CONTRACT FCD 93-53

FLOOD CHARACTERISTICS OF FEMA SITE 6A OF THE SCOTTSDALE FLOOD INSURANCE STUDY

Final Report

by
Hjalmar W. Hjalmarson, P.E.
Consulting Hydrologist

Submitted to

Flood Control District
of
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June 3, 1994
(Includes Addendum of 8/22/94-Appendix F)

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LIST OF ACRONYMS

ASCE	American Society of Civil Engineers
CofE	U.S. Army Corps of Engineers
DFA	Distributary-flow area
FCD	Flood Control District of Maricopa County
FHWA	Federal Highway Administration
FEMA	Federal Emergency Management Agency
NSSIHB	National soil survey interpretations handbook
PD	Primary diffluence
SC	Study contractor
SCS	U.S. Soil Conservation Service
TEC	Technical evaluation contractor
ULI	Urban Land Institute
USDA	U. S. Department of Agriculture
USFS	U. S. Forest Service
USGS	U.S. Geological Survey

GLOSSARY

(For flood hazard identification and use of soil surveys)

Accretion	The gradual increase or extension of land by natural forces acting over a long period of time, as on flood plains by the accumulation of sediment deposition by a stream (NSSIHB).
Aggradation	The processes of building up a surface by deposition. The accumulation of material by a stream in order to establish or maintain uniformity of grade (NSSIHB).
Aggregate, soil	Many fine particles held in a single mass or cluster. Natural soil aggregates such as granules, blocks, or prisms, are called peds. Clods are aggregates produced by tillage or logging (Camp, 1986).
Alluvial cone	A type of alluvial fan with very steep slopes and generally higher and narrower than a fan (NSSIHB).
Alluvial fan	A geomorphologic feature characterized by a cone- or fan-shaped deposit of boulders, gravel, and fine sediments that have been eroded from mountain slopes, transported by floodflows and deposited on valley floors (from Hjalmarson and Kemna, 1991). Also, a low, outspread, relatively flat to gently sloping mass of loose soil and/or rock material, shaped like an open fan or a segment of a cone, deposited by a stream at the place where it issues from a narrow mountain valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream, or wherever a constriction in a valley abruptly ceases or the gradient of the stream suddenly deceases; it is steeper near the mouth of the valley where its apex points upstream, and it slopes gently and convexly outward with a gradually decreasing gradient (NSSIHB). Also, alluvium material, such as sand, silt, or clay, deposited on land by streams (Camp, 1986).
Alluvial fan processes	Floods passing the primary diffluence are commonly sediment dominated where the large sediment concentration may have altered the fluid characteristics of the floodflow by increasing the viscosity and density. The sediment dominated floods passing the primary diffluence become unconfined and deposit debris. The deposits commonly (1) are unstratified and unsorted boulders, cobbles, sands, and fines; (2) have terminal, steep-fronted lobes of debris bordering the channel or flow path and can be perched above the surrounding land and; (3) have marginal levees of course rock fragments. Also see "hydraulic processes".
Alluvium	Sediment, including clay, silt, sand, and gravel, that has been deposited by running water.
Amorphous	Without a definite or distinctive form.
Arroyo	Flat-floored vertically walled channel of an ephemeral or intermittent stream, typical of semi-arid climates. Sometimes called a wash and with banks cut in unconsolidated material (NSSIHB).

Avulsion	A sudden cutting off or separation of land by a flood or by abrupt change in the course of a stream, as by breaking through a meander or by a sudden change in current whereby the stream deserts its old channel for a new one (NSSIHB). Stream piracy is a "slow avulsion" where a tributary to a base level stream which is degrading, can rapidly erode headward and cut into the divide separating it from another drainage basin, and provide an outlet for a section of a stream in the adjoining drainage basin.
Base level	A level below which a stream cannot erode.
Bajada	A broad deposit of alluvium formed by coalescing alluvial fans.
Bedded	Formed, arranged, or deposited in layers or beds, or made up of or occurring in the form of beds (NSSIHB).
Bedding	A collective term used to signify the existence of beds or layers in sedimentary rock (NSSIHB).
Bolsom	An internally drained (closed) intermontane basin with two major landform components: basin floor and piedmont slope (NSSIHB). A desert basin rimmed by mountains.
Braided stream	A channel or stream with multiple channels that interweave as a result of repeated bifurcation and convergence of flow around interchannel bars, resembling (in plan view) the strands of a complex braid (NSSIHB). On the average, for every fork there is a corresponding joining of the small channels. A complex pattern of converging stream channels separated by sand bars and islands.
Caliche	A general term for a prominent zone of secondary carbonate accumulation in the surficial materials of warm, subhumid to semiarid areas.... (NSSIHB). The accumulation of carbonates is similar to that in the B soil horizon but caliche is near the land surface. Also known as calcrete.
Canyon	A long, deep, narrow, very steep-sided valley with high and precipitous walls in an area of high local relief (NSSIHB).
Cementation	The process by which a binding agent is precipitated in the spaces between in individual particles of an unconsolidated deposit. The most common are calcite, dolomite, and quartz (NSSIHB). Cemented conglomerate can be very resistant to erosion by floodwater.
Clay	Soil fragmental material with a particle size below 0.002 millimeters in diameter. A group of crystalline minerals composed largely of iron and aluminum silicates.
Cobble size	Particles less than 64 mm (2.5 in.) in diameter and greater that 16 mm in diameter.
Concave/convex contours	General shape of the contour in plan view looking downstream. Convex contours bow downstream and concave contours bow upstream.
Conglomerate	A sedimentary rock composed of water transported pebbles of other rocks cemented together or compacted. A consolidated gravel.
Debris flow	A mass movement of rock fragments, soil, mud, more than half of the particles being larger than sand size (NSSIHB). Rapid mass movement of a dense, viscous mixture of rock fragments, fine earth, water, and possibly entrapped air (Hjalmarson and Kemna, 1991).

Desert varnish	A natural accretion of manganese and iron oxides, clay minerals, trace elements, and small quantities of organic matter that form dark coatings on stable surfaces in terrestrial weathering environments (Hjalmarson and Kemna, 1991).
Diffluence	Point of separation of a stream channel into two or more distributary channels (Hjalmarson and Kemna, 1991).
Distributary channel	Diffluent or separated channel downstream of a diffluence commonly having a terrace independent of other distributary channels (Hjalmarson and Kemna, 1991). A distributary channel flows away from the main (other) channel, is separate from the main channel, and commonly does not return to a single main channel.
Distributary flow	Diffuse flow where there is at least one distinct diffluence at the outflowing branch or fork of a stream where two or more distributary channels are formed. This term is for distributary-flow areas in the southwestern United States and is not to be confused with other uses such as for deltas.
Distributary-flow area	Areas with distributary flow (DFAs) have at least one channel fork or diffluence where at least two channel links are formed. Thus, DFAs are not landforms but rather areas of land where the drainage pattern is distributary as opposed to areas with the more common tributary drainage pattern. DFAs generally are systems of channel forks, joins, and outlets and the number of outlets is more than the number of forks. Because floodflow on alluvial fans commonly is distributary, alluvial fans are considered to be DFAs. Also, according to Hjalmarson and Kemna (1991), a DFA is an area, in square miles, on the piedmont downstream from the primary diffluence and limited by the potential extent of major floods.
Drainage divide	The rim or topographic ridge of a drainage basin. On piedmonts where there is a diffluence on the topographic ridge, the drainage divide is the probable boundary that bisects the defined ridge lines.
Drainage texture	The spacing of low-order drainage channels across a land surface at right angles to the drainage axis or direction (Hjalmarson and Kemna, 1991). Commonly determined at the same elevation such as along elevation contours of topographic maps.
Draw	A small stream channel, generally more open and with broader floor that a ravine or gulch (NSSIHB).
Fan apron	A sheet-like mantle of relatively young alluvium covering part of an older fan piedmont or part of an alluvial (fan) surface.
Fanglomerate	Cemented, coarse, detrital rock which originally was deposited in an alluvial fan.
Fanhead trench	A linear depression formed by a drainageway that is incised considerably below the surface of an alluvial fan. According to Bull (1964), a stream channel entrenched into the upper, and possibly the middle part of a fan.
Fan piedmont	The most extensive major landform of most piedmont slopes, formed by the lateral coalescence of mountain-front alluvial fans downslope into one generally smooth slope without the transverse undulations of the semi-conical alluvial fans and accretions of fan aprons.

Fan skirt	A zone of smooth, laterally-coalescing, small alluvial fans that issue from gullies cut into the fan piedmont of a bolsom, or that are coalescing extensions of the inset fans on the fan pediment, and that merge with the basin floor at their toeslopes.
Fan terrace	A relict alluvial fan, no longer a site of active deposition, incised by younger and lower alluvial surfaces (Camp, 1986). A fan formed during the Pleistocene Epoch.
Flood plain	A strip of relatively smooth land bordering a stream, built of sediment carried by the stream and dropped in the slack water beyond the influence of the swiftest current. Also, the lowland that borders a river, usually dry but subject to flooding.
Gulch	A small stream channel, narrow and steepsided in cross section, and larger than a gully.
Gully	A very small, commonly ephemeral, channel with steep sides cut by running water.
Hydraulic processes	Most floods passing the primary diffluence are water dominated where the sediment has not altered the fluid characteristics of the floodflow by increasing the viscosity and density.
Interfluve	The ridge between channels. More specifically, the relatively undissected upland or ridge between two adjacent valleys or drainageways containing streams flowing in the same general direction and that sheds water to those drainageways.
Intermontane basin	A generic term for wide structural depressions between mountains ranges that are partly filled with alluvium and called "valleys" in the vernacular. Bolsoms are internally drained valleys.
Intersection point	The point, shown on the longitudinal profile, at which the main channel merges with the fan surface (Hjalmarson and Kemna, 1991).
Landform	Any physical, recognizable form or feature on the earth's surface, having a characteristic shape, and produced by natural causes.
Loam	Soil material that is 7 to 27 percent clay particles, 28 to 50 percent silt particles, and less than 52 percent sand particles.
Loamy	A broad grouping of texture classes; includes all sandy loams, clay loams, loam, silt, and silt-loam textures. Sometimes subdivided into moderately fine-textured groups.
Morphology	Pertaining to the form and structure of things.
Mudflow	A debris flow that has dominantly sand size or smaller particles (Peterson, 1981). Also, a flow of a well-mixed mass of rock, earth, and water with a consistency like newly mixed concrete.
Nested DFA	A relatively small DFA located within a drainage basin. The distributary channels of a nested DFA converge into tributary channels within the drainage basin. In Arizona, some drainage basins have small "nested" areas of distributary channels within a system of tributary channels.

