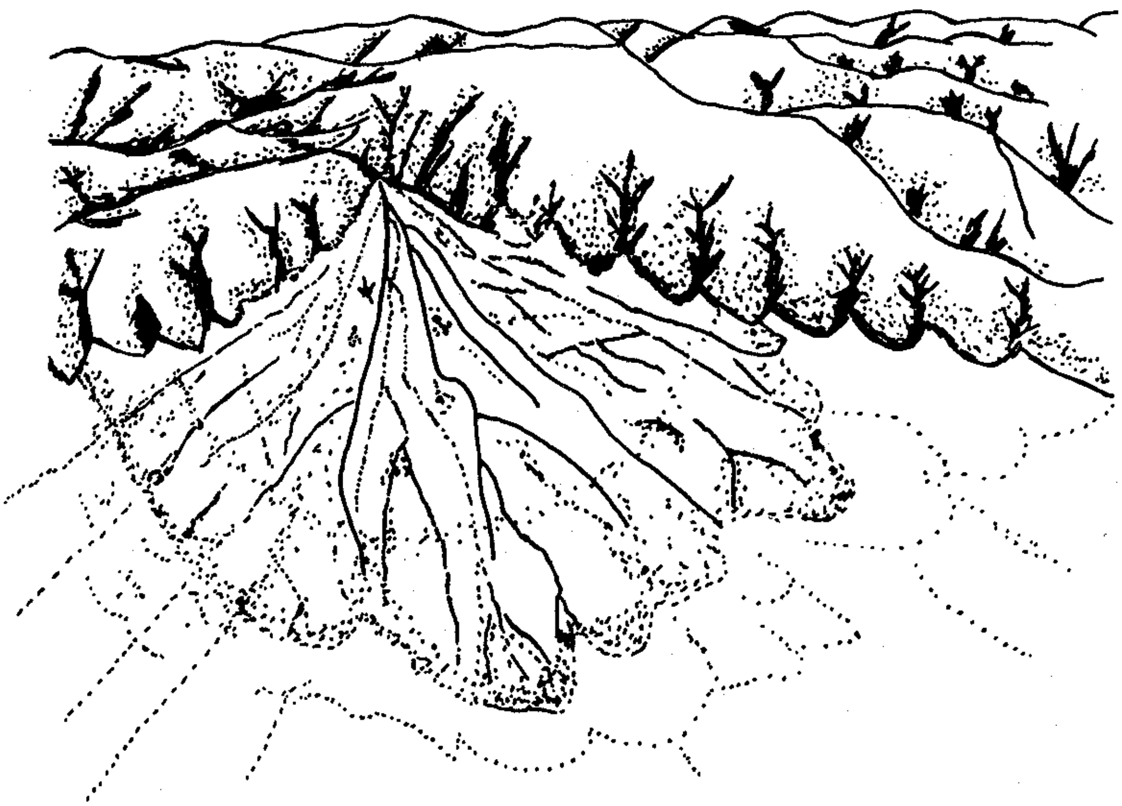
FLOOD PLAIN MANAGEMENT TOOLS FOR ALLUVIAL FANS



FINAL REPORT

Study Findings

November 1981

Anderson - Nichols & Company, Inc. Palo Alto, Calif.
assisted by
Colorado State University & Flood Loss Reduction Associates

FLOOD PLAIN MANAGEMENT TOOLS

FOR ALLUVIAL FANS

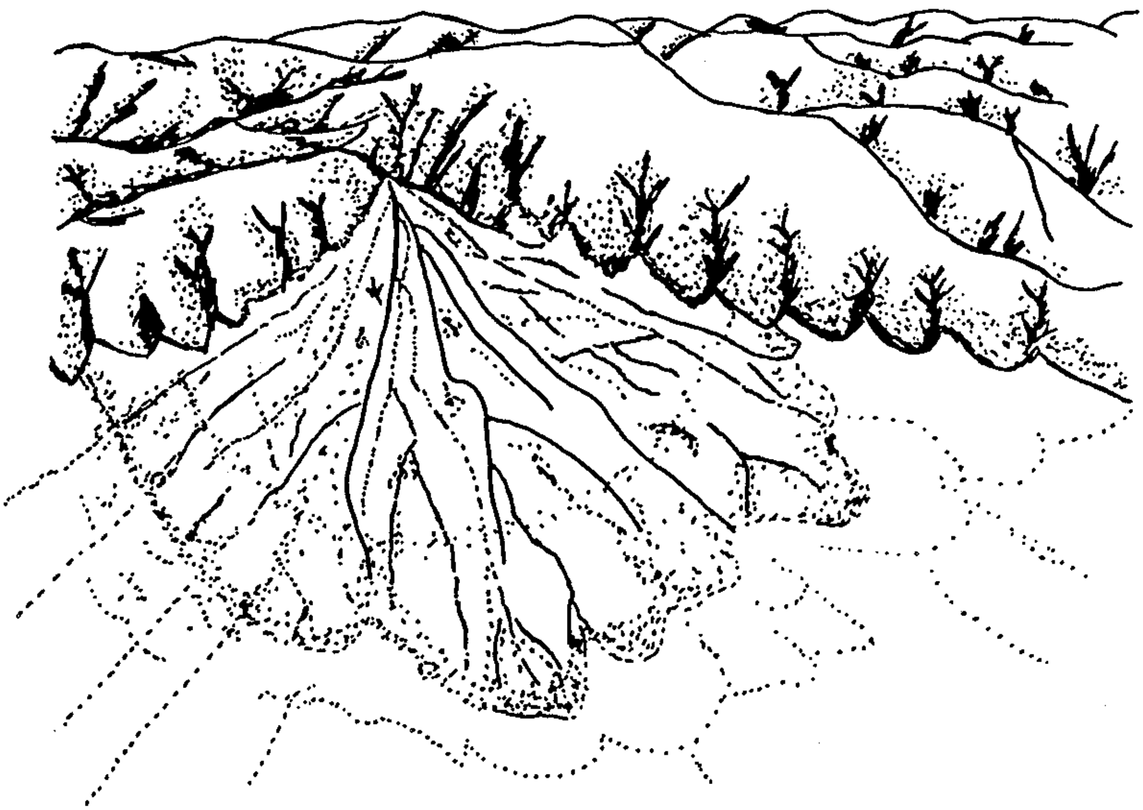


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TABLE OF CONTENTS

PART I: STUDY FINDINGS

PART II: STUDY DOCUMENTATION

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES (continued)

LIST OF FIGURES
(continued)

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1 INTRODUCTION

1.1 Background

Flood losses are a serious problem in the United States. Some seven percent of the nation's land area is subject to flooding. Such areas, located mostly along rivers, lakeshores and seacoasts, contain a disproportionaltely large share of the nation's population and wealth. These flood-prone lands are found in every state, even in the arid southwest where arroyos, dry streams and alluvial fans are subject to flash floods. The unwise use of such lands makes floods --or the threat of floods--a perennial fact of life in thousands of communities. The devastating effects of floods have accounted for approximately 75 percent of all presidential disaster declarations and for approximately 90 percent of all damages from natural disasters.

Floods cause enormous economic losses. The direct damages average almost $2.2 billion annually and are increasing. Additional billions go yearly for disaster relief, flood protection and other flood related costs. Floods also cause great suffering and hardship. During the period 1970-1979, flood related deaths averaged 200 annually and on the average, about 80,000 people are forced from their homes on the flood plains each year.

Floodplain Management

The present concepts of flood plain management are a result of the continuing adaptation of public policy to changing needs and conditions. They reflect a shift in approach based on the lessons of experience.

Prior to the 1960's, the national approach to dealing with floods consisted almost exclusively of the construction of dams, levees and other structures to impound or divert flood waters. The overall impact of flood plain developments or the flood control projects protecting them received little attention.

It was apparent by the mid-60's that, although flood control projects prevented large amounts of damage, this traditional approach required revision for several reasons:

- Developments were taking place on flood plains faster than projects could be constructed to protect them.

- The availability of flood protection through publicly funded projects proved an inducement to further development, frustrating all hope of catching up with the growing flood problem.

- The cost of the larger and larger flood control projects required to protect the additional development was becoming exorbitant, putting an unfair tax burden on the general public to subsidize those who used the flood plain without concern for the consequences.

- Upstream land development and channelization was increasing downstream flood hazards.

- Costs for disaster relief programs were rapidly increasing.

- Existing flood control structures were decreasing in effectiveness as flood plain development continued.

- The natural and beneficial values of flood plains were being rapidly diminished by both development and flood protection projects.

This recognition of the need for change led to emergence of a broader approach. This approach was designed to combat flood problems more effectively and to reconcile the objective of flood loss reduction with that of preserving and enhancing natural flood plain values. This new approach was based on:

- Controlling development of flood plains through regulatory measures and withholding financial assistance from government for new developments and improvements to existing developments in areas subject to flooding.

- Using a wider range of tools to reduce flood losses to both existing and new structures and emphasizing use of those tools causing less severe environmental impacts.

- Assumption by state and local governments and private property owners of a greater share of responsibility for the consequences of flood plain development.

- Incorporating concern for natural values into decisions about flood plain development and projects for flood loss reduction.

This new approach was implemented over a period of several years by several legislative acts and presidential orders. The most important of these were the National Flood Insurance Act of 1968 (as amended), the Water Resources Development Act of 1974, the Disaster Relief Act of 1974, Executive Orders 11988 and 11990, and the Principals, Standards and Procedures for Water and Related Land Resources Planning.

National Flood Insurance Program

The National Flood Insurance Act of 1968 (Title XIII of Public Law 90-448, Public Law 93-234, Public Law 95-128) is a key element in this new approach to flood loss reduction. It provides for identifying the more serious flood hazard areas in the nation and for a program whereby residents in those areas can purchase insurance against flood losses if the community participates in the program. Communities must regulate flood plain development to be eligible for participation. The federal government heavily subsidizes insurance costs to make premium rates affordable. Also, federal grants, loans and other financial assistance are denied in flood hazard areas of non-participating communities. In addition, the program provides assistance in hazard mitigation including relocation of severely or repetitively damaged structures.

A program of this type has been disucssed since the mid-30's and enacted--although not funded--in the 50's. Its implementation in 1968 signalled a major step forward in the rational management of flood-prone lands. At present, about 18,000 communities are participating in the program.

Implementation of the National Flood Insurance Program has proceeded since 1968 so as to obtain the maximum effect in the least time with the resources available. Efforts were focused first on areas subject to riverine flooding because that case was the best understood from the techinical standpoint and because riverine flooding affected the greatest number of communities and people. The program has subsequently expanded toward its full authorized purview by incremental additions as necessary research was accomplished, funding made available, or unusual opportunities presented. The principal thrusts have been toward dealing with more types of losses (i.e., coastal flooding, mud slides and flood caused erosion), special types of areas (i.e., alluvial fans, subsidence areas), and toward strengthening of mitigation efforts.

Alluvial Fans

Extension of the National Flood Insurance Program to alluvial fans is important for several reasons including the large number of fans which exist, the rapid growth of development on fans, and the high risk of severe damage to those developments. Throughout much of the Western and Southwestern United States, alluvial fans are favored for development because of the availability of attractive building sites, access to water and other ammenities.

Flood problems on alluvial fans are unusual in several respects. Flows tend to have a high velocity, undergo unpredictable changes in direction, and carry large amounts of debris and sediment. Moreover, the characteristics of flow may change drastically over relatively short distances between the upper and lower portions of a fan. Even soils are different from most other areas, tending to be easily eroded and highly porous. These and other differences have hampered applicaion of the flood insurance program to alluvial fans because they make it difficult to:

- Assess risk in terms of frequency of flooding at any specific location on the fan and, consequently, to determine which areas should fall under various sanctions of the program.

- Identify what flood loss reduction measures are likely to prove appropriate and cost effective in various circumstances such as the existing extent of development and particular location on a fan.

- Determine accurate stage-damage relationships as a basis for setting actuarial rates.

Some work has been accomplished toward overcoming the problem of determining flood risk on alluvial fans. A methodology now exists for assigning a statistical measure of flood risk. This study is focused on the potential effectiveness of various flood loss reduction measures.

1.2 Study Scope and Goals

A study of the effectiveness of flood plain management tools for use of alluvial fans was accomplished under contract EMW-C-0175 with the Federal Emergency Management Agency. The general goals of this study are:

1. determination of the effectiveness of nonstructural and structural flood plain management measures in reducing flood losses in different types of alluvial fans;

2. recommendation of preferred management measures for specific alluvial fan conditions;

3. development of a process for selecting management measures which considers all important aspects of flood behavior and fan conditions;

4. provision of information necessary for FEMA to develop environmental and inflationary impact assessments for management tools which are

specified in future regulations; and

5. the development of damage information for structures on fans which will assist the Flood Insurance Administration in determining insurance risks where management tools are used.

It became clear early in the study that additional, subordinate goals should be set to ensure that the selection of management tools is based on sound knowledge of flood processes on fans. These goals are:

1. the completion of a survey of developed or developing alluvial fans to identify all key fan and watershed characteristics;

2. the investigation of hydraulic and sedimentation processes on fans using both a literature search and physical model tests of idealized alluvial fan conditions; and

3. the development of a tentative and qualitative methodology for identifying the location and severity of flood conditions and flood hazards which must be managed.

The scope of this study was restricted to analyses which were directly related to evaluation and application of management tools. Investigation of flood processes on fans was limited to developing data necessary to the selection and design of measures. Evaluation of the existing FIA alluvial fan methodology and alternative hazard quantification procedures have not been pursued. The development of design principles and standards for management tools was also beyond the study scope. Future efforts, including the development of a management handbook, may be needed to provide adequate information to communities on alluvial fans.

1.3 Study Approach

The state of the art for flood plain management on fans is poorly developed at present. A good deal of uncertainty exists regarding the nature and severity of flood processes and flood hazards on fans. Engineering techniques used to identify and quantify these hazards are in an early stage of development and, as a result, the design and implementation of flood plain management measures for fans has been uncoordinated and often ineffective.

The flooding process on fans is highly complex and, at present, poorly understood by planners and engineers alike. Few detailed field observations of fan flooding and virtually no quantitative measurements of depths and velocities have been made. Existing analytic and numerical models for flood hydraulics and sedimentation do not adequately represent these processes on fans. The interations between fan and watershed conditions and hydraulic behavior are poorly documented. Hence, defensible methodologies available for achieving the goals established in Section 1.2 are limited.

A research program which incorporated a literature search, field studies, and physical model studies was selected as being a balanced, state-of-the-art approach to the problem. The literature search was designed to survey the related fields of arid-region hydrology, river mechanics, sediment transport, and flood plain management and provide the basis for field and laboratory efforts. Field study locations were selected to represent the widest possible range of fan and watershed charateristics and to provide case studies of flood plain management tool applications in existing communities. A program of physical model studies was developed to provide (1) quantitative data on flood behavior, including depth, velocity, and sediment transport rates; (2) qualitative and quantitative relationships between fan and watershed conditions and flood processes; (3) models of flood plain management tool applications and operations; and (4) analyses of the effectiveness of such tools.

Physical model studies were selected as the only viable short-term means for investigating phenomena which have only been cursorily documented in the field. As discussed in Part II, Section 2 of this report, such use is justified despite a recognized lack of data suitable for model verification. Physical models have, in the past, been used successfully to study complex hydraulics, fluid mechanics, and sedimentation problems where no analytic or field data was available. Many theories about erosion, sed iment transport and river mechanics have been developed based on physical model studies and such studies have proven to be essential to the improvement of our understanding of the responses of complex natural systems. Care has been taken to verify each model used in the present study, wherever possible, against observed flood behavior. One model was designed to be a scale replica of an actual fan and the results of prototype flood simulations were compared with field observations of a historical flood. Comparisons between model behavior and hydraulic principles were made to verify the reasonableness of the results.

As an adjunct to the study of fan flood processes and management tool effectiveness, analyses of management tool environmental, social, economic, and inflationary impacts were made. Tentative, generalized curves relating flood depths and velocities to structure damages on fans were also constructed to serve as preliminary guides for insurance rate establishment.

The study tasks covered by this report are as follows:

1. design, construct, and operate a physical model of idealized fan conditions and collect data on hydraulic and sedimentation processes during simulated flood events;

2. design, construct, and operate a physical model of a prototype fan, specifically the Rancho Mirage fan, and test whole-fan management measure performance;

3. design, construct, and operate physical models of local developed areas, such as subdivisions, and test the performance of local structural measures and nonstructural measures;

4. verify the qualitative accuracy of the models by comparing a model simulation of the 1979 flood event at Rancho Mirage with actual flood behavior;

5. develop recommendations for management tool applications based on field studies and physical model results;

6. develop a methodology for selecting management tools;

7. identify the environmental social, economic, and inflationary impacts of management tools;

and

8. develop curves which relate percent damage estimates for residential structures on fans to the depth and velocity of the flow.

1.4 Report Content and Organization

This final report discusses all aspects of the study, but focuses specifically on the physical model studies and analysis of management tool effectiveness. The project Study Plan, submitted in October, 1980, presented a detailed discussion of the tasks which were to be accomplished and the expected end products. The State-of-the-Art Report, submitted in December, 1980, provided a detailed review of historical flooding on fans, key characteristics of fans, case studies of communities which have experienced fan flooding, and existing applications of flood plain management tools.

Part I of this report presents the study findings and conclusions and includes an executive summary. Discussion of alluvial fan characteristics, flood dynamics, flood hazards, management tool effectiveness, flood plain management, damage risk on fans, and management tool impacts are provided. Part II provides documentation of physical model design, contruction, and operation, as well as documentation of experimental results. The techniques used to develop impact matrices and damage curves are also discussed.

2. EXECUTIVE SUMMARY

The following discussions summarize the principal findings of this study.

2.1 Alluvial Fan Characteristics

1. Three types of depositional landforms, fans, washes, and aprons, are often confused. Each has different flooding characteristics. The focus of this study is on fans.

2. Alluvial fan morphologic, hydrologic, and hydraulic characteristics vary widely between fans. Consequently, the extent, severity, and behavior of floods on fans depends heavily on individual characteristics.

3. Key watershed and fan characteristics which influence fan flood behavior are:

- watershed slope;
- watershed soil type and vegetation;
- forest fire frequency;
- rainfall intensity and duration;
- fan slope and topographic shape;
- existence of an entrenched channel;
- apex discharge (hydraulic) conditions;
- fan sediment type and vegetation; and
- the location, density, geometry of development on the fan.

4. Development pressures are substantial on many fans in the western and southwestern parts of the U.S. Fans adjacent to urban centers are already experiencing rapid

development. Hence, the potential for significant future flood damages on fans is high.

5. A recommended approach to identification of key fan characteristics is suggested:

- perform a field survey;
- develop detailed topographic mapping;
- obtain geologic and flood histories of the fan; and
- classify the fan according to the key characteristics.

2.2 Flood Dynamics

1. All watercourses on fans are ephemeral, with severe flash floods occurring sporadically. Channel patterns and inundation zones often change with each flood. Sediment erosion and deposition occur rapidly during floods and quickly alter channel geometries.

2. Three hydraulic zones can be identified on many fans:

- channelized zone, near the apex, where a single definable channel exists;
- braided zone, a transition area where the channel becomes unstable and multiple sinuous flow paths form; and
- sheet flow zone, where the flow spreads laterally and is very shallow.

3. Two time scales are of importance in fan flood dynamics:

- geologic time (millenia), during which the flow paths wander across a fan and the fan aggrades uniformly; and

- human time, which encompasses the typical planning horizon (100 years).

Fan flood behavior will be unstable over geologic time, but may be consistent over human time due to channel entrenchments or other restrictions on flood pathways. Planners must, during the course of a flood investigation, determine whether existing flood channels are stable over human time.

4. Flood dynamics are strongly influenced by fan and watershed characterics. Watershed characteristics affect the duration, intensity, and total volume of water and sediment that enters the fan at the apex. Fan characteristics influence the direction, hydraulic behavior, amount of sediment scour or deposition, depth, and velocity of the flow.