Pediment	Gently inclined planate erosion surfaces carved in bedrock and generally veneered with fluvial gravels. They generally occur between mountain fronts and valley or basin bottoms and commonly form extensive bedrock surfaces over which the erosion products from the retreating mountain fronts are transported to the basin or valley below. Because pediments are erosional landforms the drainage channels generally are tributary and only occasionally distributary. The drainage density of low order stream channels generally increases in the upslope direction on pediments. According to Doehring (1970) a pediment is underlain by unconsolidated rock, is usually fan-shaped in plan, and may have an alluvial veneer not exceeding 50 ft. in thickness.
Piedmont plain	Region extending from the mountain front to the basin floor that includes pediments, old fans, alluvial fans, bajadas, and distributary-flow areas (Hjalmarson and Kemna, 1991).
Plain	An extensive lowland area that ranges from level to gently sloping or undulating (NSSIHB). An extensive area characterized by a local relief of less than 200 ft. and having slopes generally less than 5 percent.
Playa	A level or nearly level area that occupies the lowest part of a completely closed basin and that is covered with water at irregular intervals, forming a temporary lake. Playa deposits are fine grained.
Potential divide (boundary)	Boundary delineating the probable limits of distributary flow resulting from floodflow that passes the primary diffluence.
Primary diffluence(PD)	Diffluence or bifurcaton below which flow is distributary and above which the 100-year flood is contained in the channel and flood plain and flow is tributary (with the possible exception of minor diffluences in the drainage basin).
Residual soils	Soils that have developed in place from the underlying rock, without having been transported.
Sand	Fragmental material whose particle size is roughly between 0.05 and 2 millimeters in diameter. As a texture class, a soil that is 85 percent or more sand and not more than 10 percent clay (NSSIHB).
Semi bolsom	A wide desert basin or valley that is drained by an intermittent or ephemeral stream flow through canyons at each end and reaching a surface outlet.
Side slope	The slope bounding a drainageway and lying between the drainageway and the adjacent interfluve. It is generally linear along the slope width and overland flow is parallel down the slope.
Silt	A soil textural class having particle sizes between 0.002 and 0.05 millimeter in diameter and 80 percent or more silt and less than 12 percent clay (NSSIHB).
Slope alluvium	Sediment gradually transported on mountain or hill slopes primarily by alluvial processes and characterized by particle sorting. In the profile sequence, the sediments can be distinguished by size.
Soil complex	Two or more soils in such an intricate pattern or in such small areas that they cannot be shown separately on maps. Complexes consist of two or more dissimilar soils occurring in a regularly repeating pattern (NSSIHB).

Soil horizon	A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in properties such as color, structure, texture, consistence, biological and chemical characteristics (NSSIHB).
Soil phase	Soils of a series that differ in features such as texture, slope, salinity, and degree of erosion. A soil phase commonly indicates the feature that affects use or management (NSSIHB).
Soil series	Soils that have profiles that are almost alike. All soils in a series have major horizons that are similar in composition, thickness, classification, and arrangement (NSSIHB).
Soil texture	The relative proportions of the various soil separates (clay, silt and sand) in a soil material (NSSIHB).
Subsidence	Sinking or settlement of the land surface, due to any of several processes. It does not include landslides. The subsidence of the few valleys in central and southern Arizona may initiate headcutting of tributary stream channels.
Swale	A slight depression in the midst of generally level land. Sheet flow is common in swales.
Terrace	A nearly level surface, relatively narrow, bordering a stream or body of water, and terminating in a steep bank. Commonly the term is modified to indicate origin, as in a stream terrace. According to (NSSIHB), a stream terrace is one of a series of platforms in a stream valley, flanking and more or less parallel to the stream channel, originally formed near the level of the stream, and representing the dissected remnants of an abandoned flood plain, stream bed, or valley floor produced during a former state of erosion or deposition.
Texture	The general physical appearance of a rock or soil, as shown by the size, shape, and arrangement of the particles that make up the rock or soil.
Toe	Boundary delineating the probable downslope limits of a distributary-flow area normally where the floodflow changes from distributary to (1) tributary, (2) sheetflow, or (3) enters a base-level stream.
Trough line	Line joining the points of greatest depth along the swale-like area where adjacent alluvial fans have joined or coalesced.
Valley flat	A flood plain landform. A general term for broad, nearly level flood-plain surfaces that are not subject to frequent inundation.

EXECUTIVE SUMMARY

The stability of flow paths and stream channels on a distributary-flow area is systematically estimated. A detailed evaluation of how to assess flow path stability is developed for use by engineers and hydrologists. The assessment is in two levels. The first level, which is a reconnaissance and quantitative assessment of channel and landform stability, is based on observations of the lack of movement of flow paths, surveyed cross sections depicting channel geometry, soil characteristics, vegetation, geology, and hydraulic conditions unique to distributary-flow areas (DFAs). The second level of stability assessment is based mostly on detailed channel and bed material characteristics, channel geometry and engineering methods used by Federal agencies including the CofE, SCS and USGS. Two categories of DFA are used: (1) an **unstable** DFA with an aggrading surface and unpredictable paths of flow and (2) a **stable** DFA with a relatively stable or degrading network of incised channels. Both levels of stability assessment are applied to a specific site near Carefree, Arizona a few miles north of Phoenix. Part of the assessment of flow path stability is subjective; the subjectivity is advantageous because the inclusion of a factor such as vegetation, which is not rigorously quantified, can influence the assessment of stability.

A most fundamental means of assessing flow path stability is the comparison of old and recent aerial photographs for evidence of channel movement. A photograph of the lower part of the DFA taken in 1940 was obtained from the National Archives and compared with photographs taken in 1953 and 1991. With few exceptions individual larger trees along the defined channels were visible on all sets of photographs. Also, the channels remained at the same position relative to the trees for the three sets of photographs. There was no evidence that channel movement destroyed trees along the channel banks or that the channels moved relative to the location of the trees.

A **distributary channel** flows away from the main (other) channel, is separate from the main channel, and commonly does not return to a single main channel. **Distributary flow** is diffuse flow where there is at least one distinct diffluence at the outflowing branch of a stream. Areas with distributary flow (DFAs) have at least one channel fork or diffluence where at least two channel links are formed. Thus, **DFAs** are not landforms but rather areas of land where the drainage pattern is distributary as opposed to areas with the more common tributary drainage pattern. Because floodflow on alluvial fans commonly is distributary, alluvial fans are considered to be DFAs. The primary diffluence (PD) is comparable to the apex of an alluvial fan.

Floodflow of stable DFAs like the site near Carefree, Arizona follows unchanging paths of flow and commonly is in incised channels and/or on stable flood plains. Floodwater that overtops the banks of channels incised in developed soils generally spreads over adjacent land between, and over stable interfluves or ridges separating the distributary channels. The distributary channels are within the surface of the landform. The banks of the channels are lined with grasses, bushes and large desert trees such as paloverde and mesquite and the interfluves are commonly covered with bushes, scattered trees and saguaro cacti. The unchanging paths of flow in the entrenched distributary channels is a significant flood hazard characteristic of stable DFAs. Of importance

but of much lesser significance than the flow path stability is the inherent difficulty of determining precise amounts of flow in each of the distributary channels. The stable paths of flow with degradation restricted by cemented material point to the presence of hydraulic processes at work on site 6A near Carefree Arizona.

Floodflow of unstable DFAs commonly is in perched channels in relation to the ground at approximately equal distances from the apex or primary diffluence. Floodwater can overtop or breach the perched banks and spread over the adjacent low-lying land. Unlike the entrenched channels of stable DFAs where floodwater overtopping the banks spreads laterally and upward toward defined ridges, the floodwater overtopping the banks of unstable DFAs spreads laterally on low-lying land possibly forming new channels. There is little vegetation in areas of mobile bed material on the most unstable alluvial fans and the type, size and density of vegetation commonly changes at the fan boundaries. The changing paths of flow point to the presence of alluvial fan processes at work with associated debris flows or high sediment loads emanating from the drainage basin.

The channel banks are stable as shown quantitatively by (1) the measured amounts of silt and clay deposited along the wetted perimeter of the channel banks, (2) the relation between the measured channel width-depth ratio and the measured percent silt-clay along the wetted perimeter at several cross sections, (3) the insufficient stream power needed to lay over or remove the trees along the channel banks at several representative cross sections, (4) the relation of tractive power and unconfined compressive strength of the channel banks based on many borings and measurements of shear stress, (5) the allowable depths of floodflow are less than the computed depths of floodflow based on measurements and computations at several cross sections, (6) relations of bankful width, mean depth and channel slope versus channel-forming discharge at several cross sections that show the DFA is not aggrading, (7) computed hydraulic geometry exponents from measured channel geometry at several cross sections, (8) vegetation cover along the banks at several transects and (9) the increase of critical shear stress associated with banks covered with grass and cryptogamic crusts. The stability of the system of channels is further confirmed by the fact that bed material entering the DFA of site 6A is conveyed through the system of defined distributary channels as shown by the uniform distribution of particle size along the channels.

The boundaries of DFAs are defined using a two stage procedure. The PD is first located using a 5-step iteration process that can be complex for some DFAs. After the PD is located, the boundaries of the DFA are estimated. Boundaries of degrading or relatively stable DFAs commonly are below ridges of interfluves separating defined distributary channels. Boundaries of some DFAs are along troughs where alluvial fans coalesced or at the edge of the deposited debris of a single fan. Soil survey information from published soil surveys and from personal communication with soil scientists such as those of the USDA Soil Conservation Service are useful and usually readily available for assessing the flow path stability and boundaries of distributary-flow areas.

A proposed flow apportionment in the stable channels below the diffluences of site 6A is based on channel conveyance and slope for flow at normal depths. The peak discharge is apportioned through the network of channel links by assuming that the flood peaks coincide at all the divides and joins. While more complex methods of integrating hydrology and hydraulics to resolve the problem may be available, such as one-dimensional split flow models and models that account for transmission losses and peak attenuation, this paper briefly describes a method of defining the flood boundaries along the distributary channels of a stable distributary-flow area.

Fundamental geologic processes are useful for the interpretation of field observations of aggrading and degrading channels, incised channels, and systems of distributary channels on pediments and Pleistocene sediments. Soil and sediment characteristics also are useful for defining abandoned depositional surfaces. Some DFA's have unique features which seem to defy generalization and some familiarity with the physical characteristics of alluvial fans and desert landforms is suggested before using the method of assessing flow path stability presented in this paper. A comprehensive assessment should intergrate geomorphology and engineering methods. The application of numerous methods to the specific distributary-flow area in question substantiates that site 6A has stable flow paths.

INTRODUCTION

Most stream systems that drain basins have a network of tributary channels which feed larger streams downstream. During times of flooding the tributaries concurrently collect overland flow and feed floodwater to receiving streams as the amount of floodflow progressively increases downstream. These tributary channels generally are on degrading landforms.

Some stream systems, especially in the arid southwestern U. S., have developed a network of distributary channels which leave the main channel. These distributary channels occur below basins drained by tributary stream channels where floodflow becomes unconfined. Floodwaters leaving the confined tributary channels of the basin commonly separate or divide into the distributary channels in a generally radiating pattern like an open fan. Distributary channels normally are on aggrading landforms or land which was formed by depositional processes. Some distributary channels, however, are on stable or degrading landforms.

Attempts to quantify the nature of flood hazards of these areas with distributary channels, which include alluvial fans and similar landforms, have been incomplete. The most notable of these is an alluvial fan method which is based on an assumption that the position of flow paths on the fan surface tends to be random and can change during flooding. Other approaches depict a system of stable flow paths with channels incised in old cemented sediments and even pediments. The - methods and approaches to quantify flood hazards on distributary-flow areas universally lack specific technical guidelines for defining the boundaries, stability, and/or flood hazards of areas with distributary channels. For example, guidelines for study contractors generally lack specific technical procedures for defining the boundaries of alluvial fans or for assessing stability (FEMA, 1993). Nor did the method used by Hjalmarson and Kemna (1991) to estimate the degree of flood hazard associated with the potential movement of flow paths result in an engineering solution to the problem. An unbiased technically specific procedure to define the extent of flooding for a wide variety of DFAs, which include alluvial fans, is needed.

The current methodology published by FEMA (1993) for alluvial fan flooding is based on a procedure developed by Dawdy (1979) and later modified to account for split flow conditions. Part of the current method is the requirement that the study contractor (SC) shall assess the reasonableness of three important assumptions in light of conditions at the particular area being studied (FEMA, 1993, p. A5-2). These assumptions according to FEMA (1993, p. A5-2) are (1) the probability density function is log-Pearson Type III, (2) the conditional probability on any contour is equal to the width of the channel carrying the discharge divided by the width of the area subject to flooding measured along the contour, and (3) the width of the "channel" followed by the flood is proportional to the four-tenths power of the flood discharge. With this spirit, a methodology is proposed that shows how to determine if a distributary-flow area is one in which the natural processes as recognized by FEMA do or do not occur. In particular, the stability of the paths of flow in terms of engineering time is assessed for conditions found in Arizona and elsewhere in the southwestern U.S. where pediments form a large portion of peidmont plains .

Channel and landform stability is evaluated on an engineering time scale. The distinction between geologic processes of the Pleistocene and Holocene Epochs is made. For example, the term "alluvial fan" is used in much of the literature in reference to Pleistocene deposits and processes. However, many of the alluvial fans formed during the Pleistocene Epoch have not been active for thousands of years; tributary drainage patterns from erosional processes have formed on these "old fan" deposits during the Holocene Epoch (past 10,000 years). In general, these old fan remnants are not actively aggrading and the paths of flow are stable in terms of engineering time.

Purpose and scope

This paper presents a method for the use of hydrologists, engineers and study contractors to determine the stability of distributary-flow areas (DFAs) and then to estimate the magnitude and extent of flooding on stable distributary-flow areas (DFAs). The procedure includes the definition of the boundaries of the DFA, the stability of the flow paths and channel geometry, and a discussion of flood boundary definition (figure 1). The method is based on presence or absence of observed flow path movement, measurements of hydraulic geometry at specific cross sections, soil and sediment characteristics, vegetation, geology, hydraulic conditions unique to DFAs and engineering methods published by federal agencies. Two categories of DFA are assessed: (1) an **unstable** DFA with an aggrading surface and unpredictable paths of flow and (2) a **stable** DFA with a relatively stable or degrading network of incised channels. The method is presented as it is applied to a specific site near Carefree, Arizona a few miles north of Phoenix and designated site 6A in this report. Although limited to a specific site in this paper, the method may serve as a basis for a universal method for Arizona or the southwestern U. S. Comments that may add insight and understanding to the procedures are given in the appendices and in *italics* throughout the paper. The method shows the paths of flow of the DFA of site 6A are stable.

Hydraulic and geomorphologic information in many published and unpublished papers and engineering methods published by federal agencies including the SCS, CofE, USGS and USFS are the basis for this method. In particular, the procedure for defining the boundaries of DFAs is modified from Hjalmarson and Kemna (1991). The use of soil survey information is from Camp (1986, and oral communication) and Cathy E. McGuire (Soils Scientist, SCS, oral and written communication). Descriptions of geologic processes by Bull (1977) and Harvey (1989) were especially helpful in the interpretation of field observations of aggrading and degrading channels, incised channels, and systems of distributary channels on pediments and Pleistocene sediments. Bull's (1977) insightful discussion of the use of soil characteristics to define abandoned depositional surfaces was valuable for assessing the stability of paths of flow. Osterkamp's (oral communication, 1993 and 1994) detailed description of the "aging" of stable channels by a donoring process also was valuable for assessing channel and flow path stability.

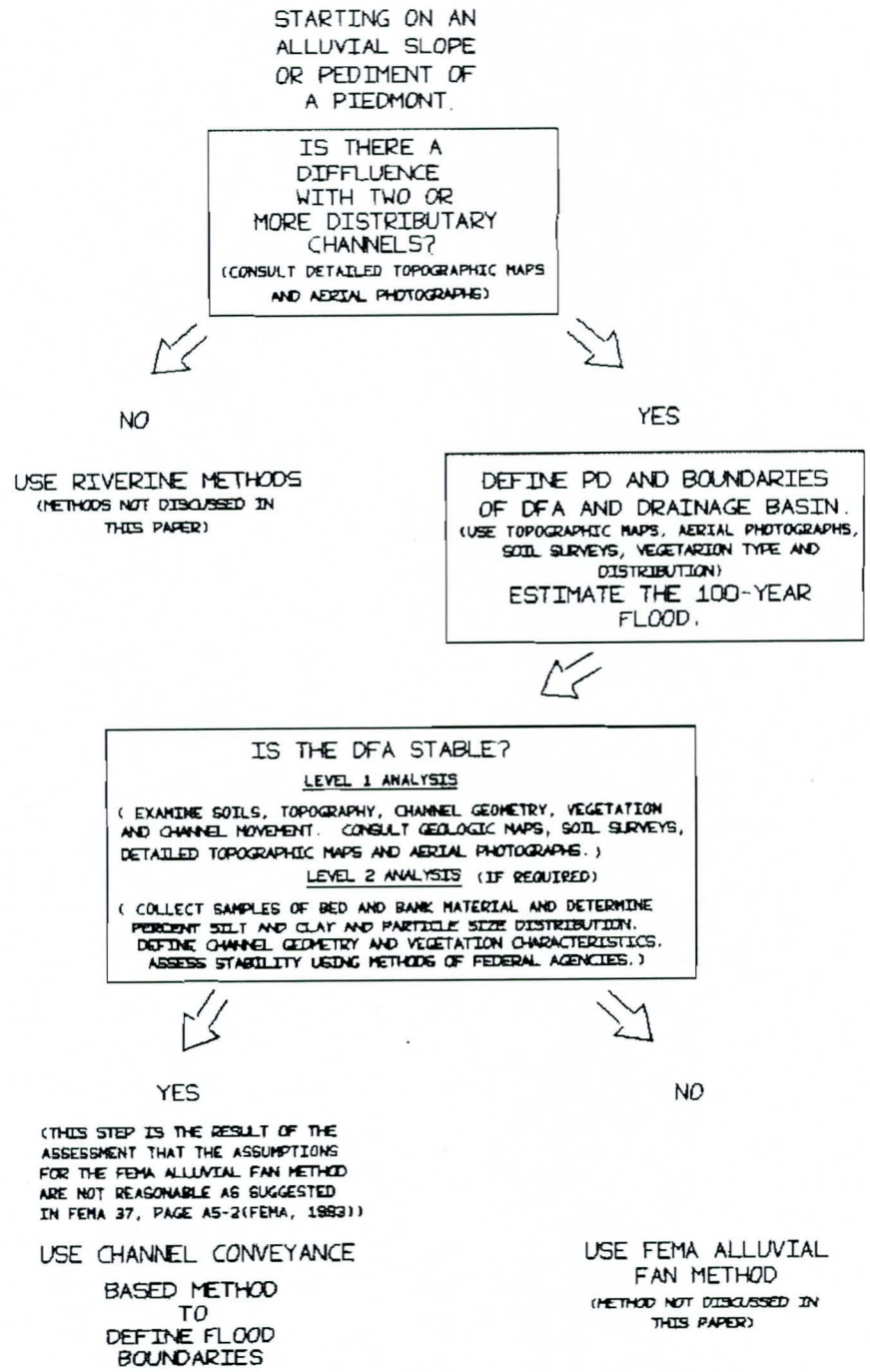


FIGURE 1.--PROCEDURE FOR DEFINING FLOOD BOUNDARIES OF DISTRIBUTARY-FLOW AREAS.

Defining flood hazards of DFAs

How should the flood hazard characteristics of distributary-flow areas be defined? The process should include several important steps as outlined in figure 1; the steps outlined by the boxes in figure 1 are described in detail in this report. First (1), before the drainage basin area above the point of interest and the corresponding hydrology can be defined, the presence of diffluences above the point of interest must be determined. Detailed topographic maps and aerial photographs are required for this step. If there is a diffluence above the point of interest, the procedures in this paper should be followed for DFAs similar to site 6A which are described later. If there is no diffluence, then use normal riverine hydraulic methods. The next step (2) is to define the primary diffluence (PD) and boundaries of the DFA and the boundaries and area of the contributing drainage basin above the PD. This procedure can be complex and additional information gleaned from soil surveys and the vegetation depicted on aerial photographs and field reconnaissance is very useful. The flood hydrology (step 3) including the peak discharge of the 100-year flood, is defined next using acceptable methods. The channel at the PD (step 2) must convey the 100-year flood. If the channel capacity is not sufficient, the PD is relocated upstream and steps 2 and 3 are repeated until a sufficient channel capacity is obtained. The potentially most difficult step (4) is the determination if the DFA has stable or unstable paths of flow. Much of this paper is devoted to determining if the flow paths are stable or unstable (third box of figure 1) because appropriate methodology for defining areas affected by flooding is dependent of flow path stability. Two levels (reconnaissance and engineering) of channel and landform stability assessment are used. If the paths of flow are considered stable in an engineering time frame (about 100 years), then a channel conveyance based method (step 5) is suggested to define the flood boundaries along the distributary channels of the DFA. If the flow paths are unstable, then other methodology or FEMA's present methodology (1993) should be used to define the flood hazard. The basic materials needed to define the flood characteristics include topographic maps, aerial photographs, and soil surveys (table 1).

A simple-universal procedure for precise definition of the boundaries of these complex features is difficult because some DFA's have unique features which defy generalization. Exceptions to the procedure are anticipated and the SC is encouraged to know where this procedure may not be applicable as indicated by the physiography and hydrology of a particular DFA. Some familiarity with the physical characteristics of alluvial fans and desert landforms is suggested before using the following general procedure. The subject is an integration of engineering, topology, geology and geomorphology and most readers may be unfamiliar with some terms. The author apologizes for this potential inconvenience but believes the topic is interdisciplinary and the reader is encouraged to consult the glossary and related publications.

Application of the method to the specific area in question substantiates site 6A has stable paths of flow and is not an active (aggrading) distributary-flow area subject to alluvial fan flooding. In fact, the second level of stability assessment, which uses several engineering methods by Federal agencies, probably was unnecessary because the first level showed the flow paths were stable. The engineering methods demonstrate how a comprehensive quantitative assessment of flow path stability can be made.