5. Any analysis of flood behavior on fans must identify and consider fan and watershed characteristics.

2.3 Flood Hazards on Fans

1. The following types of flood hazards are common on fans:

- inundation;
- sediment deposition;
- scour and undermining;
- impact forces;
- hydrostatic and buoyant forces;
- high velocities; and
- unpredictable flow paths.

2. The severity of each hazard varies with location on the

fan and with the flood dynamics of each fan. Generalities about the importance of each hazard for all fans are not possible. Identified characteristics must be used to estimate severity and location of each hazard.

3. Relationships between fan and watershed characteristics and hazard severity are defined in this report.

4. A simple, uniform approach to quantifying hazards (depth and velocity of flow) will not adequately represent the broad range of fan and watershed characteristics which exists.

5. A recommmended approach to hazard identification and estimation is suggested:

- gather data on historical flooding;
- identify watershed and fan characteristics;
- estimate location and severity of hazards based on flood history and characteristics;
- delineate areas subject to flooding; and
- use empirical relationships to quantify flood depths and velocities within the flooded zone.

2.4 The Flood Management Process

1. A flexible, comprehensive approach to flood plain management which is considerably different than that used in riverine situations is needed because:

- the hydraulics of fan flooding are more complex and erratic than that of riverine floods;
- any management action or new development is likely to substantially change down-fan flood conditions; and

- more types of hazards are present in fan flooding than in riverine floods and many of the hazards are much more severe.

2. The application of flood management tools depends, in part, on the location, density and timing of development. When a master plan for development is created before a fan becomes urbanized, choices between tools can be made to maximized benefits. If development occurs without a master plan, the flood management choices are dictated by existing structures and development patterns.

3. Three development scenarios have been hypothesized, as follows:

- low density, where structures are elevated and minimum lot sizes are enforced;
- moderate density, where either developments are protected by local measures and allowed to occupy much of the fan or are protected by reserved floodways and levees and zoned to provide for the open space required; and
- high density, where whole-fan tools such as channels are used to confine and convey the flood from apex to toe.

These scenarios can be used to focus planning decisions on the effect of density on flood plain management.

2.5 <u>Selection of Flood Plain Management Tools</u>

1. The following management tools have either been used on fans in the past or have been shown in the physical model tests to be of significant value:

- debris basins or detention dams;
- levees and channels;
- drop structures;
- debris fences;
- local dikes;
- street orientation and design;
- elevation of structures;
- watershed management; and
- flood plain zoning.

2. The design of management tools must consider the following criteria:

- performance requirements specifying the depth, velocity, and discharge which must be controlled;
- identified flood hazards and the susceptibility of the tool to those hazards;
- physical constraints such as available land;
- public acceptance potential; and
- cost.

3. A management tool selection process which considers these criteria is recommended, as follows:

- identify the type and location of flood hazards;
- develop quantitative estimates of flood depth, velocity, and path;
- identify existing and future development through the creation of a master plan;
- develop alternative flood management scenarios using different tools;
- eliminate tools that are ineffective or will be severly damaged by flood hazards;
- estimate the cost of alternative scenarios; and

- select the most cost-effective tools.

4. Although FEMA regulations do not require whole-fan tools, several communities have used channels, levees, and or debris basin to control flooding. The reasons for such decisions include:

- protection of existing structures;
- maximization of developable land;
- protection of streets, utilities and landscape;
- lower overall cost; and
- availability of federal or state funding for structural measures.

5. Local tools such as local levees, street orientation, and elevation of structures appear to be most appropriate when existing and projected development densities are low to moderate. Such measures make incorporation of flood control costs into subdivision construction costs possible.

6. When individual structures or small blocks of homes are placed within existing subdivisions, flood protection systems for these homes must be coordinated with existing tools. In general, elevation on piles should be used to avoid blockage or diversion of floodwaters and increased downstream damage.

7. The following applications of management tools are recommended for subdivisions in each hydraulic zone on the fan and for the placement of single structures.

<u>Channelized Zone</u>

- Development prohibited unless whole-fan measures are implemented.

Braided Zone

- Basements and mobile homes prohibited.
- Streets aligned and designed to convey entire flood flow.
- Use of local dikes to direct flows into streets.
- Use of drop structures between homes built on high slopes to prevent excessive erosion.
- All management tools must be coordinated with tools in existing developments.
- Whole-fan management tools can be used instead of the above provisions.

Shallow Flooding Zone

- Elevation of structures on piles or armored fill.
- Street orientation to maximize flood conveyance.
- If up-fan subdivisions use depressed streets or channels to convey floods, these tools must be continued down to the fan toe.
- Use of drop structures between homes built on high slopes.
- Whole-fan management tools can be used instead of the above provisions.

Placement of Single Structures

- In undeveloped areas, can elevate on armored fill or use local dikes provided that no added flood damage to other structures results.
- In developed areas, local dikes, channels, and armored fill must tie in with existing flood control tools.
- Elevation on piles should be used if above criteria cannot be met.
- No single placement should be allowed in the channelized zone.

2.6 Assessment of Damage Risk on Fans

1. Curves relating flood depth and velocity to approximate damages to structures have been developed. The FIA riverine curves were used as a basis and modified to incorporate the effects of velocity and sediment transport.

2. The damage curves can be used with stage/ velocity/ frequency curves to roughly assess the expected annual flood damages on a fan. Due to the, at present, limited understanding of fan flood dynamics and the high variability of flood behavior on fans, flood damages obtained in this way should be used only as rough estimates of risk.

3. Damages at given depths are substantially higher on fans than in riverine floods, due to scour, sediment deposition, and impact forces on structures.

2.7 Assessment of Management Tool Impacts

1. Matrices were created to delineate the types of environmental, social, economic, and inflationary impacts which may result from the application of the various management tools. The direction and significance of each impact are indicated along with whether the impact is temporary or permanent.

2. The matrices are general in that they apply to all fans. However, specific fan situations may incur significantly different impacts.

3. Whole-fan, structural measures have the most significant economic and environmental impacts, both positive and

megative.

4. Local measures have minor environmental impacts except for aesthetics and have less significant economic impacts than whole-fan tools.

5. Inflationary impacts are minor for all tools.

6. Social impacts are generally minor, with the exception of the major impacts of flood plain zoning on communities.

3. ALLUVIAL FAN DESCRIPTION

Alluvial (depositional) formations have topographic, morphologic, and hydrologic characteristics which differ substantially from the characteristics of most river valleys. Since the hydraulic processes and the extent of flood hazards on fans depend on these characteristics, a summary of the geologic processes which form and reshape fans is included.

3.1 Fan Formation and Modification

Three types of alluvial landforms are often confused in flood studies; and yet have strikingly different flood behavior: alluvial fans, alluvial aprons, and washes. The differences between these landforms lie in how and when they develop. All three structures form at the base of steep, highly erodible mountain masses which are subjected to high intensity, short duration rainfall events. Such rainfall events dislodge large amounts of sediment and transport the sediment to the valley floor through ravines and channels. When the flood flows leave the confinement of the rock walls of the ravine, the water spreads out, becomes more shallow, and drops the majority of its suspended sediment load onto the valley floor. Over geologic time these deposits form a segment of a cone with its apex at the mountain front. Lines of maximum topographic slope radiate away from the apex and terminate at the valley floor, where original valley slopes again dominate. Characteristic slopes of fans depend on several factors, including size of sediment particles and concentration of sediment in the discharge from the watershed.

The term wash is commonly used to denote an alluvial valley floor. Such a valley can be thought of as an alluvial fan which is restricted in extent by the proximity of rock walls. Washes are found both in the section of ravine immediately above the apex of a fan and as separate formations where the channel draining the mountain watershed remains confined until it reaches a large river. Hence, washes are typically long, narrow formations. Contour lines on a wash are typically linear and perpendicular to the confining canyon walls.

A series of fans often form along the front of steep mountain ranges where numerous small watersheds are drained by individual streams. As these fans expand out onto the valley floor, the edges, or toes, of the fans coalesce into an alluvial apron. This apron area is characterized by nearly linear contour lines and a series of parallel ravines or arroyos which drain the apron. Figure 3.1 shows two fans and an apron in the Wenatchee, Washington area and illustrates the major features of these landforms. Further discussions of alluvial landforms can be found in Ritter (1973) and Scott (1973).

Flood flows on the three landforms behave quite differently, due to the obvious differences in morphology. Floods on washes are confined by the canyon walls and attain high velocities and depths of flow. The path of floods on a wash tends to be stable and predictable, so that the flood plain is often well defined. If a wash is very wide however, braiding and meandering of the channel may occur in a manner similar to that in river valleys. Sediment deposition tends to occur uniformly across the wash and permanent incision of one channel is rare.

Flooding on alluvial aprons is generally limited to the arroyos which drain the apron. The characteristics of flow

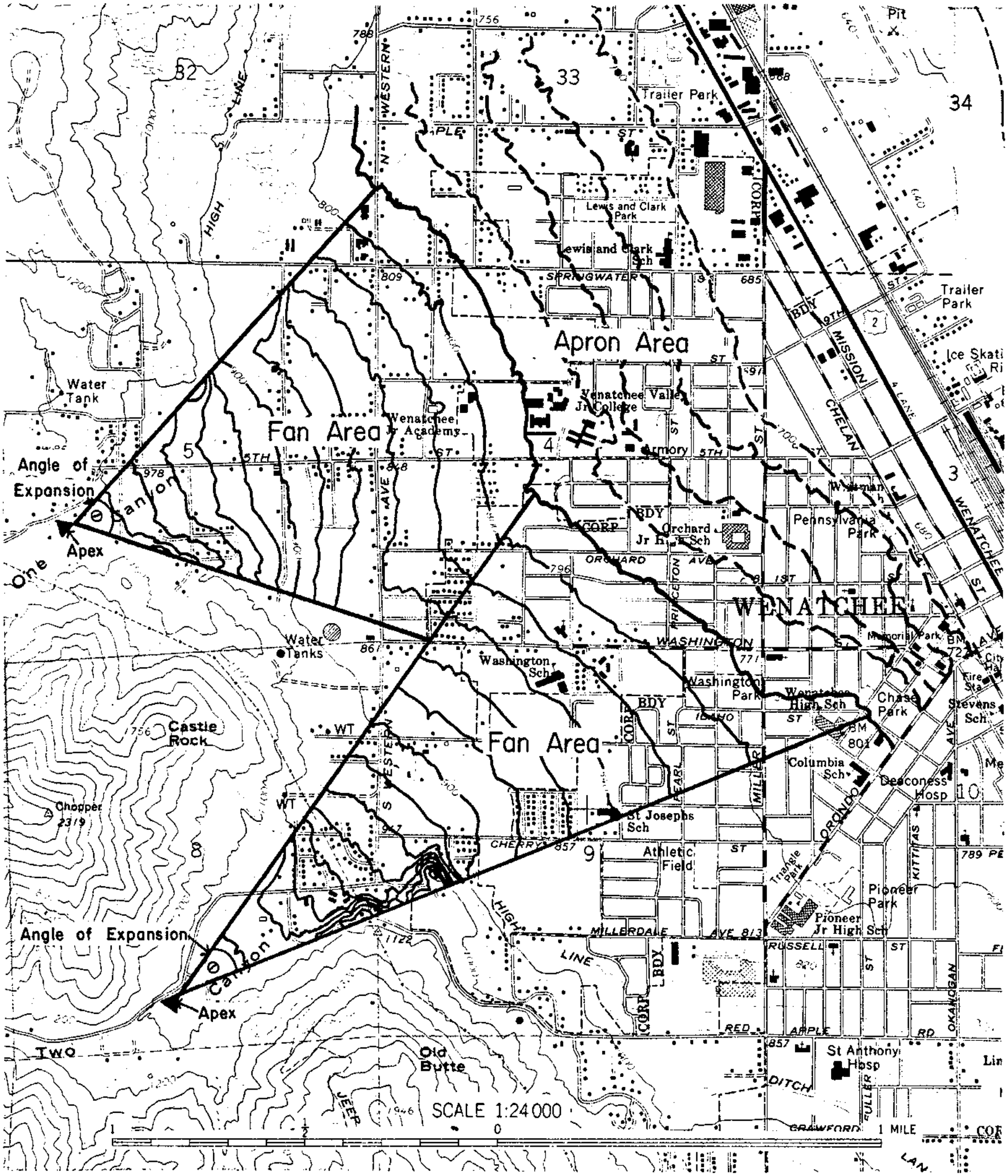


Figure 3.1 Topographic Characteristics of Typical Alluvial Fans and Alluvial Aprons (Wenatchee, Washington)

in the arroyos depend both on local drainage and on discharges from upstream alluvial fans.

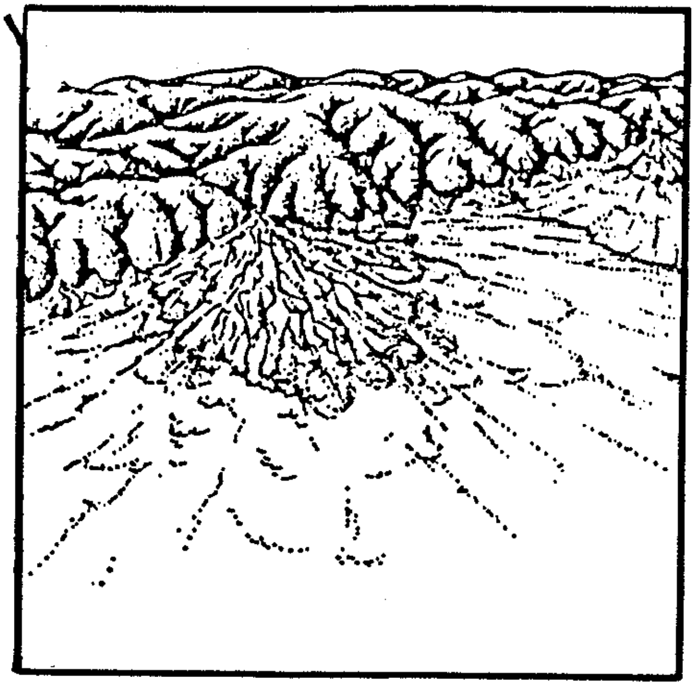
On alluvial fans, the location of the stream channel is often erratic, due to the rapid expansion of the width of the fan and the highly variable sediment load and flow rate of the discharges leaving the mountain watershed. Cutting of a channel near the apex may occur during one flood event, to be followed by channel backfilling in subsequent events. Conversely, a flood pathway may remain stable over several events, causing aggradation of that part of the fan. Eventually, the established channel will be filled by sediment and the flow will move to a new, lower elevation area in a process called an avulsion. Through multiple avulsions over geologic time, the fan aggrades uniformly so that it tends to exhibit the concentric, semi-circular contour lines shown in Figure 3.1.

If the sediment supply from the upstream watershed to a fan is reduced due to changes in rainfall patterns or increased vegetation, incision of a channel will begin at the apex. If the change in sediment supply is permanent, a stable channel or entrenchment of the fan surface results. Normal depositional patterns on the fan are altered by the entrenchment such that little deposition occurs near the apex and fan building commences at the downslope point where the entrenchment ends. A new, secondary fan is established with its apex at the end of the entrenchment and grows in the same pattern as the original fan.

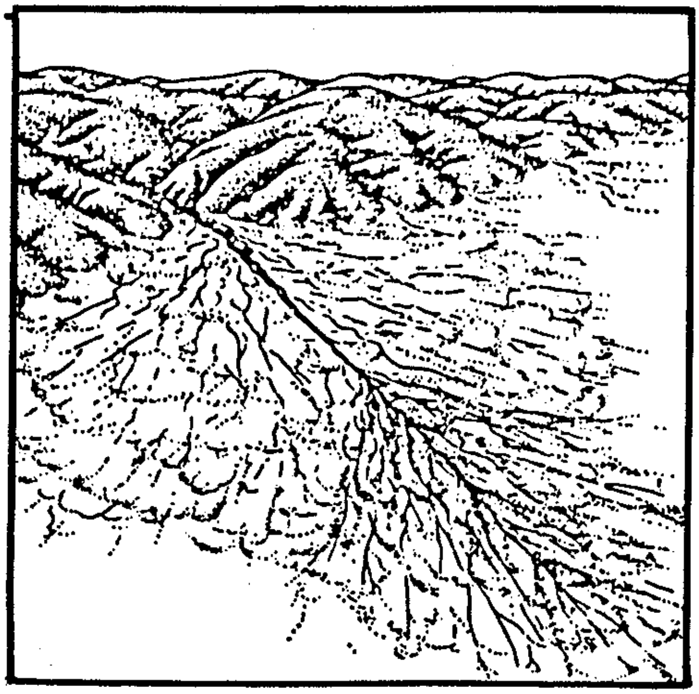
Extensive variation in alluvial fan morphology can be observed both between fans in different geographic and climatic areas and between adjacent fans in one valley. These variations make generalizations about fan structure as well as hydraulic behavior difficult. Geomorphologists often compare fan morphologies based on the relative age of fans. "Young" fans were formed by relatively recent tectonic motions and are fed by steep, sparsely vegetated watersheds with high sediment production and intense flooding events. Young fans exhibit steep slopes, uniform contours, and no incised channels. As a fan ages the depth of deposition at the apex increases and downcutting of feeder channels in the watershed above the apex continues. At some point in time, the upstream channels become lower in elevation than the apex and incision of a channel or fanhead trench occurs. Such a channel is likely to be permanent and will be cut deeper with time as watershed channels continue to erode.

A fanhead trench can also be created when sediment production in the watershed is reduced due to increased vegetation, reduction in rainfall intensity, or progressive exposure of less erodible materials. Since the sediment transport capacity or competence of the flow exceeds its sediment load at the apex, it will scour the fan surface and create an incised channel. As long as stream competence exceeds sediment supply, the channel deepening and widening will continue. A return to higher sediment productivity in the watershed, due to forest fires or increased rainfall, will often cause the channel to be backfilled and erratic flood channels and more uniform sediment deposition will again dominate.

Figure 3.2 provides a comparison between young, unentrenched fans (a) and entrenched fans (b). While the unentrenched fan forms a single smooth cone, the entrenchment conveys water and sediment down fan to a new apex area where deposition onto the new fan surface occurs. Hence the area of flooding and active sediment transport is shifted by the entrenchment away from the original fan apex. Such shifts in areas of active flooding have important impacts on development plans and flood risk analysis on fans.



ACTIVE, UNENTRENCHED FAN.



DEEPLY ENTRENCHED FAN.

FIGURE 3.2 MORPHOLOGY OF THE TWO FAN TYPES (FROM HOOKE, 1968)

3.2 Fan and Watershed Characteristics

A number of characteristics of upstream watersheds and fan surfaces can be readily identified in field surveys and then related to flood dynamics on fans. The following characteristics are thought to be key factors in alluvial fan flooding. The effect of these characteristics on flood dynamics will be discussed in Section 4. Figure 3.3 summarizes these characteristics.

Watershed Slope and Vegetation

The watersheds associated with alluvial fans in the semi-arid west tend to exhibit steep slopes and relatively sparse vegetation. The range of slopes includes values of 10% or less typical of Boise, Idaho and values of 50% and greater in the southwest. Sparsely vegetated watersheds are common in the Los Angeles area where fires repeatedly clear large areas of grass and brush. Watersheds in Boise tend to have substantial grass cover with some trees.

Sediment Size and Type

Typical sediment sizes on fans vary from less than 0.1 mm (very fine sands, silts, and clays) on mud flow fans such as those in the Los Angeles area to 4 mm (fine gravel) and larger on fans with very rocky watersheds. Mud flow fans also exhibit discontinuous deposits of very coarse gravels and even boulders which are transported by the highly viscous mud mixture. A gradation of sizes occurs naturally on fans, with the coarsest sizes being deposited near the apex and fine sizes being transported to the toe. A predominance of cohesive soils (high clay content) in the watershed and on the fan surface is typical of mud flow fans.