Table 1.--Suggested material, sources of information, activity, equipment, and computer programs to define flood boundaries along stable distributary channels.

ITEM	USE OR PURPOSE
Topographic map	Define diffluences, boundaries of DFA and drainage basin, topographic relief across DFA, paths of flow, and cross-section geometry. Required to define boundaries and for level 1 assessment.
Aerial photograph	Define diffluences, boundaries of DFA and drainage basin, and paths of flow. Recommended to define boundaries of DFA and for level 1 assessment.
Old aerial photograph	Assess movement of flow paths. Recommended for level 1 assessment.
Soil survey	Define characteristics of the soil series that make up the map units and thereby define the stability of paths of flow and surface of DFA. Also, the soil map units may coincide with the DFA boundaries. Required for level 1 assessment.
Geologic map	Assess stability of DFA and paths of flow.
Photographs of vegetation	Define diffluences and boundaries of DFA, paths of flow, and stability of paths of flow. Very important for level 1 assessment of DFAs in Arizona.
Records of streamflow and rainfall and flood reports	Define rainfall, runoff and sediment characteristics, assess movement of flow paths and define flood magnitude and frequency. Compilation of hydrologic data and flood reports is standard practice for most flood studies.
Computer program	Define hydraulic characteristics at cross sections for many subareas at many increments of stage. WSPRO (Shearman, 1990) was used for site 6A.
Engineering methods	Quantitatively assess channel and landform stability. Methods published by the USGS, CofE, SCS, FHWA and USFS were used for site 6A. Collection of bed and bank material samples and surveying of channel geometry probably required. Used mostly for level 2 assessment.
Field reconnaissance	Define and check diffluences, boundaries, stability of flow paths and channels including erosion of channels into cemented bed sediments, and hydraulics including roughness coefficients for the subdivided cross sections. Required for level 1 and 2 assessments.

Distributary flow areas

Areas with distributary flow (DFAs) have at least one channel fork or diffluence where at least two channel links are formed. Thus, **DFAs** are not landforms but rather areas of land where the drainage pattern is distributary as opposed to areas with the more common tributary drainage pattern. Because floodflow on alluvial fans commonly is distributary, alluvial fans are considered to be DFAs. Floodflow on some pediments is distributary in places and these erosional areas are also considered to be DFAs. Both aggrading landforms (alluvial fans) and degrading landforms (Pleistocene sediments and pediments of piedmonts) have systems of distributary channels.

A **distributary channel** flows away from the main (other) channel, is separate from the main channel, and commonly does not return to the main channel (plate 1). **Distributary flow** is diffuse flow where there is at least one distinct diffluence at the outflowing branch of a stream. There generally are channel forks, joins, and outlets for a system of distributary channels and the number of outlets is more than the number of forks. These flow systems, which have little to do with topographic relief, are called distributary flow areas (DFAs) **Sheet flow** also is diffuse, generally occurs where there is little topographic relief, commonly is unconfined and spreads freely, and is not considered to be distributary flow. Sheet flow may occur in portions of DFAs where the flow is diffuse and unconfined or spreads over wide-flat flood plains. Floodflow that leaves distributary-flow areas onto base-level plains such as playas commonly is sheet flow.

Most distributary-flow areas in Arizona are on piedmont plains (Hjalmarson and Kemna, 1991). Some DFAs are on eroded old-fan relics (Pleistocene sediments), a few are on a thin veneer of soil overlying a pediment, and others are on alluvial slopes in the lower part of the piedmont plain. A few DFA's are in intermountane basins and at mountain passes. Most DFAs appear to be on the south and west facing piedmont slopes below the mountains separating the many desert valleys. DFAs are not areas of stable islands along base-level ephemeral streams. DFA's in Arizona come in a wide variety of locations, ages, shapes, and sizes. Additional discussion of DFAs and alluvial fans is in Appendix A.

Geomorphology

Alluvial fans are complex landforms that commonly form by deposited debris when floodwater leaves the confines of mountain canyons and narrow channels. Alluvial fans are in various stages of progressive aging. Young fans are actively aggrading and flow paths reportedly move over wide areas depositing debris and spreading floodwater (figure 2A). As fans age they become large relative to the drainage basin upstream (figure 2B). There is less floodwater and debris per unit area of the alluvial fan and large areas become isolated from debris deposition and floodflow (figure 2C). Some alluvial slopes have networks of incised distributary channels that are hundreds or thousands of years old and stable or slightly eroding. Their distributary channels are within the surface of the landform. The paths of flow on old fans are stable (figure 2C) while flow paths on young aggrading fans are unpredictable and can change during flooding (figure 2A).

Young fans can result from tectonic uplift of a mountain relative to the adjacent basin. Over a given period of time the loci of fan deposition will be at a mountain front if the uplift equals or exceeds the sum of the channel downcutting in the mountain and the amount of fan deposition (Bull, 1977). Bull also demonstrates that fans develop incised channels where the rate of mountain or pediment-channel downcutting is (1) greater than or equal to the rate of mountain uplift and (2) is greater than or equal to the erosion of the alluvial fan deposits adjacent to the mountains (figure 3). For regions like central and southern Arizona where there is relatively little tectonic activity and mountain uplift, the loci of deposition of most DFAs has shifted permanently downslope from the mountain fronts. According to Bull (1977, p. 252) the fanhead trench can be "...removed as a possible area of deposition and the degree of soil-profile development will provide clues as to the length of time since the fanhead area last received deposits. The complete and intense weathering profiles that are characteristic of the fanhead areas of many entrenched alluvial fans also indicate that the rate of erosion of the abandoned depositional surface has been less than the mean rate of soil-profile development."

For site 6A there is no mountain upslope of the DFA. The flow is confined within a pediment that appears stable or slightly eroding (figure 3). The gradient of the channel draining the basin upstream is uniform for several thousand feet above and below the pediment (Hjalmarson. 1994. in press). The rate of pediment-channel downcutting appears (1) more than the rate of pediment uplift (there is no active fault at the edge of the pediment and therefore there is no apparent pediment uplift) and (2) greater than the erosion of the fan deposits below the pediment (figure 3). The soils of the fan deposits are well developed with considerable cementation in the lower B horizon(Camp, 1986, and Cathy McGuire, oral comminication, 1993). The calcic soils are very old (Dave Camp, oral communication, 1993) may represent millions of years of formation (Machette, 1985). The cemented soil acts like anchor points along the incised channels that restrict downcutting and lateral movement. Developed soil profiles also are common on aggrading alluvial fans but the incision of the channels into the cemented sediments of the B horizon (the calcareous layer may be more correctly called the Bk or K horizons, Machette, 1985) is characteristic of an eroding surface. The field observations and published soil characteristics show that the surface of the DFA of site 6A is stable or slightly degrading. The geomorphologic conditions closely match Bull's (1977) description of an abandoned depositional surface of an entrenched alluvial fan and possibly Lattman's (1973) description of abandoned fan surfaces.

The channels of a stable DFA (a DFA with a stable or degrading surface and incised distributary channels) commonly are entrenched as shown in figures 3 and 4. The distributary channels are within the surface of the landform. Floodwater that overtops the channel banks generally spreads over adjacent land between stable interfluves separating the distributary channels. Some of the stable interfluves generally are not flooded: the portion of stable DFAs not inundated is related to several factors including the amount of topographic relief across the DFA and the size of the entrenched channels. The banks of the channels are lined with large desert trees such as paloverde and mesquite that provide bank stability and the interfluves are covered with bushes, scattered trees, and saguaro cacti. The channels of unstable DFAs (young-aggrading alluvial

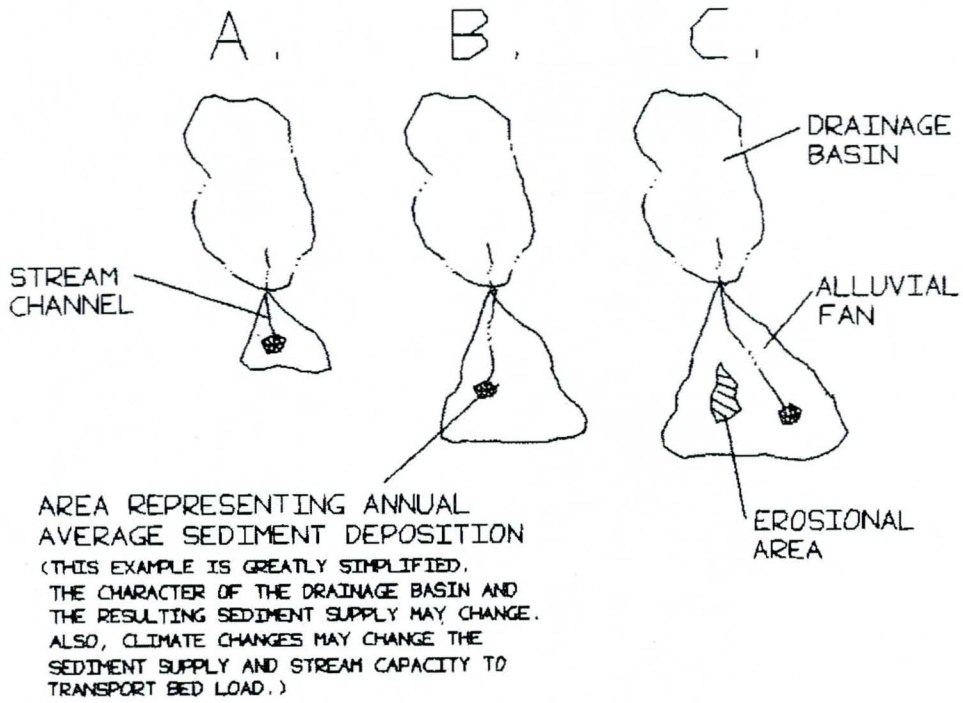
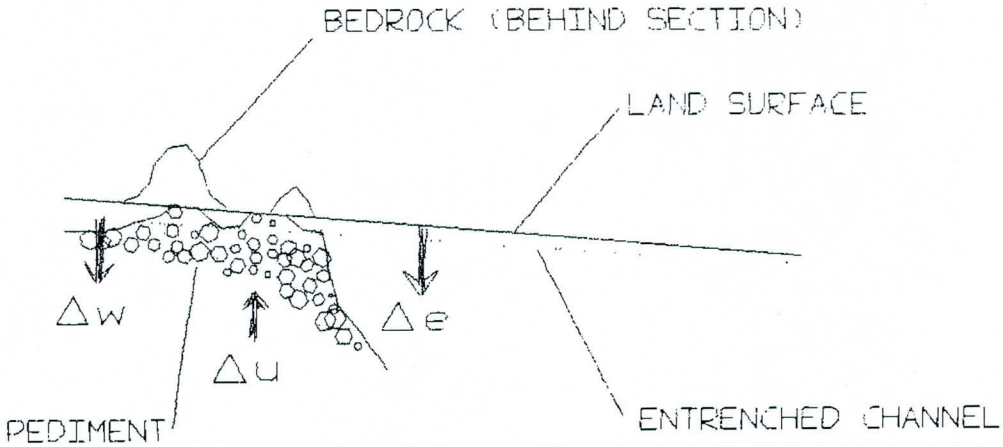


FIGURE 2.--STAGES OF ALLUVIAL FAN DEVELOPMENT



$$\frac{\Delta u}{\Delta t} \leqslant \frac{\Delta w}{\Delta t} \geqslant \frac{\Delta e}{\Delta t}$$

EXPLANATION

Δu CHANGE OF PEDIMENT UPLIFT FOR Δt

Δw CHANGE OF PEDIMENT-CHANNEL DOWNCUTTING FOR Δt

Δe CHANGE OF DFA EROSION FOR Δt

Δt PERIOD OF TIME

MODIFIED FROM BULL(1977, PAGE 249)

FIGURE 3.--SKETCH OF CROSS-SECTION SHOWING UPLIFT AND EROSIONAL CONDITIONS THAT FAVOR CHANNEL ENTRENCHMENT AT SITE 5A.

fans) commonly are perched in relation to the ground at equal distances from the apex or PD (figure 5). Floodwater can overtop or breach the perched banks and spread over the adjacent low-lying land. The active watercourses (figure 5) can fill with debris and reportedly change location (avulse) suddenly during flooding (Dawdy, 1979). There is little vegetation on the most unstable alluvial fans. In central and southern Arizona there are few, if any, saguaro cacti on unstable alluvial fans but there are scattered bushes and trees. On many alluvial fans there is a distinct change in the type, size, and density of vegetation at the fan boundaries.

This brief description of the aging and formation of alluvial fans (one kind of DFA) is a great oversimplification of a complex geologic process. The effects of factors such as climate changes, the structural warping --upwarping of uplands and downwarping of lowlands (Cooley, 1977), and changes in the base level of streams draining intermontane valleys have been ignored. The complex formation of alluvial fans by deposition of sediment from both flood flows and debris flows is also beyond the scope of this paper. Of importance is the fact that the flow paths of a DFA are either stable or unstable in both engineering time and probably during the Holocene Epoch and some surfaces of DFAs are aggrading while others are degrading.

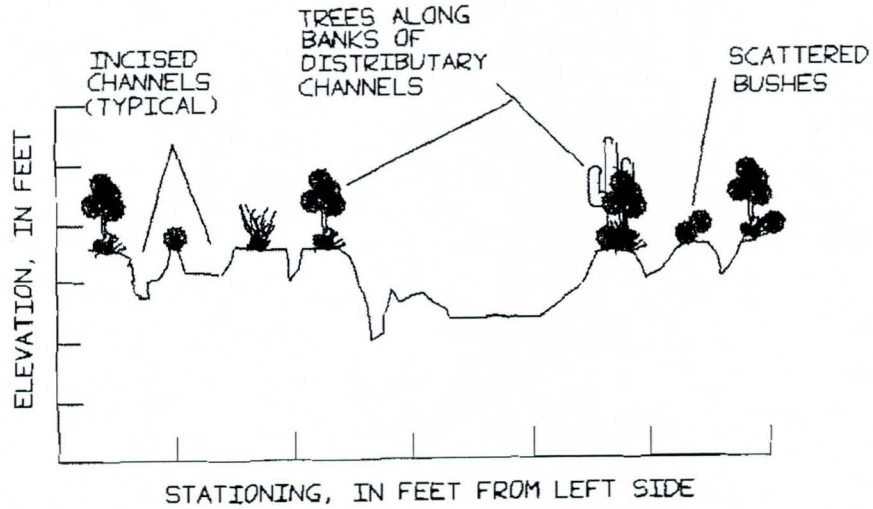


FIGURE 4.--SKETCH OF CROSS SECTION AT EQUAL DISTANCES FROM THE DIFFLUENCE OF SITE 6A.

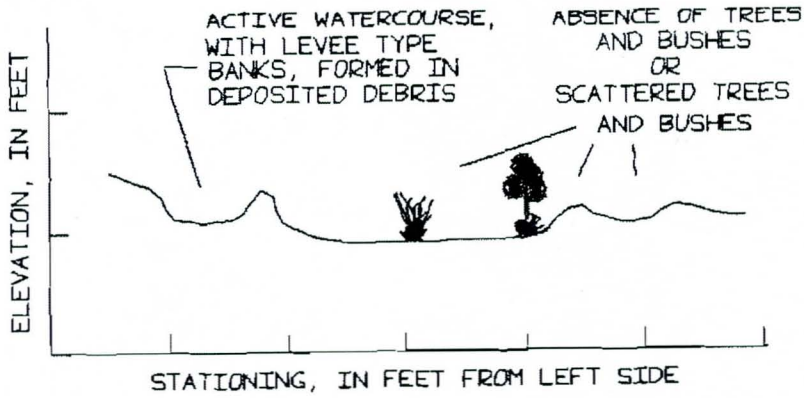


FIGURE 5.--SKETCH OF CROSS SECTION AT EQUAL DISTANCES FROM PRIMARY DIFFLUENCE OF AN AGGRADING ALLUVIAL FAN.

BOUNDARIES OF DISTRIBUTARY-FLOW AREAS

Distributary-flow areas (DFAs) can be recognized on topographic maps and aerial photographs or by inspection from a high location. A ground-based inspection of channels and topography is less effective for general definition but is essential for detailed examination of channel conveyance, channel stability, soils, desert varnish, and vegetation. For aggrading (active) DFAs the topographic map contours commonly are fairly smooth and convex when viewed downslope and the soils commonly are distinctly lighter (less red) than the soils of adjacent land. For degrading or relatively stable DFAs like site 6A the topographic map contours are less convex and in places, rather straight or even concave, and contour crenulations on 7.5-minute topographic maps reveal the presence of incised channels. The color of the soils commonly is lighter (tan or light brown) along the distributary channels than on the adjacent land. Other characteristics that are readily identifiable and generally change at the boundaries of active DFAs are the type and density of vegetation, the drainage texture, and the amount of desert varnish.

The boundaries of DFAs are defined using a two stage procedure. The PD (apex of alluvial fan) is first located using a 5-step iteration process that can be complex for some DFAs (figure 6). After the PD is located the boundaries of the DFA are estimated as described below. Boundaries of degrading or relatively stable DFAs commonly are along ridges of interfluves separating defined distributary channels. Boundaries of some aggrading DFAs are along troughs where two alluvial fans have coalesced or at the edge of the deposited debris of a single fan. The following procedure includes several comments about conditions which may be encountered on some DFAs. This procedure produced satisfactory results for site 6A in central Arizona but is untested for sites outside of Arizona.

Primary Diffluence

Primary diffluences (PDs) can be identified by using 7.5-minute and more detailed topographic maps, aerial photographs and field reconnaissance. If the drainage basin above the DFA includes land on a piedmont slope then detailed topography at a scale of 1 inch = 100 to 500 ft. with contours at 1 or 2 ft. intervals is recommended. Where there is little topographic relief, the 7.5-minute topographic maps may not show important features such as distributary channels on piedmonts which leave the drainage basin. High resolution aerial photographs are a necessity if 7.5-minute topographic maps are used and are recommended for all mapping of DFA boundaries.

To locate the PD of a known DFA on topographic maps, select a point (point of origin) on a stream where the drainage area is to be computed (figure 6, step 1). The important steps (1-5) for locating the PD are given in figure 6. Next, define the topographic divide for the basin above the point of origin (step 2). All direct runoff from precipitation within the topographic divide will be drained by the stream at the point of origin if the overall drainage system is

PRIMARY DIFFLUENCE

Step 1
Point of origin located on topographic map.

Step 2
Delineate the topographic drainage divide. Can the drainage divide be defined?

YES

NO

Step 3
Check the topographic divide using orthophotoquad maps or aerial photographs. Is the divide confirmed?

Step 4
Relocate the point of origin to upstream diffluence and return to step 1.

NO

YES

Step 5
Test and adjust the primary diffluence using discharge for 100-year flood.

BOUNDARY

Step 6
Delineate the potential divide of the distributary-flow area.

Step 7
Delineate the toe of the distributary-flow area.

Modified from Hjalmarson and Kenna(1991).

Figure 6.--Delineation of primary diffluence and boundaries of distributary-flow areas.

tributary. If the drainage area can be defined, check that no channels cross the defined ridge line (topographic divide) by using orthophotoquad maps, aerial photographs, and possibly a field inspection.

Some drainage basins on piedmonts may have small-active streams that cross the topographic divide well above the PD (figure 7). Although not common, small distributary channels on piedmonts can enter or leave a drainage basin. Where these channels convey a small portion of the total floodflow, the amount of discharge crossing the topographic divide can be estimated and added to or subtracted from the discharge at the PD. For these drainage basins with a channel fork and flow that leaves the basin into an adjacent basin, the drainage divide can be determined using methods described later for a topographic divide at a ridge between two distributary-flow areas.

The occurrence of a diffluence in a drainage basin with one channel in the basin and the other channel crossing the drainage divide into an adjacent drainage basin (figure 7) may seem illogical or impossible to some engineers and hydrologists. Many engineers and hydrologists have not experienced this phenomena because it commonly is not discernible on 7.5-minute topographic maps and is difficult to define on aerial photographs. The drainage divide may appear to be improperly identified and the question -How can a drainage divide have a channel crossing it?-may seem vexing. The fact is that channels within drainage basins on piedmonts do fork and the channels can become widely separated and drain into different intermontane basins. The author knows of at least one such diffluence on a topographic ridge where nearly equal amounts of flow divide into two otherwise distinct drainage basins. There is, for example, at least one diffluence south of Tucson, Arizona where one divided channel enters the Santa Cruz River drainage basin and the other channel enters the Brawley Wash drainage basin. For these areas the drainage divide is the probable boundary that bisects the defined ridge lines. The amount of floodflow in the channels below a particular diffluence can change if the flow paths and channel geometry are unstable at the diffluences. There is no distinct drainage divide or drainage area where the channels below a diffluence enter separate drainage systems.

Conditions at small earthen dams or stock watering ponds on piedmont slopes also should be considered. The area of the stock-water pond may only contribute to the downstream channels when there is flow through the spillway. The affect of the stored floodflow on the 100-year flood should be assessed. Also, floodflow at some stock watering ponds can be diverted across the drainage divide as described above for diffluences on topographic ridges.

If large-active stream channels cross the defined topographic divides and the divides cannot be delineated with supplementary information gleaned from the orthophotoquad maps, go to step 4 (figure 6). If the integrity of the topographic divides is confirmed, then check for DFA's within the drainage area (step 3).