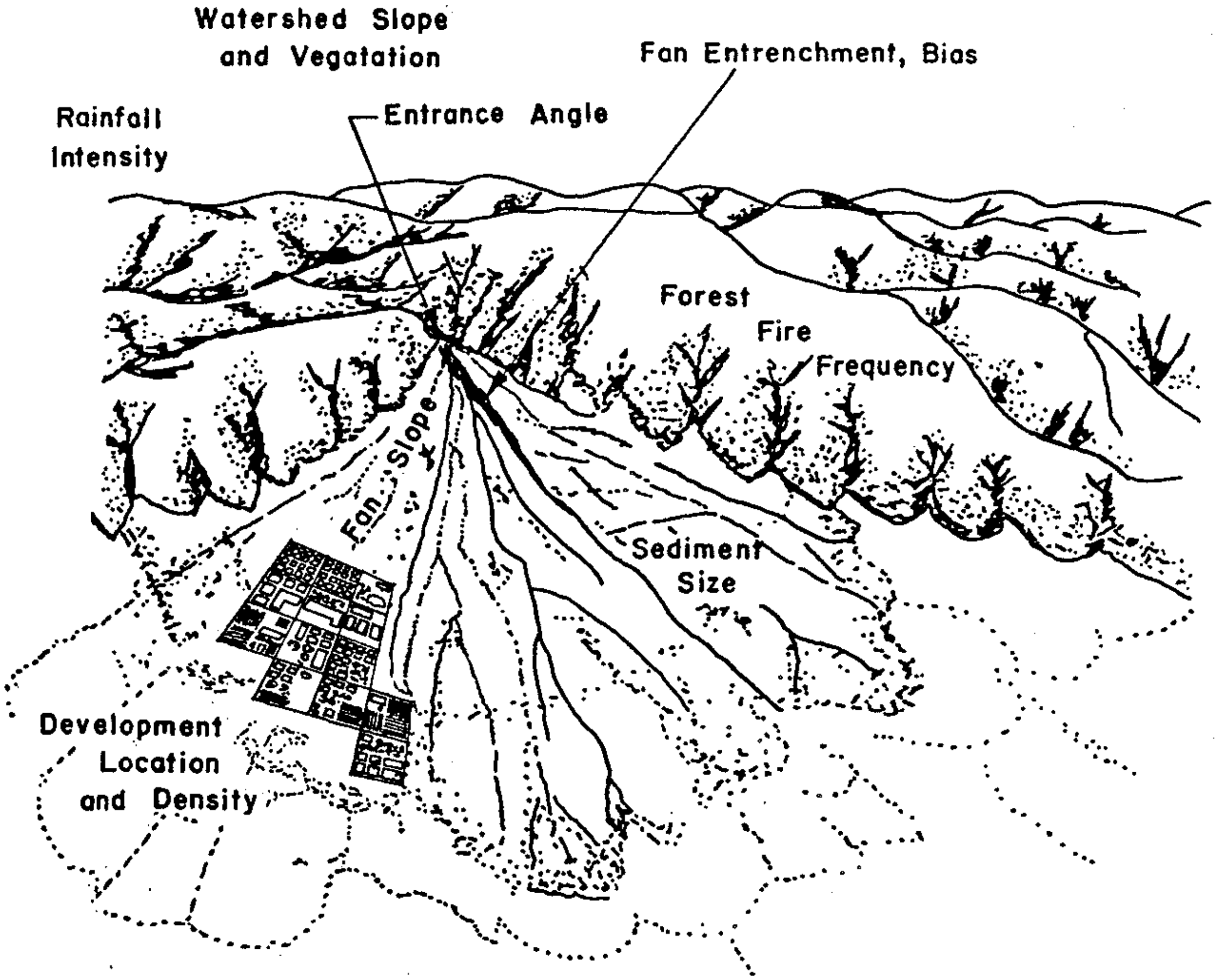


Figure 3.3 Definition of Watershed and Fan Characteristics

Rainfall Intensity

Intense, short duration thunderstorms are common occurences in the semi-arid regions of the west and are responsible for the flash floods which cause most of the property damage on fans. The variation in duration and intensity of rainfall between fans is substantial, and contributes to the highly variable behavior of fan floods.

Fan Slope

Surface slopes on fans vary from 1-2% on fans where sediment and water production in the watershed is relatively low (e.g. Boise) to 20-30% on fans built by debris flows (e.g., Glenwood Springs). Fan slope is determined by long-term watershed characteristics and, in turn, has a pronounced effect on flood dynamics.

Fan Geomorphic Bias, Entrenchment, and Entrance Angle

The shape and structure (morphology) of a fan indicates both the history of the fan (past watershed conditions and floods) and the likely behavior of future flood flows. If a fan exhibits a topographic variation which confines the flow to one part of the fan, it can be thought of as having a geomorphic bias. Flow can be similarly confined by an incised channel or entrenchment which carries the entire flood from the apex to a point downslope. Since water velocities are typically very high at the fan apex during a flood, the direction of the channel entering the fan strongly influences the path of flooding down the fan. Figure 3.2 illustrates two typical fan morphologies.

Fan Vegetation

The type and density of fan vegetation are likely to be similar to that of the associated watershed and vary from virtually no vegetation on fans in parts of the southwest to grass and trees on fans in Boise.

Location, Density, and Geometry of Developments

Many types of developments have been constructed on fans, ranging from low density ranchlands to high density subdivisions. Streets commonly run across the fan slope and homesites are created by a series of progressively lower terraces as one moves downslope. Streets oriented along the maximum slope are not common in most subdivisions. Development usually begins near the toe of the fan and moves progressively upslope in concentric rings or in somewhat detached blocks of houses. Such development has in the past been largely uncontrolled. Figure 3.4 shows the Rancho Mirage fan in 1979 and illustrates the typical development pattern leading, ultimately, to complete occupation of the fan.

3.3 Types and Distribution of Fans

Textbook and journal discussions of alluvial fan characteristics indicate that fans are a common geological feature in the semi-arid regions of the western United States (Ritter, 1973; Schumm, 1977; Bull, 1968). In many areas the fan formation is considered to offer the most desirable building sites, particularly for residential development. These two facts suggest that the overall potential for flood damages on fan areas will increase with time as development pressure grows in the western United States. The purpose of this section is to assess the extent to which flooding problems on fans and related alluvial formations (i.e, aprons, washes) are likely to increase.

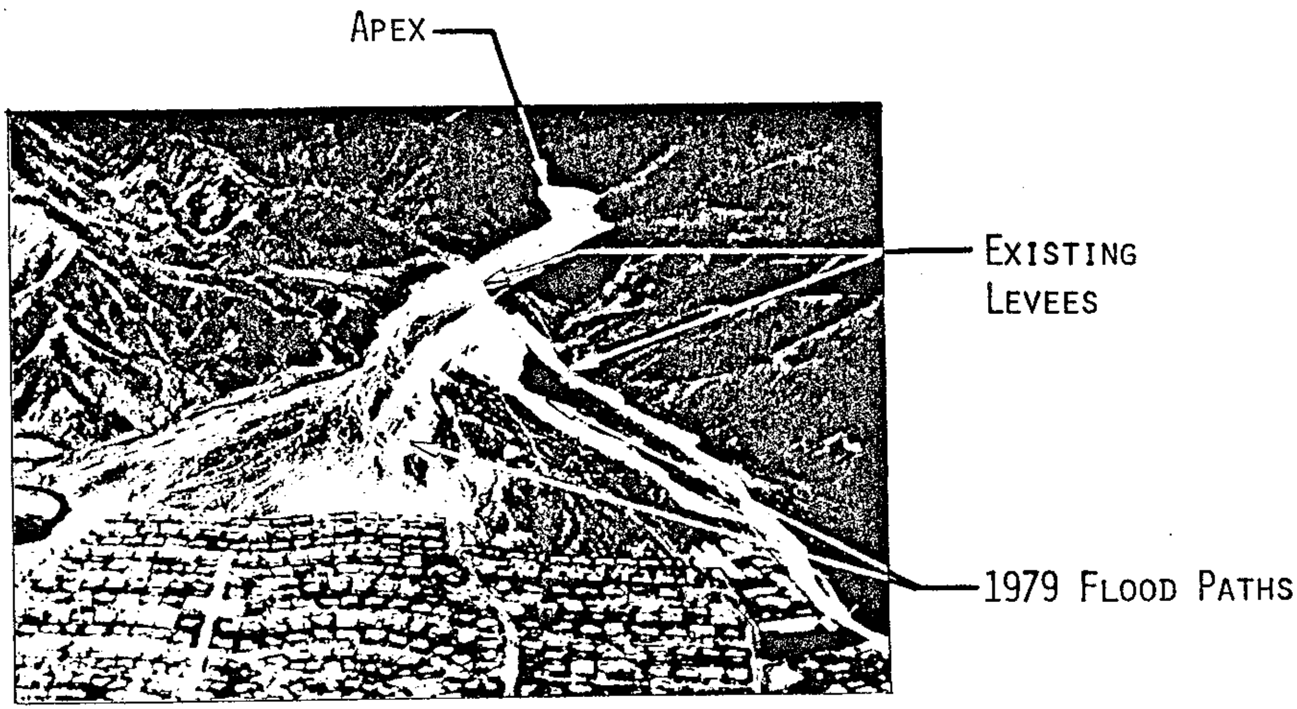


Fig. 3.4   Development on the Rancho Mirage Fan.

Generally speaking, geologists and geomorphologists are reluctant to estimate the number of alluvial fans in areas which extend much farther than the relatively small areas with which they are personally familiar. Even localized information can only be approximate, because a good deal of judgment must be used in deciding which formations are, or are not, fans. Judgments related to aprons and washes tend to be even more complex. The most successful attempt at quantifying the number of fans in large areas of the western United States was performed by the U.S. Army Natick Laboratories and reported by R. L. Anstey (1965). A total of 3876 fans were identified in 19,516 square miles of semi-arid landscape. Anstey cautions that fans with a radial length of less than 1760 feet (one-third of a mile) could not be identified and that low-slope fans may have been overlooked due to the coarseness of available maps. It should be noted that the field surveys (see State-of-the-Art Report) indicate that small fans and low-slope fans can present flood hazards which are equally serious to those on larger and steeper fans. Anstey's article reports that approximately 30 percent of the American Southwest deserts (Basin and Range physiographic provinces) are occupied by alluvial fans and aprons.

Because of their relatively gentle slopes, good drainage, and sorted composition material, alluvial fans are frequently used for roads, agriculture, and sites for urban development, especially in desert regions where the valley land is too soft and saline, and the mountains are too steep and composed of materials that are too hard for these purposes (Anstey, 1965). Although some alluvial fans are concentrated in areas where development is unlikely (over 70 percent of Death Valley, California is covered by fans), many other fans occur in, and are adjacent to, cities which are currently experiencing rapid growth.

It appears, based on the above observations, that the potential for major flood damages occurring in the future on alluvial fans is great. The value of developments "at risk" is likely to rise rapidly as populations increase in the southwestern states. While alluvial fan flooding was of no consequence two decades ago, it is now recognized as a serious problem. Unless effective measures are taken to prevent damages, the liability of federal and state disaster agencies will increase rapidly.

3.4 Recommended Approach to Fan Classification

The diversity of fan and watershed characteristics and the highly variable nature of alluvial fan flooding make a clear case for careful analysis of each fan on an individual basis. Because flood behavior is inextricably linked to these characteristics, the first step in flood analysis must be determination of fan and watershed conditions. Once the general geologic history and present condition of the fan are known, the severity of flood hazards can be estimated.

The following general approach to the identificaion of characteristics is suggested:

1. perform a field survey of the watershed and fan, identifying soil types, vegetation, slopes, topography, existing stream channels, and recent fires;

2. develop detailed topographic mapping of the fan to determine morphology and channel paths;

3. obtain the flood history of the fan, when available, and have a geologist estimate the geologic history of the fan;

4. classify the fan according to the characteristics listed in Section 3.2 using the above data.

Accomplishment of these tasks will require knowledge of fan morphology, geology, and flood hydraulics.

4. FLOOD DYNAMICS AND FLOOD HAZARDS

4.1 Flood Processes

The behavior of flood flows on alluvial fans is the product of a number of processes which are operable in either the upstream watershed or on the fan surface. Processes in the watershed include overland flow, temporary water storage, infiltration, erosion, sediment transport, and temporary sediment storage. Processes on the fan surface include channel formation through erosion, deposition of sediment causing channel braiding, infiltration, and lateral channel migration. Watershed processes transform storm rainfall into discharges of water and sediment at the fan apex. The variations in water and sediment discharge with time (peak discharge, hydrograph shape, sediment concentration) are dependent on watershed characteristics which affect these processes. Likewise, the depth, velocity, sediment concentration, and location of flood flows on the fan surface depend on the watershed discharge and the morphology of the fan itself.

A typical flash flood scenario on a fan will be described in order to illustrate the interactions which influence flood behavior. Then, in Section 4.3, the influence of fan and watershed characteristics on flood dynamics and hazards will be assessed. Rainfall associated with flash floods is usually of high intensity and short duration. Raindrops striking exposed, non-vegetated ground surfaces dislodge soil particles. As the drops combine, flow down the slope begins moving sediment toward the ravines. Steep slopes cause rapid coalescence of the runoff into small channels where high velocities cause further erosion. Detention of both water and sediment occurs where vegetation is thick or local depressions exist and alternating construction and breaching of sediment dams causes pulses of sediment and water to move down the watershed channels. Small landslides may occur in the steepest slopes of the watershed, adding to the sediment moving downslope. As the flood wave nears the fan apex, it becomes confined by a single channel, where velocities and depths of flow become very large. The sediment transport capacity of the stream enables it to carry very large volumes of sediment onto the fan, in some cases forming mud flows.

When the floodwave enters the apex of an active (unentrenched) fan, it has an immediate tendency to spread laterally, thus losing both depth and velocity and infiltrating into the porous fan surface. The resulting loss of competence causes deposition of sediment in the apex area; channel migration and braiding become significant as flow momentum is lost and sediment deposition causes alteration of the channel geometry. If sediment deposition is rapid, as is the case for low slope fans or highly erodible watersheds, channel avulsions near the apex will occur. Conversely, if initial sediment load at the apex is less than the transport capacity, erosion will occur at the apex and an incised channel will form and progressively deepen.

As the flood moves down the fan, an unsteady progression of hydraulic conditions takes place. The flow initially is in a single channel and follows the direction of the upstream watershed channel. Braiding begins at a point downstream where deposition and bed form changes cause flow instability; the width of the flooded area increases rapidly and depths of flow decrease rapidly once braiding begins. If the fan surface is smooth and no topographic constraints on the width of the flooded area exist, the braiding process will create shallow, sheet flooding conditions over much of

Figure 4.1 Flood Pathways on Idealized Alluvial Fan Model.

to this is when an extremely deep trench is formed by major changes in the watershed such as climate changes or depletion of erodible materials. Such a channel may be stable over geologic time.

Within the human time scale, many fans are not uniform and exhibit strong geomorphic biases which confine and direct the flood flow paths. The key question that must be asked in these cases is as follows. What is the likelihood that, within our planning period (typically 100 years for flooding), the present observed channel pattern on a fan will be substantially changed? If this probability is large (as when biases and entrenchments are minor or large volumes of sediment are produced in the watershed), the fan can be considered as uniform and the entire fan surface can be delineated as within the flood prone area. If the probability is small, then delineation of the flood prone area must take existing fan topography into account. High areas or areas far away from a stable entrenchment would then be delineated as areas of low flood hazard, while areas directly down-fan from a channel or within an existing flow path would be high flood hazard areas.

The geometry of flood paths and the dynamics of flood flows have been observed, both in the field studies and in the physical model results, to change substantially with distance from the fan apex. The flow is initially confined to a single channel, which increases in width and decreases in depth as it moves away from the fan apex. The flow continuously loses velocity due to friction effects and loses volume to infiltration. At some point, the ability of the flow to transport sediment falls below that required to carry the sediment suspended in the flow and substantial deposition occurs. Down fan from this point channel braiding begins and rapidly increases flow path width with distance from the apex. This braiding and spreading process continues until nearly uniform sheet flow conditions exist and the flow is very wide and quite shallow. The braiding process is often confined by local topography in the middle section of the fan. In some cases, local coalescence of braided paths into deeper channels may occur if topographic constrictions are substantial. Three hydraulic regions can be identified based on this flood flow behavior, as shown in Figure 4.2. The channelized flow zone extends from the apex down-fan to the point where braiding begins. The onset of braiding is associated with the intersection of the channel bottom (invert) and the fan surface. Below this point no lateral restriction on channel geometry exists and the flow path begins to meander. A partially confined braided zone may exist in the middle portion of the fan; the length of this zone depends on the topographic variation across the fan and may extend nearly to the toe or may be quite short. A sheet flow zone usually exists near the toe of the fan, where little variation in topography across the fan is present. Due to the major differences in the hydraulic behavior of these three regions, flood hazards will be substantially different between them. The selection of flood plain management tools must consider this variation.

Laboratory experiments using idealized physical models of typical fans (see Part II, Section 3 of this report) revealed that, while the above three-zone pattern is common, the existence and length of the channelized zone depends on fan slope, watershed sediment production, and other characteristics. Models of low slope fans exhibited a complete lack of entrenchment, as did models with very high sediment production. Experiments using the physical model of the Rancho Mirage fan (see Part II, Section 4) clearly illustrate the strong effects of local fan topography on flow direction and spreading rate.

The results of field investigations and laboratory

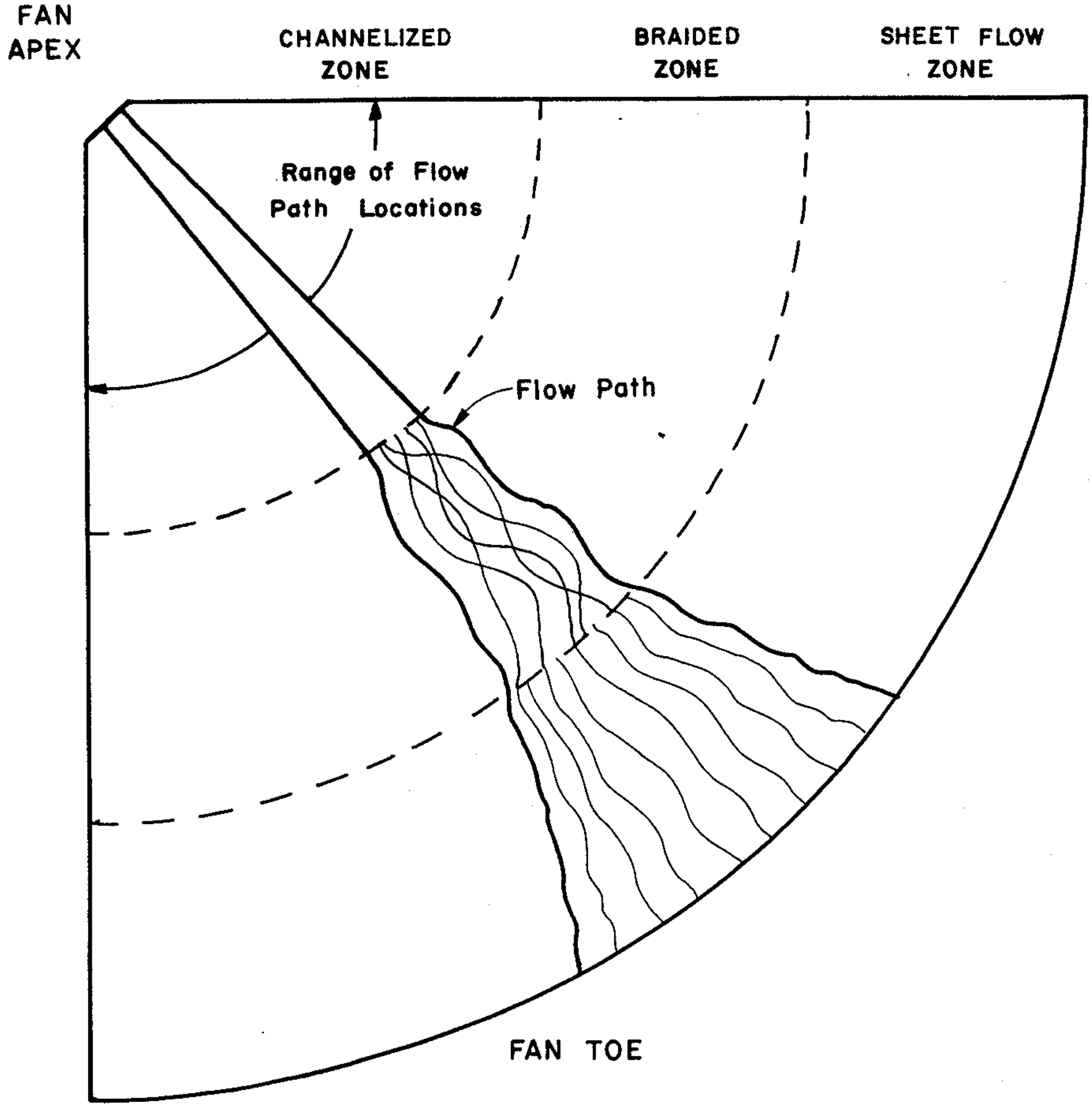


Figure 4.2 Hydraulic Zones on a Typical Fan (Idealized).

experiments clearly indicate the need to obtain detailed knowledge of a fan before flood risk is assessed. The application of simplified hydraulic relationships to a fan without consideration of slope, sediment supply, soil type, and fan morphology will result in erroneous conclusions about flood risk. A recommended approach to hazard identification is given in Section 4.5.

4.3 Types Of Flood Hazards

The flood hazards found on alluvial fans are a result of the high velocity, sediment-laden character of the flood flow. The data gathered in the field and from the physical model runs have allowed us to identify seven types of flood hazards on fans. In the subsequent listing, the nature, general magnitude, and typical location on the fan of each hazard are indicated.

Inundation

This hazard results in damage to a structure's interior and exterior through soaking and minor soiling by water. It occurs on all parts of the fan impacted by the flood flow and may cause the greatest overall damage in a flood event. The inundation of carpeting is likely at those homes exposed to flood waters that are higher than the first floor and this occurrence alone can result in major financial loss. As the flood proceeds down the fan, flood channels widen and inundate larger areas of the fan, inflicting more widespread damage at lower depths. Thus, inundation damages are most severe at individual homes higher up on the fan, but may cause the greatest total damages at lower depths near the fan toe.

Sediment Deposition

Flood waters on fans generally carry large quantities of sediment eroded from both the upstream watershed and from the fan itself. Deposition results from a reduction in the magnitude of the velocity of flow and can be caused by trees, houses, or other obstructions and by a lowered fan slope. Deposition is least likely in entrenched areas of fans and most likely upstream of obstructions or where channel slopes decrease. The costs resulting from sediment depostion make up a large portion of total damage on most fans and include the removal of sediment from structures and the hauling away of sediment from streets and yards.

Scour/Undermining

Flood flows that are carrying less sediment than their transport capacity will tend to entrain additional material, resulting in scour. Scour damage consists of the undermining of structural foundations and the loss of pavement, sod, and topsoil from streets and lawns. The constriction of flood flow in localized areas on any portion of the fan can result in scour. The magnitude of the damage from scour over the whole fan is not usually very large, but scour damage can be a major portion of the financial loss at individual sites.

Impact Damages

The hazard from high velocity impacts is greatest at the fan apex and least at the toe since velocity decreases as the flood flow spreads down the fan. The damages resulting from high velocities are due to the momentum forces applied to structural walls blocking the path of the flood channel. Momentum force hazards will be most severe at the first row of homes struck by the flood wave and decrease for homes shielded below. Total loss of a structure can result from impact forces, but this hazard does not usually constitute a large part of the total damage on the fan in a major flood event.

When debris flows occur on fans, impact forces may be the dominant cause of damages to structures. Large boulders and highly viscous mud are carried down-fan at high velocities. The momentum forces on a structure impacted by such a flow greatly exceed the strength of the structure and cause breaching of the walls and, in some cases, total destruction of the building.

Debris flow events on typical fans are rare. However, certain fans, such as those in Glenwood Springs, are subject to frequent debris flow events. Debris flows are usually confined to the upper portions of the fan because high velocities and steep slopes are needed to sustain the viscous flow.

Hydrostatic and Buoyant Forces

Water, stagnant or in motion, exerts hydrostatic and buoyant forces on buildings in flood zones. Buoyant forces can lift a home and allow it to float away if water inundates the ground under and the area surrounding the building to sufficient depths. Hydrostatic forces on the walls of structures increase linearly with depth and can result in total wall failure. Buoyant and hydrostatic force hazards are most catastrophic in the areas of deepest inundation (near the apex) but can cause damages in lower portions of the fan in areas of ponding.

High Velocites

The presence of high velocities during a flood event significantly increases the danger to livestock, pets, and humans. People commonly underestimate the dangers associated with rapid flow and may not take appropriate protective action. There is often insufficient warning of an impending flash flood to allow such measures on fans, even if people understand the dangers.

In general, velocities decrease with distance from the fan apex; however, local flow restrictions, drainage channels, and even streets may carry water at velocities exceeding 10 feet per second at the toe of the fan. Because the flood pathways are unpredictable and erratic on many fans, the presence of high velocities cannot be forecast effectively except where incised channels exist.

Unpredictable Flow Paths

In normal riverine floods, the channel and overbank areas are clearly defined and are relatively stable from one flood event to another. The path of flow on alluvial fans is characterized by unpredictable directions from one flood to another and during a single flood, making the design of flood protection efforts difficult. The unpredictable nature of fan floods begins at the apex and extends to the toe for fans with smooth surfaces. When entrenched channels and/or topographic constrictions on the flow exist on a fan, the location of flood flows in these areas will be stabilized. Hence, the severity of this hazard is dependent on fan morphology.

4.4 Effect of Fan and Watershed Characteristics

The fan and watershed characteristics discussed in Section 3.2, due to their influence on flood dynamics, have a major impact on the location and severity of flood hazards on alluvial fans. Once these characteristics are identified through field inspections and collection of data on past floods, a qualitative analysis of expected flood hazards can be made. This section identifies the key relationships between characteristics, flood behavior, and hazards.

Figure 4.3 provides a summary of the typical direction (positive, negative, or site specific) and approximate strength (high, moderate or minimal) of the correlation between characteristics and hazards. For example, high fan slope strongly correlates with a large scour hazard and with a small problem over unpredictable flow paths. This matrix is intended to be a qualitative guide to the identification of hazards which may occur on fans.

Watershed, Slope, Vegetation and Forest Fires

Steep watersheds tend to concentrate runoff more rapidly and produce short duration, high intensity floods. Sediment production is also enhanced by the high velocities generated on steep slopes. Conversely, watershed vegetation delays or stores runoff and inhibits erosion, causing smaller discharges of sediment and water. Forest fires cause abrupt reductions in watershed vegetation and, consequently, can cause large increases in sediment production and peak discharges on fans. The stability of flow channels on the fan can be seriously degraded by increases in sediment production.

The severity of all the hazards increases with the magnitude of sediment and water discharges from the watershed onto the fan. Fans associated with steep and/or poorly vegetated watersheds have historically exhibited particularly large inundation, sediment deposition and impact hazards. Mud flows are nearly always associated with one or more of these characteristics.

● HIGH
◑ MODERATE
○ MINIMAL
+ POSITIVE
– NEGATIVE
SITE SPECIFIC

FAN AND WATERSHED CHARACTERISTICS / FLOOD HAZARDS OF FAN	INUNDATION	SEDIMENT DEPOSITION	SCOUR/UNDERMINING	IMPACT DAMAGES	HYDROSTATIC AND BUOYANT FORCES	HIGH VELOCITIES	UNPREDICTABLE FLOW PATHS
FAN VEGETATION	– ◑	– ●	– ●	– ○	– ◑	– ●	– ○
FAN ENTRENCHMENT	◑	◑	●	●	◑	●	– ●
SEDIMENT SIZE/TYPE	– ○	– ●	– ●	– ◑	– ○	– ◑	– ◑
FAN SLOPE	– ○	+ ●	●	+ ●	– ○	+ ●	– ●
FAN GEOMORPHIC BIAS	◑	◑	◑	◑	◑	◑	– ●
APEX ENTRANCE ANGLE	◑	◑	◑	◑	◑	◑	◑
WATERSHED VEGETATION	– ●	– ●	– ●	– ●	●	– ◑	– ●
RAINFALL INTENSITY	+ ●	+ ●	+ ◑	+ ●	+ ●	+ ●	+ ◑
WATERSHED SLOPE	+ ◐	+ ●	+ ◑	+ ◑	+ ◑	+ ◑	+ ○
FOREST FIRE FREQUENCY	+ ◑	+ ●	+ ●	+ ◑	+ ◑	+ ◑	+ ●
DEVELOPMENT LOCATION	●	●	●	●	●	●	●
DEVELOPMENT DENSITY	+ ◑	+ ●	+ ●	+ ◑	+ ◑	+ ●	+ ◑
DEVELOPMENT GEOMETRY	◑	●	●	◑	◑	●	◑

FIGURE 4.3: CORRELATION BETWEEN CHARACTERISTICS AND FLOOD HAZARDS

Sediment Size and Type

Small sediment sizes are more easily eroded and transported than large sizes, provided that the soils are noncohesive (as is the case for fans not subject to mud flows). Hence, fans with predominantly small sediment sizes may experience rapid erosion and deposition processes which cause unstable flow paths with frequent avulsions. Sediment size and type can also be an indicator of past debris flows, since such flows deposit poorly sorted layers of sediment with large rocks and debris mixed with clays and fine sands.

Rainfall Intensity

The distribution, duration, and intensity of rainfall in the watershed are the driving forces behind the fan flood process. Hence, high rainfall intensities and longer rainfall durations are strongly correlated with all flood hazards on fans.

Fan Slope

Physical model experiments confirm the prediction, based on theory, that high slope fans tend to exhibit stable channels and, often, substantial entrenchments. Flow velocities and sediment transport capacity are higher than for low slope fans. Hence, hazards due to sediment deposition, scour, high velocities, and impact damages are strongly correlated with high slopes. The unpredictability of flow path is relatively low on a high slope fan, resulting in a concentration of flood hazards within the established path.

Fan Geomorphic Bias, Entrance Angle, and Entrenchment

These characteristics have important influences on the direction, geometry, and stability of the flow path. The entrance angle and existence of an entrenched channel at the apex determine the initial flow pattern on the fan. Pronounced geomorphic bias (topographic variation which confines the flow area to a part of the fan) forces the flow into a confined path and reduces the instability of the flow direction. Avulsions are less common on a fan which is biased or entrenched, resulting in more stable flood patterns.

The correlations between these characteristics and all hazards except unpredictable flow paths are dependent on the position of the stable flow path. If a structure is within the established path, the likelihood of damage is very high. Conversely, if the structure is outside of the established path, it is unlikely that it will be damaged at all. An entrenched or topographically confined channel will also convey large volumes of sediment and water to the lower portions of the fan, causing high hazards down-fan.

Fan Vegetation

If a fan is well vegetated, erosion processes are considerably slower than on a poorly vegetated fan. The amount of sediment being transported down-fan is less, while the increased roughness results in lower velocities. Flow paths and channels are much more stable, since bank erosion processes are slowed and deposition of sediment in the flow path is reduced. Consequently, a well-vegetated fan will experience substantially smaller hazards than a poorly vegetated fan.

Location, Density and Geometry of Developments

A developed area such as a subdivision greatly alters the local geometry and dynamics of the flow. Concentration of flow between structures, ponding of water and sediment upstream of structures, acceleration of flow around obstructions, and diversion of flows (avulsions) are common in the vicinity of developments. Hence, flow conditions are very different within and down-fan from a development than they are on an undeveloped fan.

The location of the development is a major factor, since structures near the apex or within an entrenchment will be severely damaged and will strongly influence flow paths and damages down-fan. Dense developments will experience hazards due to the high velocity, scour and inundation effects of constricting the flood flows. Structure and street geometry can either mitigate or exacerbate flood hazards within a development. Streets designed to carry flood flows without damage will, as shown by the localized model experiments (see Part II Section 5), effectively protect structures and prevent landscape damages. Conversely, a street pattern which runs across the fan slope may cause ponding, flow constriction, and unstable flow paths.

4.5 Recommended Approach to Hazard Identification

In order to identify the presence and magnitude of flood hazards on an alluvial fan, a detailed technical study of the fan should be undertaken. This section reviews the existing FIA hazard prediction methodology and then provides a brief outline of the components that should constitute the identification process. The development of a comprehensive, detailed approach to hazard identification is beyond the scope of this report.

The Federal Insurance Administration is presently applying a method of hazard analysis on alluvial fans (Dawdy, undated) that calculates depths and velocities with a one percent chance of occurrence in an average year. These depths and velocities are determined through a statistical analysis that considers both the probability distribution of flood discharges at the fan apex and the probability that the flood channel(s) will inundate particular locations down the fan. For example, if a given contour on the fan is 100 feet wide and the 10-year flood discharge flows in a channel that is 10 feet wide, the probability that a given location on this contour will be flooded by the 10-year discharge event is approximately 1%. The 1% probability depth and velocity at this contour are the depth and velocity in the 10 foot wide channel carrying a 10-year flood discharge. Depending upon the width of the fan contour and the width of the channel the 1% probability depth and velocity will correspond to different flood discharges at different fan locations.

In deriving a technique for calculating these depths and velocities, certain key assumptions regarding fan flood hydraulics were made.

1) At the time of passage of the peak discharge of a flood event, the flow is confined in a single channel from the fan apex to the toe.

2) Flows are at critical depth and velocity (Froude number = 1).

3) Below the apex, the flood channel occurs at random locations at any point on the fan.

4) The flow erodes its own channel, stabilizing the shape of the channel when the decrease in channel depth per unit increase in channel width approximates 0.005.

5) Permanent entrenchments, topographic biases, and other morphologic features which may modify flood hydraulics are either absent or have a minor influence.

The FIA methodology was developed for application on unentrenched, smoothly sloped (active) alluvial fans with little or no man-made obstructions. As such, it represented a substantial improvement over the use of standard riverine approaches (HEC-2, etc.) or the reliance on "eyeball guestimates". It provided an easily applied, simple technique which, given suitable fan conditions, predicted the approximate depths and velocities of flooding.

The data and insights gained in the present study through field investigations and physical model experiments provide the basis for substantial improvements to the methodology. The most important attributes of a widely applicable alluvial fan methodology are as follows.

1. The effect of fan characteristics such as slope, watershed conditions, and morphology should be incorporated into the method through the use of empirical equations (see Part II, Section 3) for depth and velocity.

2. The observed pattern of three hydraulic zones, channelized, braided, and sheet flow, should be considered in the predictions, since each zone has different flood hazard severity and flood behavior.

3. The Froude number and channel geometry should vary with fan conditions such as slope and sediment size.

4. Since multiple flood channels, each with substantial flow, have been observed in both the models and field studies, the effect of flow splitting (in addition to avulsions) should be considered.

5. The results of the hazard prediction methodology should be representative of actual depths and velocities at a structure during the base (100 year) flood event. This is because protective measures should be built to withstand the base flood, as is the case for riverine flood plains.

An approach to hazard identification and estimation, as suggested by the results of the field and model investigations, is summarized below.

1. Data on historical floods should be gathered, including depth, discharge, and velocity measurements, damage surveys, and personal accounts. Aerial photographs covering the fan over several years time would be helpful in establishing the history of fan formation and flood migration.

2. Field visits, aerial photography, and topographic mapping should be used to identify watershed and fan characteristics, including hydrology, morphology, vegetation, forest fire frequency, and nature of fan development.

3. Qualitative estimates of flood hazard types and severity should be made using available data and the relationships between characteristics and hazards presented in Figure 4.3.

4. The areas subject to flooding should be delineated based on fan flood history, local topography, and other characteristics.

5. Quantitative predictions of depths and velocities should be computed from empirical equations such a those presented in Part II, Section 3. The application of such equations will depend on the fan conditions identified in step 2 and the potential hazards identified in step 3.

It is clear that a detailed study of the fan and watershed, including geologic and geomorphic analysis, is required to adequately define flooding behavior and hazards.

This procedure will require considerably more effort than the application of the current FIA methodology. However, the resulting flood delineation is likely to be substantially more accurate and representative of actual fan flooding.

5. THE FLOOD PLAIN MANAGEMENT PROCESS

5.1 The Need for Master Planning

The hydraulic behavior and associated hazards of fan flooding, as discussed in Section 4, are considerably more complex than typical riverine conditions. This increased complexity is due to:

- very high velocities and associated momentum forces,
- large sediment transport capacities,
- potential for extreme scour and sediment deposition in different parts of the same fan,
- erratic, unpredictable flow paths, and
- rapidly changing channel geometries as scour and deposition take place.

As a result, approaches to alluvial fan flood protection and management must be more flexible as well as more careful than has been the norm on rivers.

The results of field and model studies reveal that any management action or new development on a fan is likely to substantially change, and sometimes exacerbate, flood problems down-fan. Due to the unstable nature of most fan floods and the conical shape of fans, a small change in channel direction or geometry near the apex can radically shift flood impacts downstream from one area to another previously unaffected location.

A whole-fan approach to flood management which considers the flood process from apex to toe will provide maximum information about the effects of development on flood behavior. In addition, such an approach allows comparison of all alternative flood management schemes (whether whole-fan, structural solutions or local, nonstructural tools) and the selection of the most cost-effective approach. A key step in this whole-fan approach is the implementation of a master plan which regulates development and specifies required management tools.

5.2 Development Scenarios

The types of management tools which are likely to be cost-effective on a fan depend, to a large degree, on the location, density, and timing of development. Three development scenarios were suggested by Tettemer (undated), as follows.

1. Low density development can be supported on the fan by allowing construction anywhere except on existing incised channels and in the immediate vicinity of the apex. This is illustrated in Figure 5.1. Floodproofing of all structures, preferably by elevation above the flood, would be required. Zoning restrictions on minimum lot sizes would be necessary to prevent constriction of flood pathways and concomitant increases in depth, velocity, and other hazards. Existing structures would not be protected unless retrofitted with dikes or other floodproofing measures. Flood damages to landscaping, streets, and utilities could be severe since they are not protected.

2. Moderate density development may be accomodated in different ways:

FIGURE 5.1 LOW DENSITY DEVELOPMENT SCENARIO
(AFTER TETTEMER, UNDATED)

- moderate density housing across much of the fan surface and
- moderate to high density subdivisions located in areas protected from flooding plus open space reserved for floodways.

Under the former scenario, local levees, channels, and enlarged streets could be used to safely convey flood flows. The use of structure *floodproofing* is also possible, but the cost of floodproofing many structures, the aesthetic problems of such measures, and the flood damages to landscaping and utilities may be substantial. Under the reserved floodway scenario, as shown in Figure 5.2, local levees are used to direct flood flows into open space and to confine the flood as it moves down the fan. No development of the floodway would be allowed, but full development could occur in the protected areas. Flood damages to landscaping, streets, and utilities would be minimal. Because much of the floodway is natural, maintenance costs would be limited to levee repairs and landscape work.