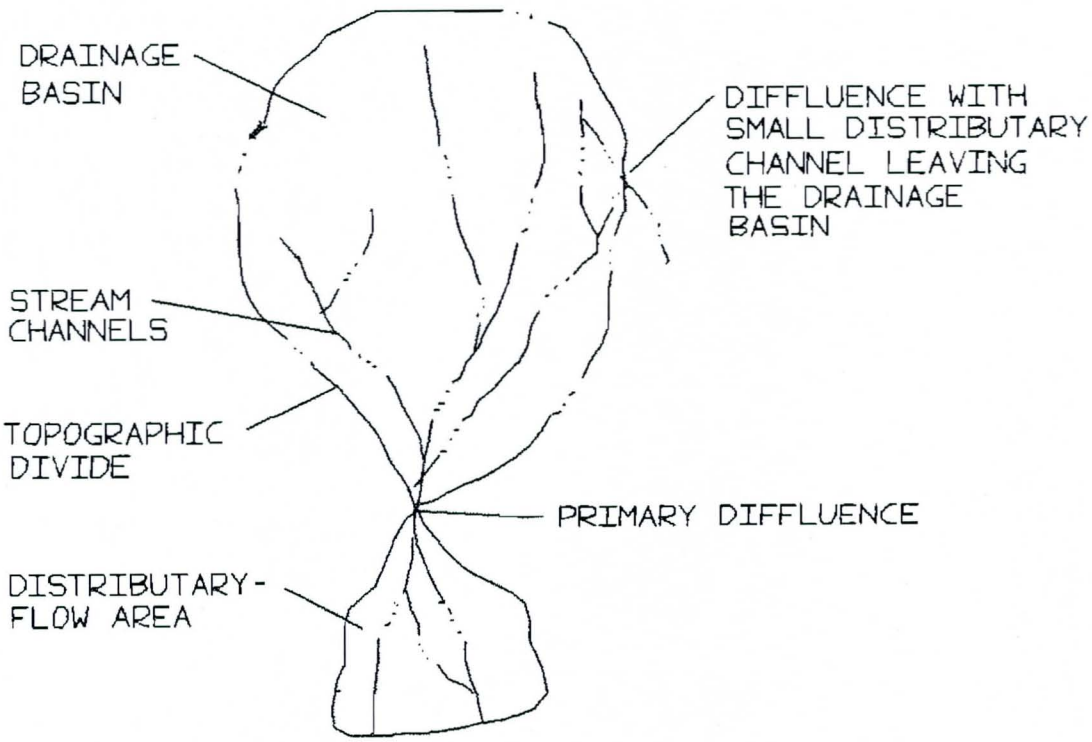


FIGURE 7.--SKETCH SHOWING SMALL DISTRIBUTARY CHANNEL LEAVING A DRAINAGE BASIN ABOVE THE PRIMARY DIFFLUENCE.

Small DFA's within the drainage basin (step 3) may be of interest. The distributary channels of these nested DFA's converge into tributary channels above the point of origin. If a primary diffluence for a nested DFA is to be located, go to step 4 and establish a new point of origin in the nested DFA.

Nested DFA's should not be confused with a braided channel. A braided channel divides into an interlacing or tangled network of several small branching and remiting shallow channels separated from each other by branch islands or channel bars. These braided channels commonly appear to be part of a single channel and in plan appear to be strands of a complex braid (Bates and Jackson, 1980, p.79). Distributary channels commonly appear to be part of a network of channels separated by defined ridges. Distributary channels commonly have adjacent flood plains and some distributary channels have erosional terraces. On braided channels and many nested DFA's, for every channel fork there is a corresponding joining of channels.

If the drainage area cannot be delineated or the amount of flow entering or leaving the drainage basin (figure 7) cannot be estimated (figure 6, step 4), relocate the point of origin to the first primary diffluence upstream. Repeat the process starting at step 1 until the final primary diffluence is found and the drainage boundary is delineated.

The characteristics of the soils, vegetation, desert varnish, slope of the stream channel, and drainage texture are used to confirm the location of the primary diffluence (Hjalmarson and Kemna, 1991). These characteristics are related to a site specific location in later in this report.

To confirm that the 100-year flood is contained in the channel at the primary diffluence (figure 6, step 5), determine the 100-year discharge for the basin of the primary diffluence using (1) regional relations of the U. S. Geological Survey such as Roeske (1978) or Eychaner (1984) or (2) rainfall-runoff methods of the U. S. Army Corps of Engineers (1990) or the USDA Soil Conservation Service (1992). Obtain channel geometry and roughness characteristics from field surveys, detailed topographic maps and aerial photographs. Use conveyance-slope estimates, slope-area computations or water-surface profile computations to determine if the 100-year flood is contained within the defined banks. A normal depth computation using a single cross section commonly will produce a satisfactory estimate of channel capacity. If the channel just upstream from the selected primary diffluence cannot contain the 100-year flood, then the primary diffluence probably is upstream and a field inspection may be needed to precisely locate the primary diffluence.

In southwestern Arizona, the channels in many of the DFA's are on the upper slopes of the piedmont plain and are firmly entrenched. The surrounding surfaces have tributary drainage systems and are eroding. Bull (1977, p. 252) attributes the entrenchment of channels in the upper part of the alluvial fans to (1) climatic changes, (2) a complex response to a perturbation of the geomorphic system, and (3) incision by floodflow at a faster rate than the rate of mountain uplift as discussed previously in this paper. For tectonically stable areas, permanent entrenchment can occur on the upper slopes of the fan; such fans are characterized by large areas of erosion as well as areas of deposition (Bull, 1964, p. 112).

As the upper slopes of the fan become entrenched, the point of deposition commonly moves downslope on the piedmont plain. This point of deposition is called the intersection point and is the primary diffluence of some DFA's. Dawdy (1981, p. 379) clarified the application of his method (Dawdy, 1979) for evaluating flood hazards on alluvial fans by stating that in the case of permanently entrenched fans, his method should be applied below the intersection point.

Bull (1977, p. 252) stated that many fan-head trenches are temporary and may exist only from 10 to 10,000 years before radically changing form and (or) position on the piedmont plain. He describes how the balance of stream power and the resisting power of the channels determines whether a given reach of channel will aggrade or degrade and if and how much the intersection point will move upslope or downslope on the piedmont plain. Climatic change and man's effects on the geomorphic system can result in the relocation of an intersection point (Bull, 1988, p. 160-161).

For the definition of flood hazards of DFA's, it is necessary to locate a primary diffluence that is stable in an engineering time frame. Two major factors should be considered to make this decision. First, the channel must convey the 100-year discharge within the confines of ridges that define the channel and adjacent flood plains at and above the PD. Second, the flow path must be stable and not subject to change during engineering time. While the geometry of the channels at the primary diffluence may change, the path of floodflow must be stable and not be subject to avulsions. A channel entrenched in cemented sediment is evidence the path of flow is stable.

Other indicators of surfaces with stable distributary paths of flow in engineering time include prolific desert varnish and the weathering-related filling of soil pore space with fine sediment (Hooke, 1967, p. 439-440). The color of the soil surrounding the banks of the channel at the primary diffluence is one of many soil characteristics that determines soil stability. Young, recently deposited soils tend to be light in color (Cathy McGuire, oral communication at site 6A, 1993). The presence of dark-colored reddish soils indicates that sufficient time has elapsed for the profile to develop; clays and carbonates have moved, iron has oxidized and structure developed. Where light-colored soils are present a few inches below the surface, a strong chance exists that deposition has and will occur in engineering time. The presence of darker-colored reddish surfaces or subsurfaces a couple of inches below the surface indicates the absence of major deposition in engineering time and surface stability (Cathy McGuire and Dave Camp, oral communication at site 6A, 1993). Where light-colored soil indicates overflow channels or abandoned channels, the primary diffluence should be relocated upstream to a more stable reach; for the sample of sites studied by the author a more stable reach was always found (Hjalmarson and Kemna, 1991).

Where the channel is deeply entrenched with a capacity several times that needed to convey the 100-year flood, the stability of the flow path is easier to assess. However, where debris flows are likely, the channel should be carefully examined for evidence of debris flows that occurred during the past few thousand years and the likelihood of an avulsion resulting from debris

deposition should be assessed. Debris flows or heavily sediment laden flows can be expected for sites with perched channels and banks described previously in this paper (figure 5). Perched channels and banks can occur along depositional lobes of debris flows. For some DFAs with unstable flow paths the PD is located at the mountain front where floodflow leaves the confines of bedrock banks.

Debris flows are not expected for sites similar to 6A where the drainage basin is not steep and covered with dense desert vegetation. There are no mountains in the drainage basin. Recent (Holocene Epoch) scattered deposits forming channel banks are stratified and in thin layers and material is not deposited on the outside of meander bends. The recent deposites are not compact, are not muddy, and are easy to dig out.

Boundaries

After the primary diffluence is located, the boundaries of the DFA can be defined following steps 6 and 7 (figure 6). Starting at the primary diffluence, define the topographic ridge and or trough lines on each side of the DFA (step 6). The ridge lines are on the shoreward side of the outermost channels (figure 8). The boundaries between some coalesced DFA's are like swales and appear slightly concave in plan when viewed looking downstream (See the left side (looking downstream) of DFA B, figure 8). These trough lines are at the "thalweg" of the coalescing alluvial fans. Tributaries to the DFA are severed, and the boundaries are continued on the opposite bank of the tributary (See the right side of DFA B, figure 8). The potential dividing ridge line may appear to cross over into adjacent DFA's. Areas of overlapping DFA's are separated by a probable boundary that bisects the defined ridge lines for the two areas or at the thalweg of the trough line. The potential topographic divides are perpendicular to the topographic contours and split any X-shaped confluence-diffluences where the channels from each DFA join and then divide. The boundaries and probable boundaries are defined from the primary diffluence to the toe of the DFA.

In addition to using the topographic divides to define the boundaries of the DFA, the soil characteristics can be used to supplement and substantiate the delineation. Soil maps that delineate the boundary between recent deposits of soil and older developed soil also may assist in boundary definition. In fact, recent maps by the U. S. Soil Conservation Service that depict soil units on 7.5-minute series orthophotobase maps define the boundaries or general location of some DFAs. Soil complexes on flood plains and drainageways as depicted by the SCS (Camp, 1986) generally correspond to areas of DFAs subject to inundation by floodwater emanating from the PDs. However, the detail of the mapped soil units on the 7.5 minute series of soil maps is not sufficient to show many distributary channels and the general boundaries of some DFAs.

If 7.5-minute or more detailed maps of soils are unavailable, differences in soil color on the piedmont that could depict the boundaries of DFA's commonly are clearly revealed on natural color aerial photographs. A light-colored surface may represent young soils, and the yellow, brown, and reddish-brown color of adjacent surfaces may represent older soils.

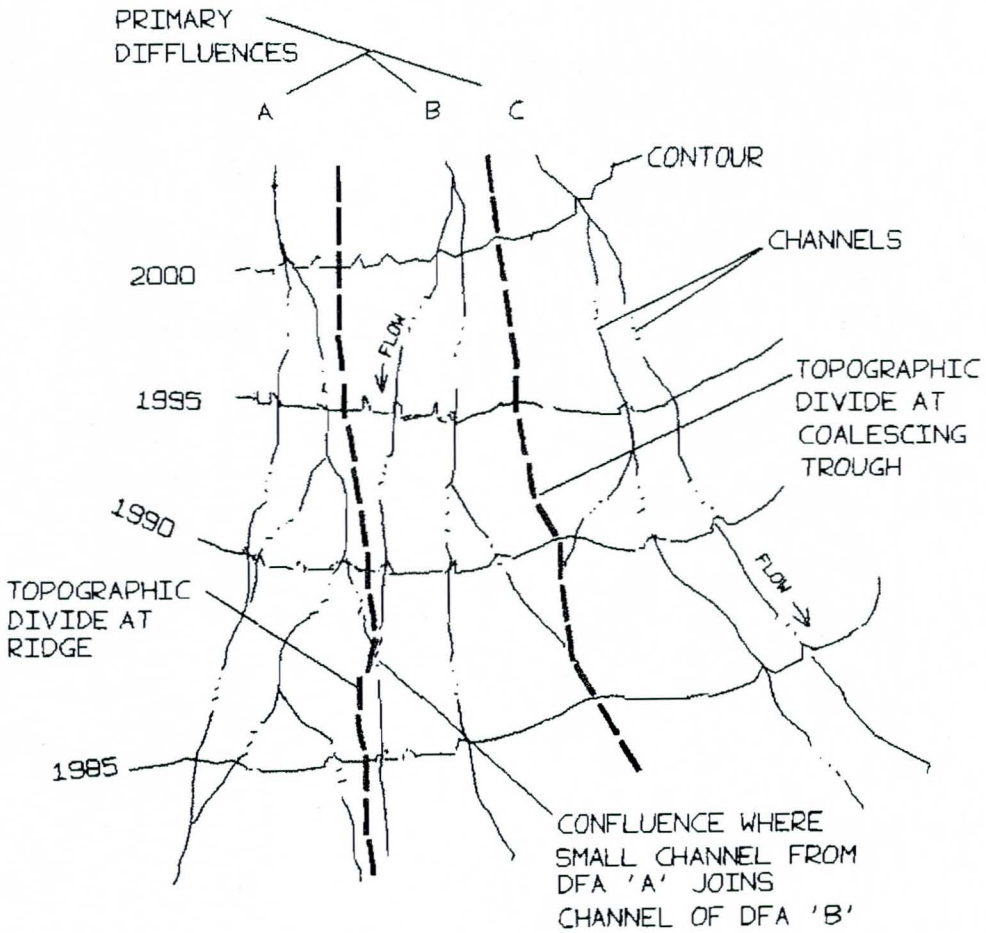


FIGURE 8.--SKETCH OF COALESCING DISTRIBUTARY-FLOW AREAS WITH ESTIMATED BOUNDARIES

Dark appearing surfaces that take hundreds to thousands of years to form on varnished rocks can also be easily seen on color aerial photographs. Dark surfaces form the boundaries of some DFA's and also indicate the limits of riverine flooding and significant deposition. The lighter surfaces of recent deposits on unoxidized sand, gravel and boulders commonly delineate the DFA's. Desert varnish on stable stones of large alluvial surfaces can be a reliable indication of the absence of significant floodflow during the past few thousand years. A dark-brown desert varnish on the surface of stones exposed to the atmosphere may indicate that the stones have been undisturbed for perhaps 3,000 to 5,000 years (Dorn and Oberlander, 1982). A black-surface stain indicates the absence of significant flood depths and velocities for perhaps 10,000 years or more. According to Dorn and Oberlander (1982), a blackish manganese-rich varnish takes many thousands of years to coat completely the tops of stones. Desert varnish is seldom found on the surface of stones such as granite fragments that weather easily in the desert environment of the southwestern United States. A typical varnished stone in central and southwestern Arizona has a dark-brown "varnished" top and a reddish-brown "rusted" bottom.

The boundaries of some DFA's with a network of channels that are firmly entrenched in old-fan relics of the Pleistocene may not coincide with the boundaries of the 100-year flood that emanates from the PD. Channels of these DFA's may be isolated from floodwater that emanates from the PD through a long period of erosion along the channels and of the surface of the old-fan. Likewise, there may be entrenched channels within a DFA that (1) have become isolated through erosion and no longer convey floodflow from the PD or (2) have formed from erosion of inactive fan areas and never have conveyed floodflow emanating from the PD (See figure 2).

The toes of DFA's are defined using several factors (step 7, figure 6). The DFA cannot extend beyond the base-level stream. The toe also cannot extend beyond where the stream patterns change from distributary to tributary over the width of the DFA. Also, the toe ends where the floodflow is unconfined across the width of the DFA and becomes sheet flow. The presence or absence of confined flow can be difficult to define especially where channels gradually become smaller and less significant downslope Like the lateral boundaries, it may not be feasible to define precisely a narrow boundary at the toe. The toes of many DFA's are irregularly shaped as the distributary channel system changes to tributary channels of sheetflow at various distances below the PD. The washes and plains that form the base level represent the downstream limit of the toe. Soil color also may change, indicating lower or upper limits of recent sediment deposition. Lastly, the profile of the piedmont may show a rapid decrease in slope that corresponds to the location of the toe. The toe is located on the basis of the above considerations, and the boundary is drawn approximately parallel to the contours connecting the potential divides.

Analysis of site 6A

The PD and boundaries of the DFA and the topographic divide of the drainage basin for site 6A are defined on plate 1. Floodflow both leaves the DFA of site 6A in the upper pediment and enters the DFA in the old fan area below the pediment. Site 6A appears to have been an alluvial fan in the recent geologic past (perhaps the Pleistocene Epoch) and some of the fanhead morphology has not been destroyed by erosion. The remaining (present) system of incised channels is complex and exemplifies the difficulty of precisely defining the boundaries of DFAs for quantitative hydrologic definition. Even though the site is complex the proposed method is applicable. The following description of the selection of the PD and boundaries reflects the independent work of several hydrologists and the final results are essentially the same.

For site 6A a point of origin(step 1, figure 6) was selected in section 22 near the 2,000 ft. contour(plate 1, sheet 1). Steps 1-4 (figure 6) were followed. Floodflow appeared confined from about one mile upstream near the center of section 22 (plate 1) for about three miles upstream to near the center of section 1. A small distributary channel, however, was observed on aerial photographs near the north edge of section 13 (See flow arrow on plate 1, sheet 1, also sheet 2) and a field inspection indicated about 10 percent of the discharge of a large flood could leave the channel of site 6A at this location. The PD was relocated upstream of the diffluence in section 1 (plate 1, sheet 1), the drainage basin was defined, the 100-year peak discharge was estimated using a HEC 1 model, and the level of the flood was computed and found to be a few-feet below the top of stable banks in an area with scattered large granite boulders.

Another HEC 1 model that uses a composite channel which represents the hydraulic characteristics of the network of distributary channels of site 6A has recently been completed. The model, presented in a report "Hydrologic analysis for Wash 6a" by Coe and Van Loo Consultants, Inc., demonstrates how the hydrology of a complex DFA like site 6A can be estimated. The DFA of site 6A has several distributary channels and inflow from an adjacent DFA. The model does not account for transmission losses but the peak discharge of the 100-year flood was reduced about 600 ft^3/sec. along each mile of the DFA as floodwater spread over the wide flood plains of the channels and was temporarily stored.

An alternate PD is located near the edge of the pediment (See plate 1, sheet 1 or 2). A PD at this location would be more traditional because it is at the lower edge of the pediment where the drainage texture changes. Hjalmarson and Kemna (1991) selected the PD at this location partly on the basis of changes in the drainage texture. Floodflow is confined for about two miles below the alternate PD to the 2120 ft. contour(plate 1, sheet 2). Because there is little change in drainage area between the PDs and downstream to the 2120 ft. contour, there is little difference in the peak discharge downstream after the flow leaving site 6A is subtracted. For this particular site, the PD could be located between the 2120 ft. contour and the selected PD(plate 1, sheet 2) with an accounting for the flow leaving the basin to the north. The 100-year discharge is unconfined below the 2120 ft. contour where floodflow first separates into two distinct channels. The 100-year flood is in six channels further downstream (plate 1).

The gradient of the channel is 0.020 and nearly uniform above and below the PD. There is no change in gradient at the PD and flow is concentrated to the PD by granite outcropping. Granite outcropping and scattered room size granite boulders indicate the channel is eroding. Hydraulic processes are apparent with no evidence of active alluvial fan processes with associated debris flows. A description of the adjacent drainage system to the north is in Hjalmarson (1994, in press).

The boundaries of the DFA of site 6A generally are low-stable topographic ridges. The boundaries include distributary channels along the right (north) side which may convey floodflow if low ridges are overtopped (plate 1, sheet 2). These channels to the right appeared to drain an eroding area, like that shown in figure 2C, that is isolated from the distributary flow. These channels were included in the DFA until the hydraulic computations confirmed they are not part of the distributary network for the 100-year flood. Only one small tributary shown on plate 1 was severed as the boundaries were extended downstream. Aerial photographs and detailed topography (scale of 1 inch = 200 ft. with 2 ft. contours) were needed to define the boundaries of the DFA. The color of the soils of the small channels within the defined ridges are distinctly lighter that the soils of the interfluves.

Soil structure and texture are related to color. Soils in the channels are light colored, sandy, stratified, and lack soil structure. Soils on the interfluves tend to be redder (because of clay movement and age), have higher clay content, and show moderate to high degree of soil structure (Cathy E. McGuire, Soils Scientist, SCS, oral and written communication).

RUNOFF, FLOODFLOW AND SEDIMENT MOVEMENT OF SITE 6A

Storm runoff and sediment movement and deposition characteristics of site 6A are described in this section. Information based largely on data collected at streamflow gaging stations in Maricopa County, data collected at many DFAs in Arizona, and data collected for two storms that produced runoff in and near site 6A is presented. On June 22, 1972 a severe thunderstorm system moved over northeast Phoenix and Paradise Valley. Very heavy rains in amounts more than four inches fell within a two hour period. Although the storm center was to the south of site 6A, there was considerable runoff in the area. Conditions gleaned from photographs of flow and sediment deposition in nearby distributary channels are briefly described for the June 22, 1972 flood. Another storm that occurred on the morning of October 23, 1956 also produced heavy rains(Durrenberger and Ingram, 1978) but no runoff and sediment information for site 6A was found for this storm. A third large storm occurred during this study on October 6, 1993 and is described in detail. The center of the October storm also was to the south of site 6A.

The "pulse" nature of runoff and sediment transport of sites like 6A results in a very complex hydraulic system. Small floodflows from the drainage basin transport sediment into the network of distributary channels where it is either conveyed through the DFA to the toe or is temporarily deposited in the channels because floodflow is lost to infiltration and the energy of the remaining floodflow is insufficient to transport all of the material. For some storms all of the runoff is lost to infiltration and all the sediment is deposited in the channels. Runoff from the DFA transports-sediment in the system of tributary channels and as sheetflow to the distributary channels where deposited sediment may be remobilized or the locally derived sediment may be deposited depending on the relative amounts of floodwater and transported sediment. At any given time there is deposited sediment(pulses of sediment) in places along the distributary channels.