3. High density development can be safely accomodated on fans through the use of whole fan management tools, as illustrated in Figure 5.3. The structural tools could be designed to reduce the peak water and sediment discharges, contain the flood in armored channels, and convey flows to the fan toe. Nearly all of the fan surface is made available for development. Should an extreme flood event (greater than the 100 year flood) occur, extensive damage can be expected. Local management tools such as

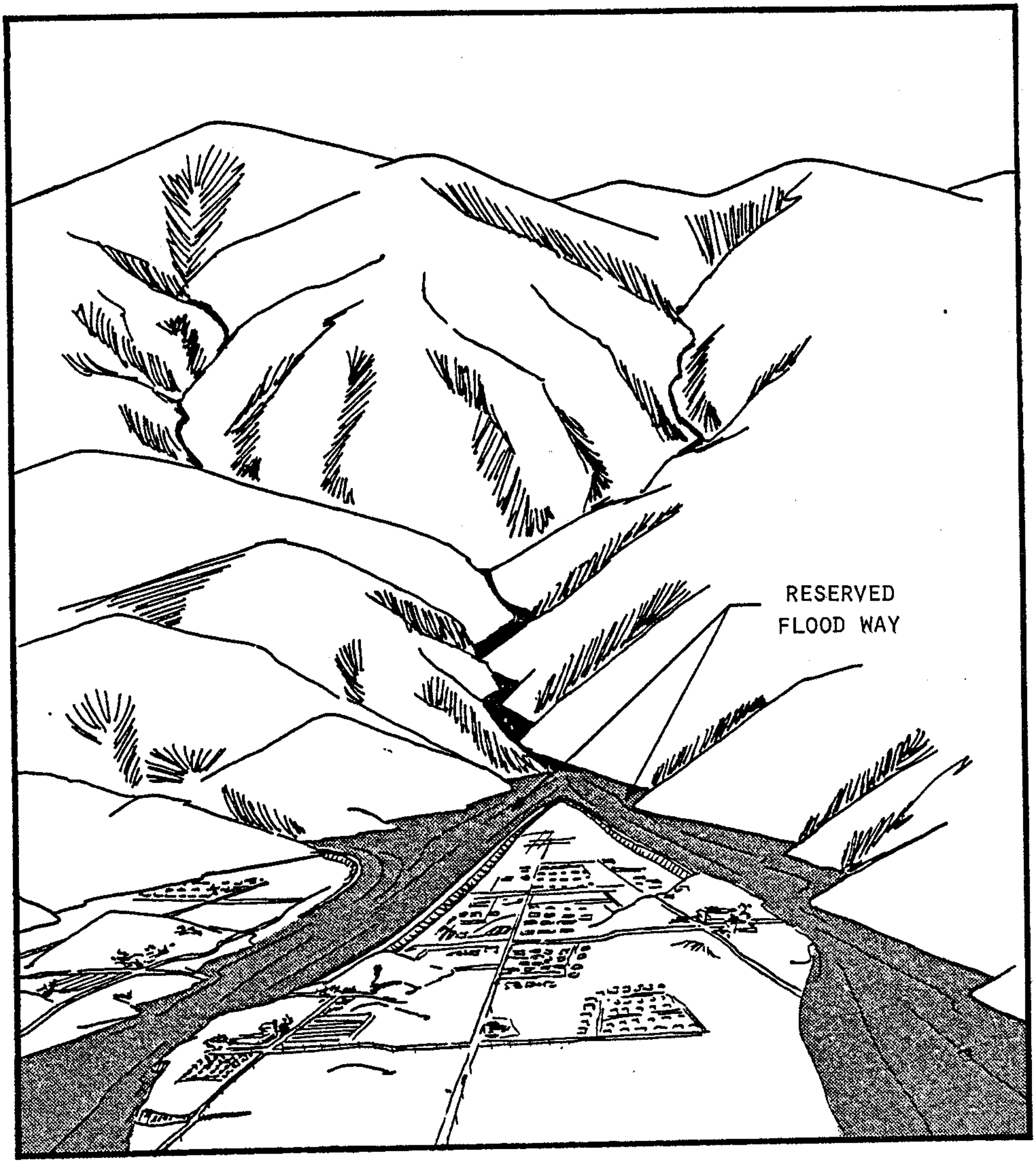


FIGURE 5.2 MODERATE DENSITY DEVELOPMENT SCENARIO WITH RESERVED FLOODWAY (AFTER TETTEMER, UNDATED)

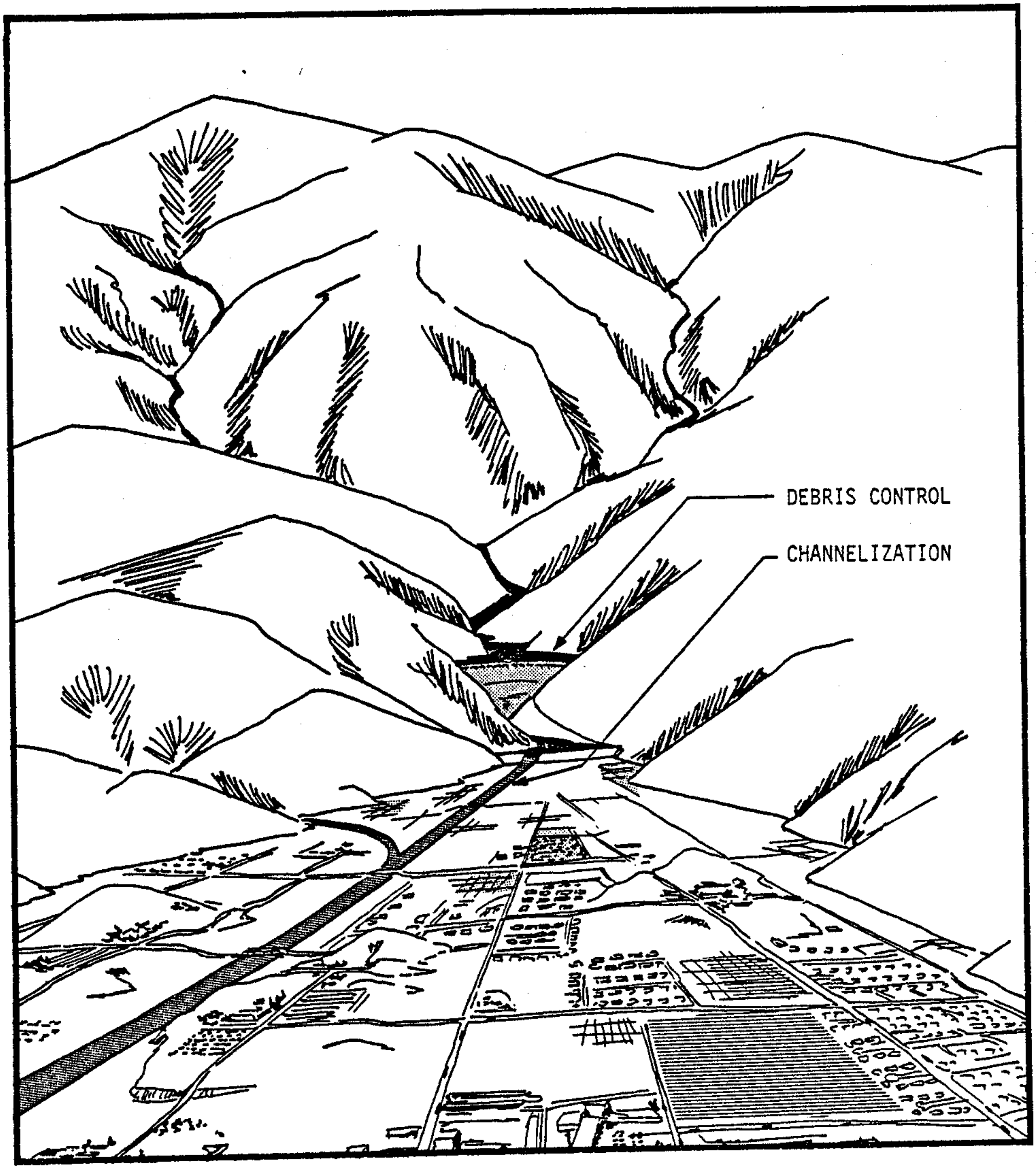


FIGURE 5.3 HIGH DENSITY DEVELOPMENT SCENARIO
(AFTER TETTEMER, UNDATED)

conveying flows in depressed streets or structure elevation are theoretically possible. It is likely, however that application of such tools to an entire fan would be very costly.

The scenarios discussed above are predicated on a planning process which is initiated when a fan is sparsely developed. Existing moderate or high density development will, of course, limit the options available to planners. Protection of existing structures will require the use of management tools which divert flows away from such structures. Land available for floodways could be limited if significant development has occurred.

5.3 Recommended Master Planning Approach

The establishment of a master plan for development at the earliest stages of fan urbanization will maximize available flood management options and minimize the number of structures with high flood risks. A master plan should carefully consider the flooding problem and include:

- a flood management plan which specifies the type of management tools to be used, the location of these tools, and design standards for structural tools;

- a zoning plan which establishes a development scenario in coordination with the flood management plan and limits subdivision densities as appropriate;

- an open space plan which allows for flood flow conveyance, as appropriate, by reserving natural areas for either floodways or structural tools (e.g., debris basins, channels, or levees);

- a development plan which requires that roadways be oriented, where possible, parallel to the slope and that flow blockage be minimized;

- building codes which require proper elevation of new flood-prone structures and proper construction and maintenance of dikes, armored fill and other local management tools;

- a requirement that subdivision flood control plans conform to the master plan and do not cause increased down-fan flood hazards;

- a maintenance program which ensures timely, effective maintenance of installed management tools; and

- an inspection program that ensures proper construction and maintenance of management tools.

Such a master plan must, of necessity, be based on an analysis of flood hazards on fans, as described in Section 4.5. Once the location and severity of hazards is established, flood management tools can be selected (as discussed in Section 6) and a management plan can be designed. This plan is then the basis for the zoning, open space, and development plans. Building codes and subdivision requirements can be formulated to enforce the local aspects of the flood management plan. Maintenance and inspection programs will be needed to enforce the plan and assure reliable flood protection.

6. SELECTION OF FLOOD PLAIN MANAGEMENT TOOLS

6.1 Management Tools Considered

Field investigations, a literature search, and meetings with local community officials have identified a number of management tools which have been used, with varying degrees of success, by communities on alluvial fans. One of the major objectives of this study was to assess the applicability and effectiveness of such tools and to make recommendations as to the use of management measures. In the following discussion each tool is described and typical applications are cited. Later sections discuss measure effectiveness and recommended usage.

Debris Basins or Detention Dams

These measures can be placed on fans at the apex or across stable channels and typically consist of a natural or excavated basin confined by an earthen dam equipped with outlet works and spillway. The purpose of most such installations is to reduce the peak flood discharge of water and sediment. Debris basins are designed to trap most incoming sediment permanently, while detention dams trap sediment and water during the flood peak and then release both as the flood subsides. Both types of structures have been used on several fans and aprons in the United States.

Levees and Channels

Levees can be used to confine or channelize flow anywhere on a fan, but are typically used to convey flow all the way from fan apex to toe. Design of levees and channels varies widely, from the unarmored, uncompacted berms constructed on the Rancho Mirage and Palm Desert fans to the concrete lined canals built on the aprons near Albuquerque. Typical channels have trapezoidal cross-sections and invert slopes equal to the fan surface slope. Hence, velocities in the channel during floods can be extremely high (20 feet per second or more). Channelization plans include deepening and straightening of natural watercourses, lining of natural channels with grass, riprap or concrete, and construction of new canals. Channels are sometimes combined with an upstream debris basin or detention dam. The upstream facility reduces peak water and sediment discharge, preventing excessive scour and/or sediment deposition and allowing a smaller channel.

Drop Structures

Reinforced walls or armored, steep slopes can be used to dissipate flow energy in either channels or landscape areas. These drop structures can be constructed across the slope of the fan between buildings to prevent cutting of localized gulleys and to stabilize ground slopes in residential areas. Concrete drop structures placed in channels help prevent the very high velocities and intense scour found normally in steeply sloped channels.

Debris Fences

These structures are used only where debris flows are common and are designed such that water and sediment flow through the fence, while large rocks and debris are trapped. They typically consist of vertical steel I-beams mounted in a massive concrete foundation and projecting 6-8 feet above ground level. The vertical beams may be 1-2 feet apart, so that only the larger (most destructive) boulders and debris are stopped.

Local Dikes

Dikes have been used to protect individual structures or small subdivisions, but can also be used to direct flood waters into streets or channels for safe conveyance down-fan. In a developed area, local dikes should be coordinated with street layout and orientation. Use of dikes by individual homeowners without such coordination could result in severe damages to adjacent structures. The design of dikes varies widely, from simple masonry walls with no structural reinforcing to massive earthen berms. Armoring of dikes has been neglected on many fans.

Street Orientation

Streets in developed areas can be aligned along the maximum slope to provide flow carrying capacity. When combined with local dikes and drop structures between homes, streets can carry all of the flood flow through a subdivision. Figure 6.1 shows one way these tools might be used. Such use requires heavy armoring of street sides and large flow depths; conditions which require depression of the streets and special treatment of side streets and driveway entrances. Transitions between subdivisions or between streets and open space must be smooth to avoid excessive scour or sediment deposition.

Elevation of Structures

Piles or fill may be used to elevate structures above the base flood elevation and effectively remove them from the flood hazards. Elevation on piles allows flow under the building and minimizes obstructions in the flow path, while elevation on fill substantially obstructs flow. A subdivision built on fill requires an alternative flow conveyance system such as armored streets. Elevation on

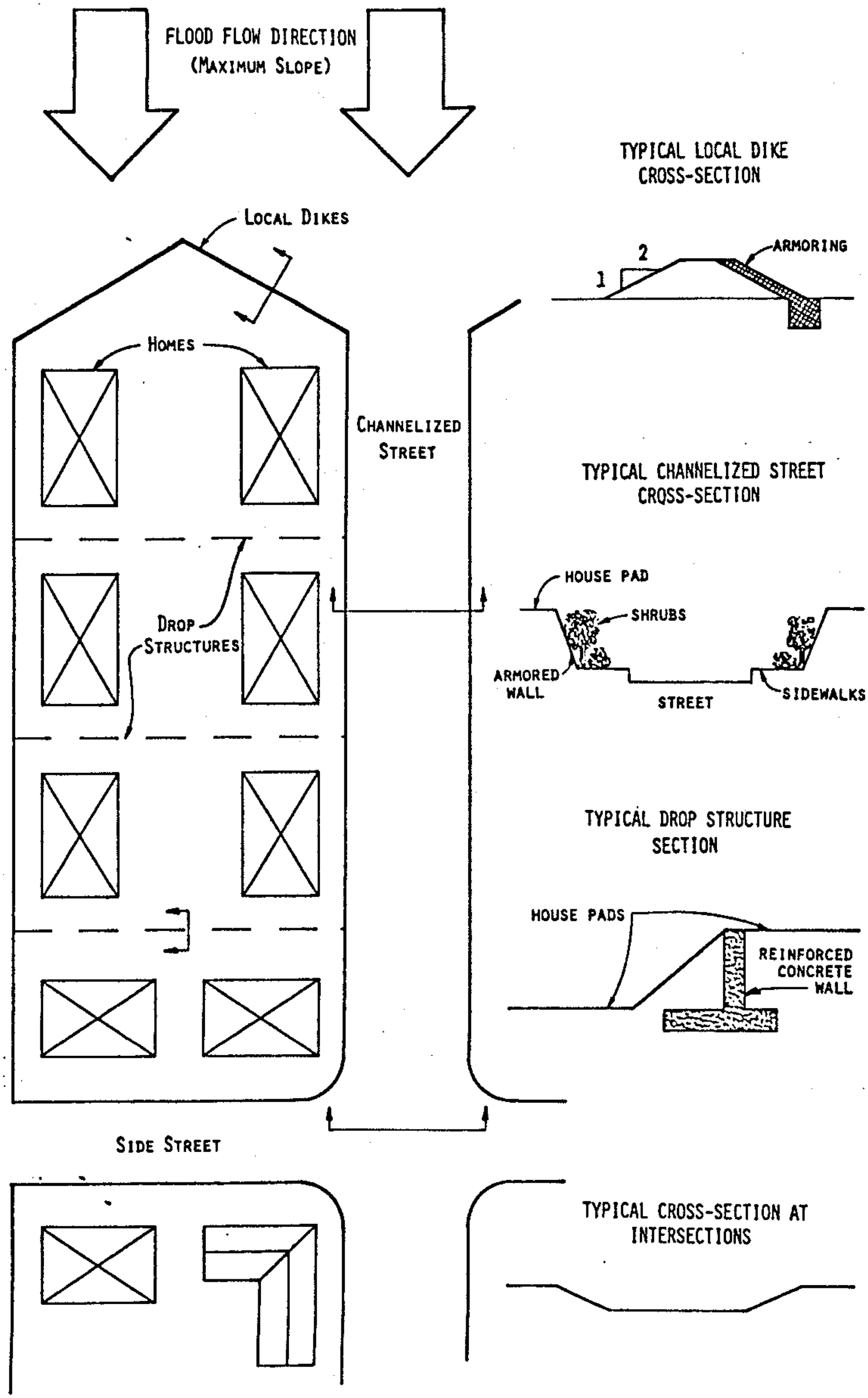


Figure 6.1: Use of Streets for Flood Conveyance

fill has been implemented by several communities, but without proper armoring or provision of flood conveyence capacity. Elevation on piles has, to date, been used on individual structures, but has not been applied to entire subdivisions.

Watershed Management

This measure includes the use of reforestation techniques and forest fire controls as well as terracing, where feasible, to minimize runoff and sediment production from a watershed feeding a fan. Such techniques can be used in combination with all other measures to reduce their required capacity. Use of watershed management is highly dependent on the watershed slope, soil characteristics, and climate.

Flood Plain Zoning

Zoning is used to reserve fan areas for flow conveyance, detention, or diversion and to prohibit or limit development in high flood hazard areas. The unpredictable nature of flooding on fans makes such zoning difficult and uncertain unless either (1) much of the fan is zoned as a floodway or (2) controls on the flow path, such as armored levees, are installed to direct the flow as needed. The amount of land which must be removed from development can be substantially reduced through the use of control measures. Zoning has not been widely used to date, due to the substantial development pressures which exist on many fans in the Southwest.

6.2 Evaluation and Selection Methodology

The selection of management tools should be based on a thorough understanding of the flood hazards on the fan, existing development, proposed development density and orientation, and the economic and political realities of the subject community. Available management options include a variety of measures which, either singly or in combination, should provide adequate flood protection. This section defines the key issues which must be considered and suggests a methodology for selecting flood plain management tools.

The design of management tools depends on:

1. performance requirements,
2. susceptibility of the tool to anticipated forces (hazards) during floods,
3. physical constraints on size and orientation,
4. public acceptance, and
5. cost.

Of these considerations, physical constraints and performance requirements are site and application specific, while cost, susceptibility, and public acceptance are related to the measure itself.

Performance requirements specify the discharge, velocity, sediment load, and/or depth of flow which must be contained or controlled by the measure. They are determined from hydrologic and hydraulic analyses of the watershed and fan, and, in turn, determine the scour, deposition and momentum forces affecting the measure. Physical constraints include such restrictions as available land, existing channel patterns, existing development density, and previously installed measures.

Susceptibility of a tool to hazards on fans will be assessed in Section 6.3 based on tool performance in the physical models, reported performance of tools on prototype fans, and guidelines for flood management tool design (e.g., "Levee Design Manual," U.S. Army C.O.E.). Susceptibility is severe when destruction or neutralization of the measure due to the hazard is likely. Proper design of the measure and/or diligent maintenance may prevent degradation of measure performance. Hence, discussions of susceptibility serve as indicators of the kinds of hazards which deserve special attention for each management tool.

Public acceptance of a management measure typically depends on the following factors: aesthetics, disruption of the community, perceived safety effects, and cost to the individual, either directly or through taxes. Because fans are typically completely dry except when actual flood events occur, few citizens recognize the magnitude of flood hazards. Natural flood channels on many fans are poorly defined and highly irregular, making it difficult for citizens to recognize parts of the fan which are susceptible to flooding. Finally, the unstable nature of flood paths on fans makes definition of a flood zone difficult and in many cases results in much of the fan being classified as flood plain. All of these factors contribute to a generally very low level of acceptance for management tools on fans.

Planning studies may look at management tool costs at three levels: individual homeowner, government, and minimum long-term cost for the entire community. Since certain measures emphasize government costs (debris basins and channels), while others place most of the burden on homeowners or developers (elevation of structures), measures can sometimes be selected to place the cost burden appropriately.

Management tools should be selected through a process which considers:

- fan and watershed characteristics,
- the location and severity of hazards,

- the flooding pattern on the fan,
- prediction of future flood behavior,
- existing and projected development, and
- the effectiveness of the various management tools available.

In the past, measures have often been selected with little understanding of the dynamics of flooding on fans and little concern for the effect of development density on measure performance. This has led in several instances to the failure of levees, dikes, and other installations and very heavy damages to properties on the fans.

The following selection process considers all of the key issues which influence management tool performance and ensures a comprehensive approach to flood plain management on alluvial fans.

1. The type and location of flood hazards on the fan should be identified based on a qualitative analysis of fan and watershed characteristics and a review of historical flooding behavior. A geologist and a hydrologist would be required to analyze the characteristics and predict future fan behavior. Sections 3, and 4 deal with these issues.

2. Quantitative estimates for the depth, velocity, width and path of the design flood (100-year event) should be developed from empirical formulas for channel geometry and behavior. Several formulas for computing these quantities are presented in Part II, Section 3 of this report.

3. The identification of existing and future

development on the fan provides a basis for flood plain management. The logical way to obtain development data is to create and implement a master plan for the fan. This plan may include alternative development scenarios which can be individually considered based on flood plain management needs.

4. Alternative management scenarios can then be identified based on different combinations of management tools that would be compatible with the development plan. These scenarios would be based on required performace, physical constraints, and public acceptance potential, as well as the compatibility of various tools. The recommended applications for management tools presented in Section 6.4 provide a framework for this identification process. Recommended management approaches are discussed in Section 6.5.

5. Tools which are inappropriate, e.g., will not withstand the flow conditions on the fan, will not adequately reduce or eliminate flood hazards, or will not be compatible with other implemented tools, can be eliminated based on the discussions in Section 6.3, the physical model results, and experience with floods on fans.

6. The cost of each tool can then be estimated based on preliminary designs using the quantitative estimates of hydraulic behavior obtained in step 2. Tools which do not appear to be cost-effective, are financially infeasible, or have excessive public acceptance

problems should be eliminated from consideration.

7. The final selection of management measures, if more than one candidate remains, will be dependent on community needs and the ability of the various interest groups to pay the costs.

6.3 Effectiveness of Management Tools

Experience with management tools in past floods (e.g., Palm Desert, Rancho Mirage, Bullhead City) provides some indication of effectiveness. Public reaction to flood management plans in some areas (e.g., Albuquerque, Palm Desert, Los Angeles) indicates probable public response to implementation of such plans. However, the rather short history and limited scope of flood management activities on fans provides only limited experience. Evaluation of tools must also be based on the physical model tests performed during this study.

Figure 6.2 summarizes the relative susceptibility of each management tool to each hazard type found on fans. Where susceptibility is severe, failure of the tool is probable unless adequate protective measures are implemented. Susceptibility can be used as an indication of maintenance requirements as well as design standards for management tools. Where extreme damage to a measure is indicated, e.g., local dikes installed near the fan apex, such applications should be avoided.

The effectivenes of individual management tools in reducing specific hazards is summarized in Figure 6.3. Each tool is assumed to be adequately maintained and fully protected against the hazards. Individual measure effectiveness and

● EXTREME
◑ MODERATE
○ MINOR

FLOOD HAZARDS ON FAN / MANAGEMENT TOOLS	INUNDATION	SEDIMENT DEPOSITION	SCOUR/UNDERMINING	IMPACT DAMAGES	HYDROSTATIC AND BUOYANT FORCES	HIGH VELOCITIES	UNPREDICTABLE FLOW PATH
DETENTION DAM OR DEBRIS BASIN	◑	◑	◑				●
LEVEES AND CHANNELS	●	●	●	◑			●
DROP STRUCTURES		○	●	○			○
DEBRIS FENCES		●		◑			○
LOCAL DIKES	●	●	●	●			◑
STREET ORIENTATION LOCAL DRAINAGE	○	●	●	○			●
ELEVATE ON PILES	○	◑	◑	●	○		○
ELEVATE ON FILL	○	○	●	○	○		◑
WATERSHED MANAGEMENT							
FLOODPLAIN ZONING						◑	●

FIGURE 6.2: MEASURE SUSCEPTIBILITY TO DAMAGE BY HAZARDS

● VERY EFFECTIVE
◑ EFFECTIVE
○ MINIMALLY EFFECTIVE

FLOOD HAZARDS ON FAN / MANAGEMENT TOOLS	INUNDATION	SEDIMENT DEPOSITION	SCOUR/UNDERMINING	IMPACT DAMAGES	HYDROSTATIC AND BUOYANT FORCES	HIGH VELOCITIES	UNPREDICTABLE FLOW PATH
DETENTION DAM OR DEBRIS BASIN	◑	●		●	◑	●	●
LEVEES AND CHANNELS	●	◑	◑	●	●	●	●
DROP STRUCTURES	○	◑	●	○	○	◑	◑
DEBRIS FENCES		◑	○	●		○	○
LOCAL DIKES	●	●	◑	○	●	○	◑
STREET ORIENTATION LOCAL DRAINAGE	◑	◑	◑	○	◑	○	○
ELEVATE ON PILES	●	●	◑	○	●		
ELEVATE ON FILL	●	◑	○	◑	●		◑
WATERSHED MANAGEMENT	◑	●	◑	●	◑	◑	◑
FLOODPLAIN ZONING	●	●	●	●	●	●	

FIGURE 6.3: EFFECTIVENESS OF MEASURES AGAINST HAZARDS

hazard susceptibility are discussed below. Section 6.4 recommends specific applications for management tools, while Section 6.5 recommends an approach to flood management.

Debris Basins and Detention Dams

Susceptibility:

- Floods larger than basin capacity will cause excessive discharges or dam overtopping.
- Substantial filling of the basin by sediment occurs during each flood.
- Erosion of dam due to local channel formation and migration can damage the structure.

Effectiveness

- Decrease all major hazards except scour by decreasing peak water and sediment discharges.
- May cause increased scour and channel cutting downstream due to abrupt reduction in sediment load.
- Debris basins may reduce sediment load but not significantly reduce peak discharge.
- Detention dams attenuate peak sediment and water discharges but do not permanently trap either; total sediment deposition may not be significantly reduced.
- If the flood path migrates away from the basin or dam, the tool is useless.

Public Acceptance

- The public may consider these measures to be unsightly and dangerous.
- Costs are high, and are typically paid by federal and state agencies.

Required Maintenance

- Removal of sediment after each flood.
- Repair of channels and spillway.

Levees and Channels

Susceptibility

- Unarmored levees and channels are extremely vulnerable to scour damage and potential failure due to velocities exceeding 20 feet per second. Levees on Rancho Mirage and Palm Desert fans have been breached by floods. Physical model tests (Part II, Section 4.5) show rapid erosion and undercutting of unarmored levees.
- Riprap lined channels and levees resist moderate floods but may be severely damaged by large events as shown in the physical model studies.
- Sediment deposition may cause channel blockage and levee overtopping where abrupt decreases in velocity occur.
- Upstream debris basins or detention dams will substantially reduce risks of overtopping or sediment deposition, but may increase scour problems.

Effectiveness

- When properly designed, armored, and maintained, channels eliminate all flood hazards on the fan.
- Since velocities are extremely high in the channels, safety problems are important.
- A levee/channel system must be continuous from apex (or debris basin if used) to the toe of

the fan. Below the end of the channel, flow braiding and flood path instability recur.

- Abrupt changes in channel shape, capacity or direction cause, as shown in the model tests, local scour or deposition and failure of the channel. Such changes should be avoided.
- Channels are most effective when used in combination with debris basins or detention dams.

Public Acceptance

- General perception of reliability and good protection, despite poor past performance.
- Viewed as unsightly and disruptive to community.
- Safety hazard for children.
- Costs are high, and are typically paid by federal and state agencies.

Required Maintenance

- Sediment removal and channel repair after each flood.
- Routine inspection and maintenance of levees.

Drop Structures

Susceptibility

- Drop structures, because they are designed to dissipate large amounts of energy in a small area, are subject to severe erosion and potential undermining. The foundation and structure must be robust to prevent failure.

Effectiveness

- Substantially reduce scour on steep slopes and stabilize ground surface; ineffective against other hazards.

- In terraced subdivisions, where horizontal house pads are separated by steep banks, drop structures prevent headcutting and formation of channels between structures. As shown in the model tests (Part II, Section 5.4), the reduction in scour hazard is substantial.
- Where channels are used to convey floods down-fan, drop structures can be used in the channels to safely dissipate energy and prevent channel erosion and failure.

Public Acceptance

- While drop structures are commonly used in channels, no uses of them in terraced subdivisions were observed.
- Acceptance is likely to be very good, since they are inexpensive, can be installed by developers, can be retrofitted to existing communities, and can be covered completely by landscaping.

Required Maintenance

- None, except for inspection and repair, if necessary, after floods.

Debris Fences

Susceptibility

- Because they are designed to stop debris, such fences will collect sediment and boulders until they are buried.
- Impact forces on the fences during mud or debris flow events can be large, potentially

causing failure.

- Floods may, unless confined, be diverted around the obstruction caused by a debris fence.

Effectiveness

- Reduce, but not eliminate, impact damages to homes and debris deposition in streets and yards.
- Not effective against other hazards.
- Useful only for debris flow events.
- No examples of use in the U.S. were found.

Public Acceptance

- Acceptance is likely to be good, because costs are low and the fences are inobtrusive.
- Costs can be paid by developers or communities.

Required Maintenance

- Periodic inspection and repair.
- Cleaning of fences after floods.

Local Dikes

Susceptibility

- Dikes are subject to overtopping, scour, and impact force damages if improperly designed.
- Sediment deposition upstream (due to blockage and slowing of flow) may seriously reduce effective dike height.
- Safe design requires that substantial freeboard, adequate armoring of dike face and toe, and resistance to impacts be built into local dikes on fan.

Effectiveness

- Well-designed dikes can successfuly protect individual homes or blocks of homes by diverting flood flows.
- Failure of a dike may cause greater damage than if no dike existed.
- Effective only where they are part of an integrated plan for the entire area. They must be tied into conveyance channels to prevent flooding of other areas by diverted flows.
- Unarmored dikes are of little value, since failure is likely during flood events, as shown in the local model tests (Part II, Section 5.6).

Public Acceptance

- Acceptance is likely to be good due to low costs and a high level of perceived protection.
- Dikes generate more public confidence than they deserve in many cases, since design of local dikes is often inadequate to withstand flood events.
- Costs are paid by developers or homeowners.

Required Maintenance

- Inspection and repair, including removal of sediment, after each flood.

Street Design and Orientation

Susceptibility

- Subject to scour due to extremely high velocities and sediment deposition.
- Streets must be substantially depressed below ground surface and the side-walls armored to

- prevent overtopping and erosion damages.
- Streets not oriented along maximum slope may experience erosion along the down-fan side.

Effectiveness

- When combined with houses raised on armored fill and diversion dikes placed upstream of the development, streets can safely convey the entire flood flow.
- Effectiveness is dependent on the hydraulic capacity of the dikes and streets. Smooth connections between upstream and downstream streets with no sharp bends or blockages are essential to a safe design.
- Physical model results (Part II, Section 5.3) show this to be a very effective management tool for new subdivisions.
- Safety hazards due to extremely high velocities (in excess of 20 feet per second) are serious.

Public Acceptance

- Poor, due to problems with aesthetics (each street is a concrete lined channel), access from driveways, and safety.
- Aesthetic problems can be mitigated by landscaping curb and wall areas.
- Added costs of street orientation and depression are small for new developments and can be paid by developers. The cost of depressing streets in existing developments would be large.

Required Maintenance

- Inspection, repair, and debris removal after floods.

Elevation of Structures on Piles or Fill

Susceptibility

- Unarmored fill is highly susceptible to erosion damage, potentially causing undermining of the associated home. Adequate armoring is essential.
- Scour around piles, if severe, could cause failure of one or more piles. Piles must be driven down to below the maximum possible scour depth.

Effectiveness

- Elevation on piles allows unhampered flow under structures and minimizes scour and deposition hazards. Structures on piles have minimal influence on flood path and hydraulics.
- Elevation on fill (even if armored) can obstruct the flow and increase velocities and erosion in adjacent properties.
- Elevation on fill is effective only when armored and used in combination with upstream dikes and channelized streets.

Public Acceptance

- Elevation on piles has not been well received due to aesthetic problems, safety problems for children, and access difficulties.
- Elevation on fill has been used extensively, but without sufficient regard for scour and flow conveyance problems.
- Costs are low and typically paid by developers.

Required Maintenance

- Inspection and repair after floods.

Watershed Management

Susceptibility

- Reforestation is not susceptible to any flood hazards.
- Terracing may be damaged by erosion.

Effectiveness

- Can substantially reduce all hazards on fans if watershed vegetation is stabilized and increased.
- Arid and semi-arid areas may not support increased vegetation.
- Can be used to reduce costs of debris basins, channels, and other tools by reducing sediment and water discharges.

Public Acceptance

- Excellent, due to improvements in aesthetic aspects of the watershed.
- Costs are typically low and can be paid by state or local agencies.

Required Maintenance

- Normal forest management activities.

Flood Plain Zoning

Susceptibility

- Erratic nature of flow paths on fans may cause floods to impact areas outside of those zoned for the floodway. Flow controls such as armored levees may be required to prevent this.

Effectiveness

- Prevents or restricts development in defined flood plains, provided a stable flood plain can be defined.
- Can be used to restrict density and/or require elevation on piles within flood prone areas.
- Does not eliminate flood hazards, but can be used to minimize amount of property at risk.
- Most effective when used in combination with other tools.

Public Acceptance

- Poor, due to development pressures on many fans in the southwest.
- Direct costs are minimal, but opportunity costs to developers and loss of tax base to communities can be substantial.

Required Maintenance

- Maintenance of reserved areas to minimize flood flow disruption.

6.4 Recommended Applications for Management Tools

Selection of the appropriate tool for application to a particular fan depends on four major factors: types of hazards present, the hydraulic zones where development is expected to occur, the existing development density, and projected future development densities. Section 6.3 has discussed tool effectiveness against hazards. Figure 6.4 summarizes the recommendations regarding specific management tools to be used under combinations of the other three factors. These recommendations consider the types of hazards encountered in different fan zones, the effect of development on the severity of these hazards, the impact of existing development on the feasibility of implementing each

SPARSE EXISTING DEVELOPMENT

HYDRAULIC ZONES	PROJECTED DEVELOPMENT DENSITY: Sparse	Moderate Density	High Density
Channelized Flow	No Construction Zoned Open Space	No Construction Zoned Open Space	Debris Basin* and Channel
Braided Flow	Elevation on Piles	Local Levees and Street Conveyance	Local Levees and Street Conveyance
Sheet Flow	Elevation on Piles or Armored Fill	Elevation on Piles or Armored Fill	Local Levees and Street Conveyance

MODERATE DENSITY EXISTING DEVELOPMENT

HYDRAULIC ZONES	Sparse	Moderate Density	High Density
Channelized Flow		Debris Basin* and Channel	Debris Basin* and Channel
Braided Flow	——	Local Levees and Street Conveyance (if feasible)	Debris Basin* and Channel
Sheet Flow	——	Local Levees and Street Conveyance (if feasible)	Local Levees and Street Conveyance (if feasible)

HIGH DENSITY EXISTING DEVELOPMENT

HYDRAULIC ZONES	Sparse	Moderate Density	High Density
Channelized Flow	——	——	Debris Basin* and Channel
Braided Flow	——	——	Debris Basin* and Channel
Sheet Flow	——	——	Debris Basin* and Channel

* WITH FLOOD STORAGE

Figure 6.4 : Recommended Management Tools for Development Scenarios

tool, and the effectiveness of each tool for eliminating or reducing the hazards when the projected future development density is achieved. The following discussion centers on the relationships between the four factors and management tool applications. Then recommended management tools are discussed for different development conditions.

Effect of Hazard Type

The flood hazards which are common on alluvial fans are substantially different from typical hazards associated with riverine flooding. Consequently, measures for controlling or eliminating these hazards on fans must be viewed differently.

- Elevation on unarmored fill and use of unarmored levees and dikes may result in destruction of these measures due to scour problems.

- Channels and levees may be filled or rendered useless by sediment deposition, and will require dilligent maintenance.

- Local dikes designed to protect small areas will divert flood flows to other parts of the fan and cause concentration of much higher damages at other locations.

- Flood detention facilities must allow for large amounts of sediment deposition.

- The erratic and unpredictable nature of flood paths makes local protection of structures or subdivisions difficult because the location and direction of peak flood flows cannot usually be predicted. Such local measures must be accomplished on nearly all parts of a fan which have no stable entrenchments or strong morphologic bias.

- High velocities cause severe erosion and/or overtopping of levees, dikes, channels, and streets wherever rapid changes in flow direction occur. Flow conveyance structures must be smooth and continuous to avoid such problems.

- Debris and viscous sediment/water mixtures moving at high speed, as frequently occur on fans in the Los Angeles basin and elsewhere, may severely damage houses raised on piles, walls, levees, and local dikes which would withstand the clear water flows typical of riverine flooding.

Failure to consider these effects during design and construction of management tools may result in catastrophic failure and severe flood damages. Cases where such failure has occurred include Rancho Mirage and Palm Desert, California and Bullhead City, Arizona.

Effect of Hydraulic Zone

The three definable hydraulic zones discussed in Section 4.2 exhibit substantially different flood behavior and hazards, requiring different approaches to flood management.

- The channelized flow zone exhibits very high velocities with large scour potential and large sediment loads. Management tools that are designed to control the flow (channels or levees) must be heavily armored. Local flow controls such as dikes and depressed streets are likely to be ineffective due to the force of the channelized flow. Consequently, development of this zone should be avoided unless complete control of floodwaters, using debris basins and/or channels, is assured.

- In the braided flow zone the hydraulic conditions are erratic and may alternate between channelized and braided conditions. Depths of flow and velocities are lower; other hazards are less severe. Local management tools can be used, provided that they are adequately armored. Use of streets or channels for conveyance may be effective, provided that upstream diversion dikes ensure that the erratic flow paths are always directed into the channels. Elevation on fill should be avoided unless flow is confined to armored streets or channels.

- The sheet flow zone is characterized by shallow flooding; although velocities are lower, supercritical flow conditions are common. Local management tools, including elevation on armored fill, can be used. Flood behavior can be substantially altered by development and by management tools in the up-fan hydraulic zones. Hence, up-fan development must be coordinated with development in this zone.

Effect of Existing and Projected Development Density

Existing and projected development densities have a major impact on the appropriateness and feasibility of management tools. Substantial existing development compounds the difficulty, cost, and effectiveness of implementing most tools.

- Sparse existing development provides maximum flexibility and a wide choice of feasible management tools. As shown in Figure 6.4, whole-fan tools (e.g., debris basin and channel system) are needed only for the case where high development densities are expected in the channelized zone. Elevation on armored fill is recommended only in the sheet flow zone, where velocities and erosion are relatively low. Elevation on piles or on armored fill appears to be cost-effective only in areas of sparse or medium density development. Local levees and street conveyance for flood waters appear to be the best tools for a variety of development and hydraulic conditions, because they are relatively inexpensive, can be implemented by developers, and work effectively for all but channelized flows.

- When moderate density development has already taken place without proper planning for flood conveyance, the options for flood management are drastically reduced. Whole-fan measures are the best choice in the channelized flow zone, since other tools are ineffective. Adequate flood plain zoning is not possible when development has already occurred. If existing development is left unprotected, management tools used to protect new development must be carefully designed to avoid aggravating existing flood problems. For example, if streets are used to convey flood flows in new developments but down-fan existing streets do not have sufficient capacity or do not connect smoothly to the new streets, severe flooding of the existing homes could result.

Local levees and street conveyance can be used effectively only if the existing development pattern allows the use of streets as channels.

- When an area of a fan has been fully developed at high densities without regard for flood management, only whole-fan management tools will provide adequate protection for the existing structures. In fact, piecemeal application of local management tools such as dikes and elevation on fill will result in greater damages for some structures, while other structures are protected. This is because dikes and armored fill divert flows rather then containing and controlling the flood.

It is clear from the above discussions that flooding on sparsely developed fans can be managed more easily and cheaply than flooding on developed fans, unless such development has followed a flood management plan. The number of available options decreases rapidly with existing development density. This alone is sufficient justification for the establishment of a comprehensive flood management plan (master plan) before significant development occurs.

One additional management option has not been included in Figure 4.3 because it does not provide flood protection for existing structures on a fan. This option, which can be thought of as a "minimum expenditure" plan, provides only for flood protection of new structures using elevation on piles. This allows continued development of an area without changing the existing hydraulic conditions (e.g., area open to flood flows, slope, etc.) or increasing damages to existing structures. All management costs, which are small, are borne by developers and homeowners.

6.5 Recommended Management Approach

The development of a balanced, coherent approach to flood plain management on fans requires consideration of several complex issues:

1. FEMA's regulatory and statutory role,
2. the role of local communities in fan development,
3. the political and economic appropriateness of non-structural versus structural management tools,
4. the political and economic appropriateness of whole-fan versus local management tools,
5. the practical aspects of protecting new single structures or subdivisions within existing development,
6. the present state-of-the-art in flood analysis on fans, and
7. the results of field investigations and model studies regarding the effectiveness of management tools on fans.

Certain of the above issues and their implications for the management approach are discussed first, followed by a delineation of a recommended approach.

FEMA Versus Local Community Roles in Fan Development

FEMA currently requires that communities join the Flood Insurance Program, that no new structures be constructed within the floodway, and that all new structures built within the flood plain be elevated above the base flood elevation. Local communities are otherwise free to use zoning, structural tools, or non-structural tools to minimize flood damages. If structural measures (e.g., dams, channels, levees) are implemented, the delineated flood plain and floodway (FIS mapping) are altered to reflect the new flood limits. Non-structural measures (e.g., zoning, elevation, floodproofing) do not alter the flood plain.

On alluvial fans with no entrenched channels the flood plain, based on the 100-year flood limits, could occupy most of the fan surface. The floodway could be defined as the entire channelized hydraulic zone. Under existing FEMA statutes, all new structures on such a fan must be elevated, while no structures can be built in the channelized zone.

Existing statutes provide limited guidance regarding control of sediment deposition, scour, and other hazards on alluvial fans. FEMA requires that any obstructions to flow in the flood plain not increase flood related hazards, including inundation and scour. On alluvial fans, this requires that structures built upstream of existing developments not increase the velocity, depth, or scour potential of flood flows. All management tools must be integrated with downstream developments. The burden of proof that flood management tools meet FEMA requirements has, in the past, fallen on local communities.

Whole-fan Versus Local Tools

While FEMA has not required that whole-fan tools be implemented in flood-prone areas, many communities rely on structural tools such as dams, levees, and channels for flood protection when either the value of existing development is high or development pressures are great. Local, nonstructural measures are presently required within the flood plain, but few examples of extensive non-structural tool employment on fans exist. The political and economic decisions made by communities to date have largely dictated whole-fan tools. The reasons for such decisions include:

- protection of existing structures,
- maximization of developable land,
- protection of landscape, streets and utilities,
- lower overall costs, and
- availability of state and federal funding for structural measures.

In cases where large blocks of funding for structural measures are not available, non-structural measures are necessary.

Case studies and model studies indicate that whole-fan tools are appropriate where existing or projected development densities are high. Local measures (e.g., local dikes, street alignment, elevation of structures) appear to be most appropriate when existing and projected development densities are low or moderate. Flood control costs are incurred over the entire development period and can be incorporated into subdivision construction costs.

New Structures Within Existing Development

When individual structures are built within existing subdivisions, flood control tools must become part of the existing flood protection systems. Where no flood protection exists, options for the new structure are limited. Elevation on piles should be used unless it can be shown that no additional flood damages to existing structures will result from construction of other tools (e.g., local dikes or elevation on armored fill). Similarly, subdivisions must be constructed such that no added flood damages to existing property result.

State-Of-The-Art of Flood Analysis on Fans

Considerably more research, including field studies of fans and flood events in progress, will be required to develop a hazard quantification methodology which represents the flood processes discussed in Section 4. Physical modeling results (see Part II, Section 3) provide considerable insight into these processes and allow the development of tentative empirical relations for fan flood hydraulics (see Part II, Section 3.3). The physical models could not, however, be quantitatively verified due to a complete lack of prototype data. Hence, use of these relations for flood prediction will have to wait until field data corroborates physical model results.

Given the present state-of-the-art, the selection and design of flood control tools on fans should combine qualitative analyses of flood behavior (fan characteristics, hydraulic zones, historical flooding patterns), engineering experience and judgement, and the existing quantitative methodology to establish the depth, width, and velocity of flood flows.

Recommended Approach

The following approach to flood plain management on fans is based on the considerations presented in Sections 4, 5, and 6 of this report. It is intended to be a general model for more detailed sets of regulations and guidelines which will, over time, be created by FEMA and communities.

1 Hazard Identification should be accomplished on all developing fans as early as possible and should follow the approach recommended in Section 4.5.

2. A Master Plan should be created by communities (as recommended in Section 5) and used to regulate development.

3. Selection of Management Tools should be made by the community based on identified hazards, the flood management map, the master plan, and FEMA regulations and guidelines (see Section 6.2). The following general guidelines for management tool selection are appropriate.

Channelized Zone

- Development prohibited unless whole-fan measures are implemented.

Braided Zone

- Basements and mobile homes prohibited.
- Streets aligned and designed to convey entire flood flow.
- Use of local dikes to direct flows into streets.
- Use of drop structures between homes built on high slopes to prevent excessive erosion.
- All management tools must be coordinated with tools in existing developments.
- Whole-fan management tools can be used instead of the above provisions.

Shallow Flooding Zone

- Elevation of structures on piles or armored fill.

- Street orientation to maximize flood conveyance.
- If up-fan subdivisions use depressed streets or channels to convey floods, these tools must be continued down to the fan toe.
- Use of drop structures between homes built on high slopes.
- Whole-fan management tools can be used instead of the above provisions.

<u>Placement of Single Structures</u>

- In undeveloped areas, can elevate on armored fill or use local dikes provided that no added flood damage to other structures results.
- In developed areas, local dikes, channels, and armored fill must tie in with existing flood control tools.
- Elevation on piles should be used if above criteria cannot be met.
- No single placement should be allowed in the channelized zone.

4. A <u>Review of Subdivision Plans</u> should be made by local agencies to ensure both compliance with the master plan and proper design of selected management tools. The developer should provide:

- plans for flood control tools,
- an engineering report that documents the adequacy of the proposed flood control tools,
- an analysis of flood impacts of the proposed tools on down-fan development, and
- a maintenance plan.

7. ASSESSMENT OF DAMAGE RISKS ON FANS

7.1 Use Of Damage Curves

Depth/damage curves relate flood stage to damage costs for individual structures. By using damage curves in conjunction with stage/frequency curves, expected annual flood damage for a given structure can be computed and used as a basis for setting appropriate flood insurance premiums. As part of this study depth/damage curves for structures on alluvial fans have been developed following the procedure described in detail in Part II, Section 7 ,of this report. Stage/frequency curves are a function of the hydrologic properties of the fan and the hydraulic characteristics of a specific location on the fan and must therefore be developed on a reach-by-reach basis in separate engineering studies for each fan.

7.2 Damage Curves For Unprotected Structures

Damage curves for unprotected structures on alluvial fans are shown in Figures 7.1, 7.2 and 7.3. These curves were derived in the absence of a significant base of historical flood data and are therefore subject to considerable uncertainty. The damage curves represent modifications of the FIA riverine damage curves to account for the greater damages caused by the sediment-laden, high velocity flood flows characteristic of alluvial fans. A rigorous theoretical derivation of the depth/damage relationships for high velocity flows was attempted, but insufficient information necessitated the employment of a qualitative development approach. Our modifications to the FIA riverine damage curves will improve current damage analyses on fans,

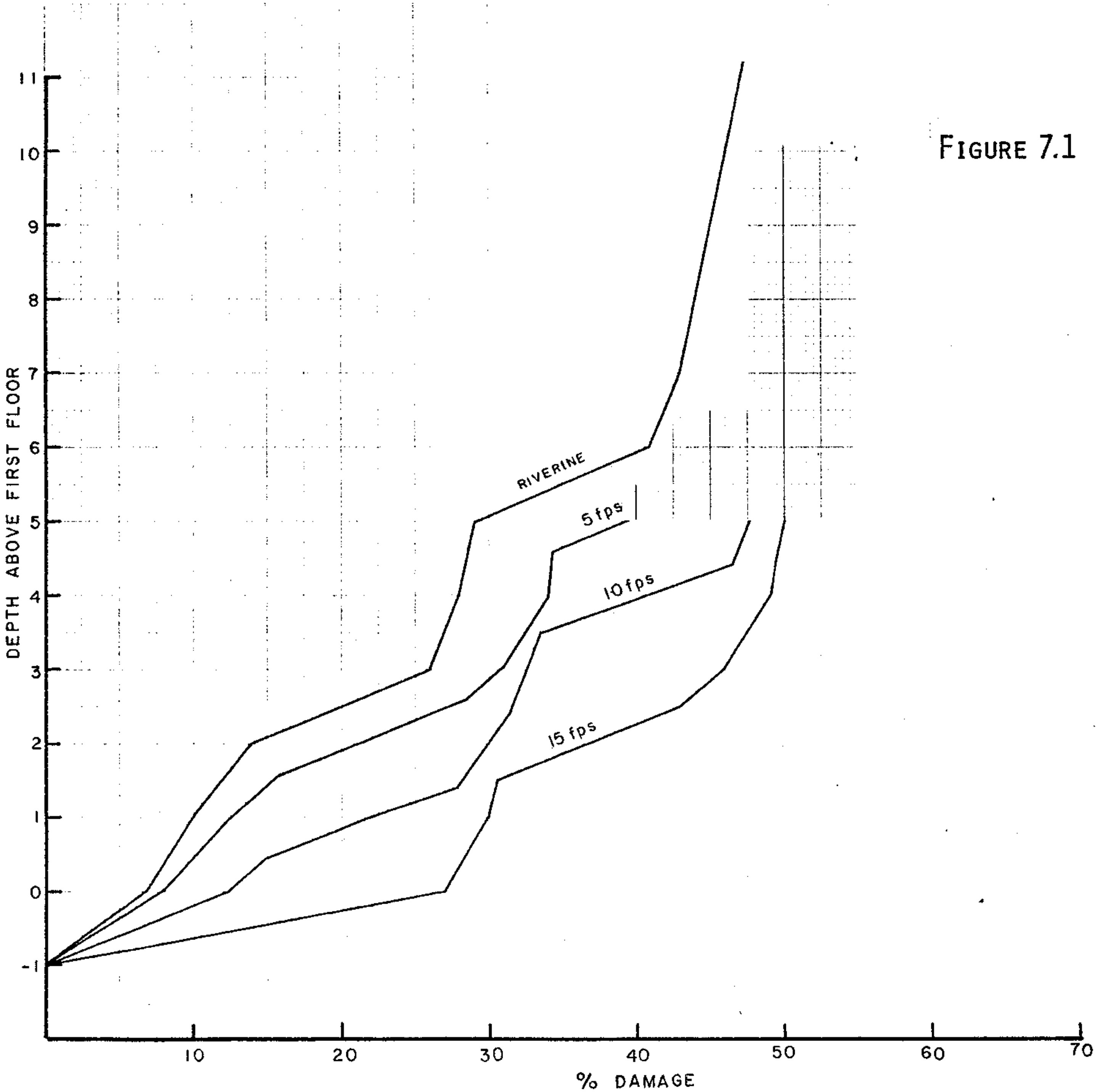


FIGURE 7.1 <u>ALLUVIAL FAN CURVES</u>
1 STORY - NO BASEMENT

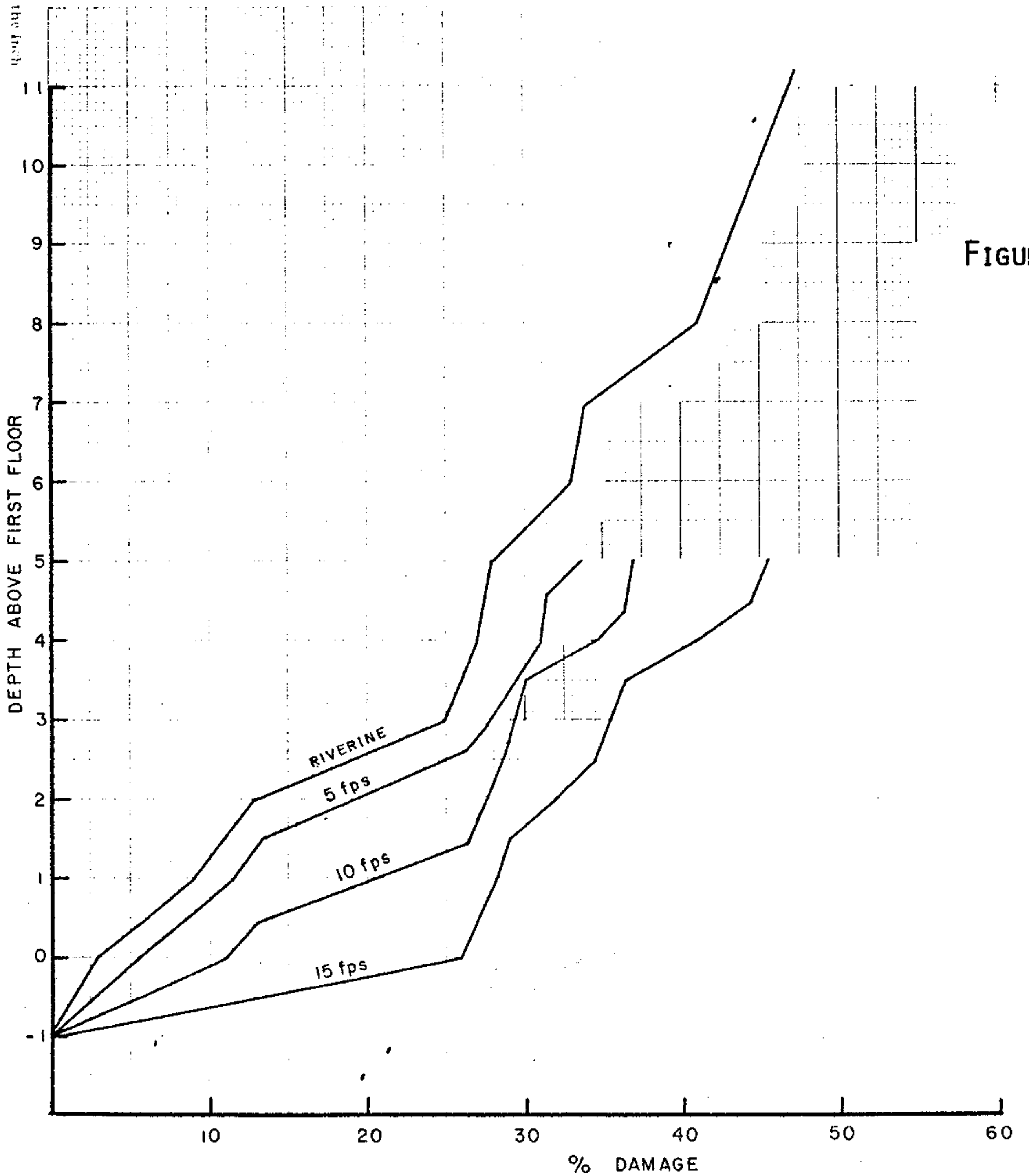


FIGURE 7.2 <u>ALLUVIAL FAN CURVES</u>
SPLIT LEVEL - NO BASEMENT

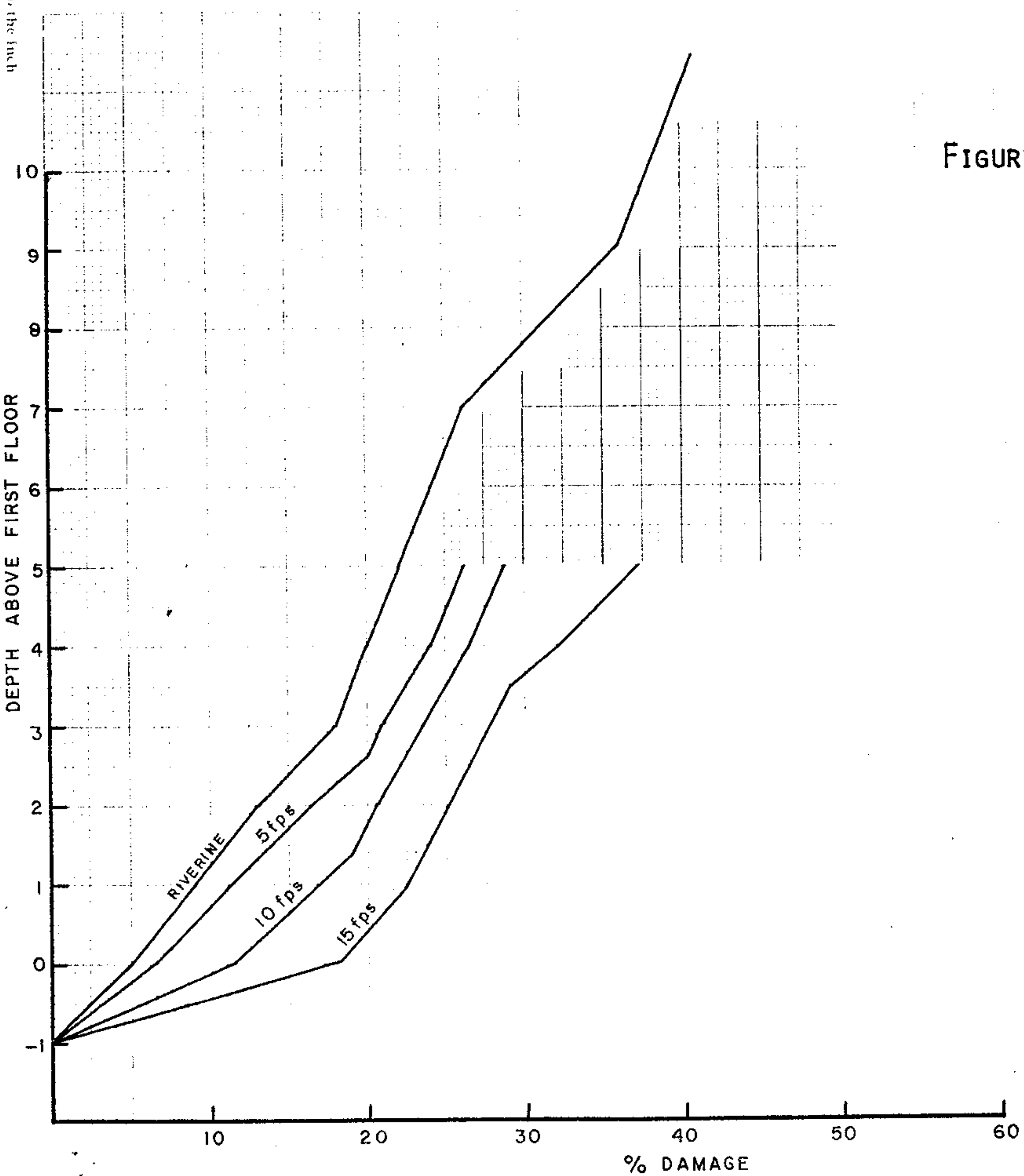


FIGURE 7.3 <u>ALLUVIAL FAN CURVES</u>
TWO OR MORE STORIES -
NO BASEMENT

but the collection of further experimental or historical damage data will allow for refinement of the fan damage curves to further improve damage predictions.

The curves relate depths up to 5 feet (referenced to the first floor of the structure) to per cent damage for three different types of structures at three different velocities (5, 10, and 15 feet per second). Damages for a single flood event or expected annual damages can be predicted with these curves using data on stages and velocities and their frequencies of occurrence. Methodologies for the prediction of stages and velocities on fans are in a relatively early stage of development, thereby impeding the accomplishment of thorough damage analyses.

7.3 Damage Prediction for Structures Protected by Management Tools

Since the depth/damage curves derived for alluvial fans are based upon depths referenced to the elevation of the first floor of the home and are applied to specific velocities, they can be used without alteration for homes subject to the reduced flood depths and velocities resulting from flood plain management measures. Raising the elevation of the first floor (through flood-proofing programs) or lowering the depth of the flood waters around the home (through local dikes or whole-fan structural controls) will result in lower depths for damage prediction without requiring alteration of the damage curves. Control measures that result in a lower flood velocity can be applied to the damage curve developed for that lower velocity.

8. ASSESSMENT OF IMPACTS CAUSED BY MANAGEMENT TOOLS

8.1 Impact Matrices

The approach used to assess the impacts of the flood control measures evaluated in this report is done through the utilization of impact matrices, (shown in Figures 8.1 through 8.4). Impact matrices are designed to qualitatively compare large numbers of alternatives and the external factors associated with their application. In essence, matrices help to identify the alternatives which have the least amount of impact.

All associated impacts under consideration are inserted in the left hand column of the matrices and all selected measures to be evaluated are placed in the top row of the matrices. Each measure listed along the top has a column below it with an individual box for each of the impacts listed along the left hand column. The columns under each flood control measure are divided into three sub-columns. The first sub-column under each measure is used to indicate whether the impact is likely to be permanent or temporary; the second sub-column under each measure indicates whether the impact has a positive or negative effect on existing conditions; and the third sub-column indicates whether the impact is significant or minor for each measure.

Each of the alternative flood control measures are then evaluated for each of the impacts listed in the left-hand column. An appropriate symbol is inserted in each of the three sub-columns to record this evaluation. An overall comparison of each of the measures can then roughly be made by noticing the number of blackened boxes under each measure. This gives a direct indication of the number of

FIGURE 8.1: ENVIRONMENTAL IMPACTS OF SELECTED MEASURES

Impacts	DETENTION DAMS/ DEBRIS BASINS			LEVEES/CHANNELIZATION			DROP STRUCTURES			DEBRIS FENCES			STREET ORIENTATION/ LOCAL DRAINAGE			STRUCTURE ELEVATION ON PILES			STRUCTURE ELEVATION ON FILL			WATERSHED MANAGEMENT			FLOODPLAIN ZONING		
Hydrologic																											
Modifications In Flow	P	+	Significant	P	+	Significant	P	+	Significant	P	+	Significant										P	+	Significant			
-Channel Flow	P	+	Significant	P	+	Significant				P	-	Minor										P	+	Significant			
-Overland Flow	P	+	Significant	P	+	Significant	P	+	Significant	P	+	Significant	P	+	Significant	P	+	Minor	P	+	Significant	P	+	Significant	P	+	Minor
Channel Stability	P	+	Significant	P	+	Significant																P	+	Significant			
Flood Frequency	P	+	Significant	P	+	Significant																P	+	Significant			
Air																											
Quality	T	-	Minor	T	-	Minor							T	-	Minor	T	-	Minor	T	-	Minor	T	-	Minor			
-Particulate Pollution	T	-	Minor	T	-	Minor							T	-	Minor	T	-	Minor	T	-	Minor	T	-	Minor			
-Dust	T	-	Minor	T	-	Minor							T	-	Minor	T	-	Minor	T	-	Minor	T	-	Minor			
Visibility	T	-	Minor	T	-	Minor							T	-	Minor	T	-	Minor	T	-	Minor	T	-	Minor			
Odor	P	-	Minor							P	-	Minor	P	+	Minor							T	-	Minor			
Noise																											
Quality (Magnitude & Duration)																											
-During Construction	T	-	Significant	T	-	Significant	T	-	Minor	T	-	Minor	T	-	Significant	T	-	Minor	T	-	Significant	T	-	Minor			
-After Management Tool Implemented	T	-	Minor	T	-	Minor	T	-	Minor	T	-	Minor															
Water																											
Surface Water Quality	P	+	Minor	P	-	Significant	P	+	Minor	P	+	Significant	P	+	Significant	P	+	Minor				P	+	Significant	P	+	Minor
-Non-point Pollution Source	P	+	Minor										P	-	Minor	P	+	Minor				P	+	Significant	P	+	Minor
-Sediment Load	P	+	Significant	P	-	Significant	P	+	Minor	P	+	Significant	P	+	Significant				P	-	Significant	P	+	Significant	P	-	Minor
-Nutrient Load	P	+	Minor				P	+	Minor													P	+	Significant	P	+	Minor
-Temperature																											
-Dissolved Oxygen							P	+	Minor																P	+	Minor
Ground Water Quality													P	-	Minor	P	+	Minor				P	+	Significant	P	+	Minor
-Non-point Pollution Source													P	-	Minor	P	+	Minor				P	+	Significant	P	+	Minor
-Groundwater Contaminant Transport																						P	+	Minor	P	+	Minor
Ground Water Recharge	P	+	Significant	P	-	Minor				P	+	Minor	P	-	Significant	P	+	Minor				P	+	Significant	P	+	Minor
Land																											
Soil Characteristics And Geology	P	-	Significant																P	+	Minor	P	+	Significant	P	+	Minor
Erosion	P	-	Significant	P	-	Significant	P	-	Significant	P	-	Minor	P	+	Significant	P	+	Significant	P	+	Significant	P	+	Significant	P	+	Significant
Deposition	P	+	Significant	P	-	Significant	P	+	Minor	P	+	Significant	P	+	Significant	P	+	Minor	P	-	Significant	P	+	Significant	P	+	Significant
Soil Compaction	T	-	Minor				T	-	Minor				T	-	Minor	T	-	Minor				P	+	Minor	P	+	Minor
Natural Drainage	P	-	Minor	P	-	Significant				P	-	Minor	P	+	Significant	P	+	Minor	P	-	Minor	P	+	Significant	P	+	Significant
Area Impacted By Flooding	P	+	Significant	P	+	Significant	P	+	Minor	P	+	Minor	P	+	Significant							P	+	Significant	P	+	Significant
Topography				P	-	Significant	P	+	Minor	P	-	Minor							P	-	Significant	P	+	Significant			
Unique Physical Features																											
Biota																											
Vegetation And Ground Cover	T	-	Minor	P	+	Minor										P	+	Significant	P	+	Significant	P	+	Significant	P	+	Minor
-Productivity													P	+	Minor							P	+	Significant	P	+	Minor
-Diversity	P	+	Minor	P	+	Minor										P	+	Minor	P	+	Significant	P	+	Significant	P	+	Minor
-Stability/Resilience	P	+	Minor	P	+	Minor										P	+	Minor	P	+	Minor	P	+	Significant	P	+	Minor
Wildlife																						P	+	Significant	P	+	Minor
-Population Size/Productivity																						P	+	Significant			
-Diversity	P	+	Minor													P	+	Minor				P	+	Significant			
-Stability/Resilience	P	+	Minor													P	+	Minor				P	+	Significant			
Habitats	T	-	Significant	T	-	Significant	P	-	Minor	P	-	Minor	T	-	Significant	P	+	Minor	P	+	Minor	P	+	Significant	P	+	Minor
Migration				P	-	Minor	P	-	Minor	P	-	Minor				P	+	Minor	P	-	Minor	P	+	Minor			
Unique And Endangered Species																						P	+	Minor	P	+	Minor
Aesthetics																											
Open Space Quality	P	-	Significant	P	-	Significant				P	-	Minor	P	-	Minor	P	-	Significant	P	-	Significant	P	+	Significant	P	+	Minor
Landscape	P	-	Significant	P	-	Significant	P	-	Minor	P	-	Minor	P	-	Significant	P	-	Significant	P	-	Significant	P	+	Significant	P	+	Minor
Scenic Views And Vistas	P	-	Significant	P	-	Significant	P	-	Minor	P	-	Minor				P	-	Significant	P	-	Significant	P	+	Significant	P	+	Minor
Natural Resources																											
Accessibility Of Existing Resources				P	-	Minor				P	-	Minor															
Depletion Of Natural Resources				T	-	Minor	T	-	Minor																		
Expenditure Of Scarce And Non-renewable Resources	T	-	Minor																								

KEY

P = Permanent Impact

T = Temporary Impact

\+ = Positive Impact

\- = Negative Impact

(Minor symbol) = Minor Impact

(Significant symbol) = Significant Impact

Blank spaces indicate "No Impact"

FIGURE 8.2: SOCIAL IMPACTS OF SELECTED MEASURES

Impacts	DETENTION DAMS/ DEBRIS BASINS	LEVEES/CHANNELIZATION	DROP STRUCTURES	DEBRIS FENCES	STREET ORIENTATION/ LOCAL DRAINAGE	STRUCTURE ELEVATION ON PILES	STRUCTURE ELEVATION ON FILL	WATERSHED MANAGEMENT	FLOODPLAIN ZONING
Community									
Community Cohesion		P − ■	P − ◢	P − ◢	P − ■	P − ◢	P − ◢		P − ■
Community Growth/Population	P + ■	P + ■							P − ■
Community Facilities/Infrastructure					P − ■				P − ■
-Water Supply	P + ◢				P − ◢			P + ■	P + ■
-Fuel And Energy Consumption					P − ◢				P + ■
-Waste Disposal					P + ◢				P + ■
-Transportation/Circluation		P − ◢			P − ■				P − ■
-Public Services - Fire, Police, Schools, Emergency Services									P − ■
Population/People									
Health									P + ■
-Physiological Well-being									P + ■
-Psychological Well-being	P − ■	P − ■				P + ◢	P + ◢		P + ■
Safety	P − ◢	P − ■			P − ◢	P + ◢	P + ◢		P + ■
Cultural Patterns/Life-styles									
Displacement Of People (Residents)		P − ◢			P − ■				P − ■
Displacement Of Structures (Homes & Businesses)		P − ◢			P − ■				P − ■
Recreational Opportunities								P + ■	P − ◢
Demographic Characteristics (Location, Distribution, Density, Growth Rate)									P − ■
Employment									P − ■
Effect On Real Income (Amount)									P − ◢
Housing And Property Values	P + ◢	P + ◢	P − ◢	P − ◢	P − ◢	P + ■	P + ■		P − ■
Land Use									
Pattern Of Land Use Development	P + ■	P + ■			P + ■				P + ■
Historic And Archaeological Sites									P + ■

KEY

P = Permanent Impact

T = Temporary Impact

\+ = Positive Impact

− = Negative Impact

◢ = Minor Impact

■ = Significant Impact

Blank spaces indicate "No Impact"

FIGURE 8.3: ECONOMIC IMPACTS OF SELECTED MEASURES

Impacts	DETENTION DAMS DEBRIS BASINS	LEVEES CHANNELIZATION	DROP STRUCTURES	DEBRIS FENCES	STREET ORIENTATION LOCAL DRAINAGE	STRUCTURE ELEVATION ON PILES	STRUCTURE ELEVATION ON FILL	WATERSHED MANAGEMENT	FLOODPLAIN ZONING
Reduction of Damages to Existing Property									
Buildings	P + Major	P + Major	P + Major	P + Minor	P + Major	P + Major	P + Major	P + Minor	
Building Contents	P + Major	P + Major	P + Minor	P + Minor	P + Major	P + Major	P + Major	P + Minor	
Vehicles	P + Major	P + Major	P + Minor	P + Minor	P - Major		P + Major	P + Minor	
Utilities	P + Major	P + Major		P + Minor		P - Major	P + Minor	P + Minor	
Streets & Roads	P + Major	P + Major		P + Minor				P + Minor	
Bridges	P + Major	P Major		P + Minor				P + Minor	
Standing Crops	P + Major	P + Major		P + Minor				P + Minor	
Livestock	P + Major	P + Major						P + Minor	
Cropland	P + Major	P + Major		P + Minor				P + Minor	
Landscaping	P + Major	P + Major	P + Major	P + Minor	P + Major		P + Major	P + Minor	
Reduction of Damages to Future Property									
Buildings	P + Major	P + Major		P + Minor	P + Major			P + Minor	P + Major
Building Contents	P + Major	P + Major		P + Minor	P + Major			P + Minor	P + Major
Vehicles	P + Major	P + Major		P + Minor	P - Major			P + Minor	P + Major
Utilities	P + Major	P + Major		P + Minor				P + Minor	P + Major
Streets & Roads	P + Major	P + Major		P + Minor				P + Minor	P + Major
Bridges	P + Major	P + Major		P + Minor				P + Minor	
Standing Crops	P + Major	P + Major		P + Minor				P + Minor	
Livestock	P + Major	P + Major						P + Minor	
Cropland	P + Major	P + Major		P + Minor				P + Minor	
Landscaping	P + Major	P + Major		P + Minor	P + Major			P + Minor	P + Major
Reduction of Emergency Costs									
Evacuation & Reoccupation	P + Major	P + Major	P + Major	P + Minor	P + Major	P + Minor	P + Minor	P + Minor	P + Major
Flood Fighting	P + Major	P + Major	P + Major	P + Minor	P + Major	P + Major	P + Major	P + Minor	P + Major
Debris Removal	P + Major	P + Major	P + Minor	P + Major	P +			P + Minor	P + Major
Disaster Relief	P + Major	P + Major	P + Major	P + Minor	P + Major	P + Major	P + Major	P + Minor	P + Major
Increased Cost of Normal Operations	P + Major	P + Major	P + Minor	P + Minor	P + Major	P + Minor	P + Minor	P + Minor	P + Major
Reduction of Business & Financial Losses									
Interruption of Commerce	P + Major	P + Major	P + Minor	P +	P + Major	P + Minor	P + Minor	P + Minor	P + Major
Unemployment	P + Major	P + Major	P + Minor	P +	P + Major	P + Major	P + Major	P + Minor	P + Major
Lost Taxes	P + Major	P + Major	P + Minor	P +	P + Major	P + Major	P + Major	P + Minor	P + Major
Intensification Benefits									
Urban Land Use	P + Major	P + Major	P + Minor		P + Major	P + Major	P + Major	P + Minor	P - Major
Agricultural Land Use	P + Major	P + Major						P + Minor	
Location Benefits									
Urban Land Use	P + Major	P + Major	P + Minor		P + Major	P + Major	P + Major	P + Minor	P - Major
Agricultural Land Use	P + Major	P + Major						P + Minor	

KEY

P = Permanent Impact — + = Positive Impact — Minor = Minor Impact (half-black square)

T = Temporary Impact — - = Negative Impact — Major = Major Impact (black square)

Blank spaces indicate "No Impact"

FIGURE 8.4: INFLATIONARY IMPACTS OF SELECTED MEASURES

Impacts	DETENTION DAMS/ DEBRIS BASINS	LEVEES/CHANNELIZATION	DROP STRUCTURES	DEBRIS FENCES	STREET ORIENTATION/ LOCAL DRAINAGE	STRUCTURE ELEVATION ON PILES	STRUCTURE ELEVATION ON FILL	WATERSHED MANAGEMENT	FLOODPLAIN ZONING
Cost Impact on Consumer									
Food									
Housing			T, -, Minor			T, -, Minor	T, -, Minor		P, -, Minor
Transportation		P, -, Minor							
Other Goods & Services									
Cost Impact on Business									
Land									P, -, Minor
Construction			T, -, Minor			T, -, Minor	T, -, Minor		
Operations									
Transportation		P, -, Minor							
Raw Materials									
Supplies									
Labor									
Cost Impacts on Government									
Construction	T, -, Significant	T, -, Significant	T, -, Minor	T, -, Minor	T, -, Minor	T, -, Minor	T, -, Minor	P, -, Minor	
Operation & Maintenance	P, -, Minor	T, -, Minor		T, -, Minor				P, -, Minor	
Transportation Systems		T, -, Significant	Minor						
Public Service Functions									P, +, Minor
Tax Revenues									
Effect on Productivity									
Commercial									
Industrial									
Agricultural									
Individual									
Governmental									
Effect on Competition									
Agricultural									
Manufacturing									
Effect on Supplies of Important Products and Services									
Food									
Water	P, +, Minor							P, +, Minor	
Housing									P, -, Minor
Transportation		P, -, Minor							
Recreation	P, +, Minor	P, +, Minor							P, +, Minor

KEY

P = Permanent Impact

T = Temporary Impact

+ = Positive Impact

- = Negative Impact

◪ = Minor Impact

■ = Significant Impact

Blank spaces indicate "No Impact"

significant impacts caused by each measure. One can then look at the number of positive and negative signs in the second sub-column to determine whether each measure has an overall beneficial or detrimental impact. Finally the P's and T's inserted in the first sub-column will give an indication of the duration of the impacts caused by each measure.

A quick comparison of the flood control measures and their corresponding impacts can then be made by considering just the significant, permanent impacts (filled in boxes with the letter P) of each measure. This will actually compare the major long-term impacts associated with each measure and aid in identifying the alternative with the least overall impact.

Discussions of impact matrix development and the impacts of each management tool are presented in Part II, Section 8 of this report.

8.2 Conclusions Regarding Management Tool Impacts

The following general conclusions regarding management tool impacts are derived from the impact matrices and discussions (Part II, Section 8.4).

1. Whole-fan, structural measures (dams, levees, channels) have the most significant positive and negative environmental and economic impacts.

2. Structural measures tend to improve economic, hydrologic, water quality, and biota conditions, but degrade air, noise, land and aesthetic conditions.

3. Local measures have generally minor environmental impacts, with the most significant negative impacts accruing to aesthetic and biota conditions.

4. Local measures have considerably less significant economic benefits than whole-fan measures.

5. Inflationary impacts are minor for all measures.

6. Social impacts are minor, except for substantial negative impacts of flood plain zoning and moderately negative impacts of channels and street orientation.

7. Watershed management and flood plain zoning have significant environmental benefits.

GLOSSARY

Alluvial Fan - Fan-shaped depositional landform found at the base of mountain ranges and created from stream sediment.

Apex - Point on the fan where stream first deposits sediment (at the highest point of the depositional cone).

Apron - Coalescence of several fans into a broad, sloping plain.

Avulsion - Action of water whereby it leaves an established flow channel and forms a new flow path.

Bias - Fan topography which tends to confine flood flows to one part of the fan.

Braiding - Flow pattern consisting of many interconnected channels separated in places by numerous low islands.

Debris Flow - A viscous mixture of mud that does not conform to the hydraulic properties of water and is capable of carrying boulders and debris weighing many tons.

Entrenched Channel - Flow path eroded into a fan that is significantly lower than the fan's surface.

Ephemeral Stream - A watercourse which contains water only during flood events and is typically subject to flash flooding.

Flood Plain - The area of a fan impacted by flooding (ususally defined by the 100-year flood).

Flood Proofing - Any measure taken to protect an individual structure from flood damage.

Floodway - A reserved area of the flood plain which carries the bulk of the flood flows, with typically high velocities and depths of flow.

Froude Number - A non-dimensional number indicating among other things, whether flow is supercritical (greater then 1) or subcritical (less than 1).

Local Tools - Management measures, such as, local dikes, drop structures, and elevation, which protect only a small part of a fan.

Morphology - Shape and structure of a fan, resulting from its' geologic history.

Sheet Flow - Water flow in shallow, widespread (sheet-like) layers without defined channels.

Toe - Base of the depositional cone of an alluvial fan.

Wash - An alluvial valley floor.

Whole-fan Tools - Management measures, such as channels or debris basins, which are designed to control flooding over much of a fan.