The general "pulse" nature of runoff and sediment transport of highly ephemeral streams that have flow on less than 1 percent of the days is depicted by Hjalmarson (1991, p.61) and Osterkamp (1980). Hjalmarson shows that for periods of many years most of the runoff from small arid basins in the southwestern U. S. at similar latitudes of site 6A occurs for only a few hours . Osterkamp shows that ephemeral alluvial stream channels are formed by the infrequent large floods and the channel width, if free to adjust, undergoes a long period of gradual readjustment until there is another large "channel forming" flow. The channel width of the distributary channels of site 6A are not free to adjust because of the stabilizing vegetation along the banks. The depth of the channel and the bed elevation, however, may undergo some readjustment similar to that described by a simple power function (Simon and Cliff, 1987).

Channel adjustment trends of depth and bed level following large floods may be defined by simple power equations of the general form (Simon and Cliff, 1987):

$$D = d(t)^b$$

where D = Depth of channel for a given year,
d = depth before the flood,
t = time since perturbation, in years,
b = exponent indicative of nonlinear rate of adjustment (Osterkamp, 1980,p. 197) or "healing" of channel depth.

The above hypothetical relation depicts the pulse nature of mobile bed ephemeral streams like those in site 6A where channel geometry slowly returns to "base" conditions following large floods.

The DFA of site 6A is unusually large relative to the area drained above the PD because the area is old and relatively inactive (See Appendix C for comments). Much of the area presently drained above the PD is a mild sloping pediment where mountains possibly once stood. Stable or slightly eroding DFAs, like those for site 6A are found below relatively milder slopes such as pediments.

Large amounts of floodwater can be lost to infiltration and flashy peaks are attenuated as flow divides. As found for other DFAs in the arid southwestern U.S. (Thomas, Hjalmarson and Waltemeyer,1993), much of the peak discharge of large floods on the DFA of site 6A might be lost to attenuation and infiltration. The effect of transmission losses on floodflow of site 6A, which is not quantified in this paper, can be estimated using methods by the Soil Conservation Service (Lane and others, 1983).

The channels of the DFA of site 6A are formed in the Pleistocene sediments and the channel banks typically are lower than the adjacent land (figures 3 and 4). The channels and channel banks are within the landform. The channels are lined with trees and bushes and there are scattered bushes and trees on the interfluves. There are a few channel banks that are higher than the shoreward land but these are within the landform and are erosional features. The channels depicted by Boyd Lare (written communication), a retired engineer from the CofE, for alluvial fans that Dawdy (1979) partially based his model on are formed by aggradational processes. The channel banks are depositional mounds and are higher than the shoreward land at equal distances below the PD (figure 5). When these channels fill with debris or the banks are overtopped, avulsions occur and floodwater spreads over adjacent areas. Because of the unstable nature of "Lare's" fans, there are few trees and older vegetation along the channels of these fans in central New Mexico.

There is a general relation between DFAs with small drainage basins and discharge intensity--flood peak discharge at the PD divided by the DFA (Hjalmarson and Kemna ,1991, p. 29). Sites like site 6A, with a low discharge intensity (Hjalmarson and Kemna, 1991,table 4, site 2), have a lower relative degree of flood hazard than sites with large discharge intensities. The low degree of hazard is common to DFAs with relatively stable flow paths. Further comments are in Appendix C of this paper.

Storm of June 22, 1972

This storm produced record amounts of runoff at downstream sites. Very heavy rains in amounts up to 4 inches in 2 hours were recorded. The heaviest rain probably was to the south of site 6a in the Phoenix Mountains and also along the McDowell Mountains. The peak discharge for Indian Bend Wash that drained 139 $mi.^2$ was 21,000 ft^3/sec and is the highest peak since at least 1922. Unit peak discharges at miscellaneous sites determined by the USGS were from 528 to 956 $ft^3/s/mi^2$ at the southern end of the McDowell Mountains and from 1,920 to 3,400 $ft^3/s/mi^2$ along the north side of the Phoenix Mountains (nearby recorded rainfall was 3.24 in.) a few miles south of site 6A. Based on the author's long experience as a hydrologist in Arizona, this storm may have produced the largest peak discharge at site 6A since at least 1963. There was a considerable amount of runoff in the area near site 6A (figures 9 and 10).

Bed material is deposited in roadway dip crossings during runoff mostly because the dip crossings act as sediment traps. Examples of deposited sediment in road dip crossings at neighboring distributary channels draining similar basins to the south are shown in figures 11 and 12. The banks of the stream channels are steeper and the channels are narrower above and below the dip crossings. The flow diverges as it enters the dip crossings, looses kinetic energy, and deposits sediment. The streambeds are composed of gravelly sandy loam of granitic origin that is mobilized by small flows. The beds of the channels that emanate from the PDs are soft and in places difficult to walk in and can give the false appearance that very large amounts of sediment move into the area. There is an abundant supply of sediment in the drainage basin but the net movement is limited by the infrequent and short lived flows.

An example of bank erosion of poorly developed soils at a site located five miles to the south of site 6A is shown in figure 13. The peak discharge at this location is unknown but floodwater overflowed the banks onto the surrounding land.

a. Looking northeast at sheetflow and small headcut. The floodwater is less confined and there are fewer trees than at site 6A. The landslope is 2.0 percent.

b. Looking east at floodflow along north side of Pinnacle Peak Road and at overland flow from the northeast.

Figure 9.--Floodwater on flood recession of June 22, 1972 at Pinnacle Peak Road about 0.6 mile west of Scottsdale Road and 5 miles south of fan 6A.

Note: Scene is approximately 6 miles south of the toe of the DFA of fan 6A. The floodflow in the scene is less confined and there are fewer trees than at site 6A.

Figure 10.--View looking northeast and upstream at sheetflow from Cave Creek Road about 0.7 mile north of Bell Road on June 22, 1972.

Figure 11.--View looking southeast and across channel at sediment deposition in dip crossing of Scottsdale Road shortly after a flood on June 22, 1972. The scene is from the downstream side of the roadway about 1 mile south of Dynamite Blvd. to the south of site 6A. The deposited sediment on the roadway is a few inches deep.

Figure 12.--View looking south and across channel at deposited sediment in dip crossing of Scottsdale Road, about 3.8 miles south of Dynamite Blvd., on recession of a large flood on June 22, 1972.

This channel is formed in loosely packed medium-grained sandy material unlike the developed soils in the DFA of site 6A that contain more clay and cement binder. The younger loosely packed materials forming some of the channel banks of the distributary channels in site 6A have erosion potential during major floods. These younger soils, however, are bounded by the older materials that are more erosion resistant and there are more trees and bushes along the channels in site 6A. There are few trees and bushes along the channel banks in the above scene.

Figure 13.--View looking downstream and southwest at receding floodwater in channel below Pinnacle Peak Road 0.1 mile east of Scottsdale Road on June 22, 1972.

Storm of October 6, 1993.

During this study moist air from a tropical storm resulted in rainfall that produced significant flooding in the area. Runoff data for the storm of October 6, 1993 were collected a few hours after the storm on October 7, 1993; field observations and measurements and estimates of peak discharge in site 6A were made. Runoff was estimated from the peak discharges using regional peak discharge-runoff volume relations for storms in Arizona. Rainfall data and isoyets showing total storm rainfall for October 6, 1993 are from the Flood Control District of Maricopa County. The rainfall and runoff for the storm of October 6 are described.

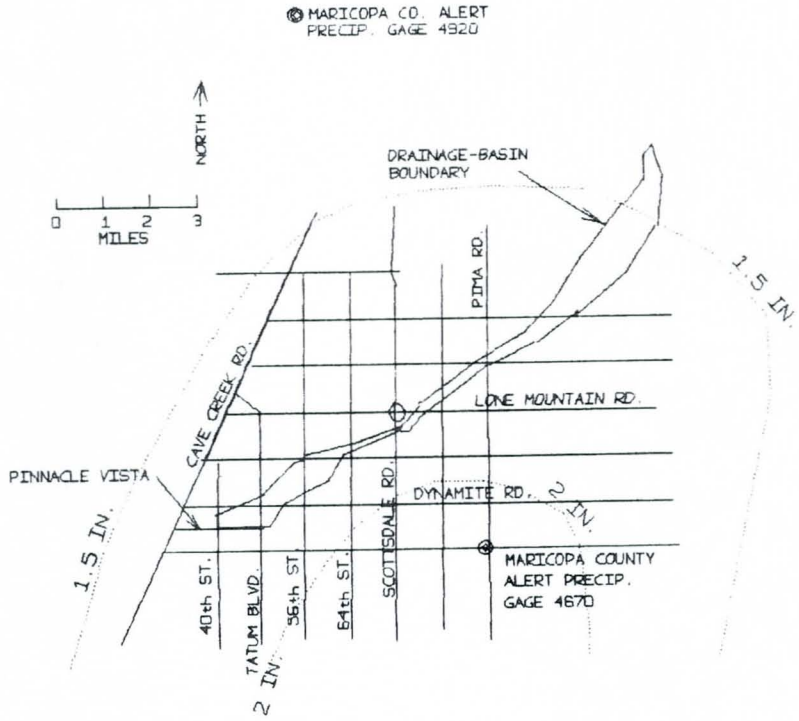
Rainfall

The heavy rainfall was the result of tropical storm Norma converging with a cold front associated with a strong Pacific low pressure system. The heavy rain occured from about 11:00 am through 3:00 PM in the Phoenix metropolitan area. The center of the storm was a few miles to the south of site 6A. Recorded precipitation for the storm was greatest along the center of the southern boundary of site 6A (figure 14). A description of the storm and recorded amounts of rainfall are given in the October 6, 1993 storm report by Stephen Waters of the Flood Control District of Maricopa County.

Rainfall amounts for site 6A were from slightly less than 1.5 inches at the northeastern end of the basin to about 1.9 inches near the center of the basin (figure 14). Average storm rainfall for the 6.22 square mile area of site 6A upstream of 40th Street and Pinnacle Vista Drive was 1.69 inches (Table 2). Rainfall amounts varied with time at the surrounding rain gages with maximum intensities occurring at various times between 1:00 and 1:45 PM (table 3). The storm rainfall amount and intensity for site 6A probably was between a 10-and 25-year recurrence interval with about a 3-hour duration (Waters, 1993).

Runoff

During the field inspection of runoff characteristics, as depicted by floodmarks and flood effects such as sediment deposition, of the distributary-flow area of site 6A several hours following the storm, large amounts of runoff loss to infiltration in the tributary areas along the interfluves between the distributary channels was apparent. Typically, runoff from the intense rainfall was apparent for rather short distances along poorly defined rills and the smallest channels but, for example, the combined peak discharge of several tributary channels was less than the sum of the maximum peak discharges of the tributaries. Losses of storm runoff to infiltration along the rills and small channels appeared to be a large portion of the runoff. Also, deposits of transported leaf litter and debris from sheet flow indicated a large portion of sheet flow was lost to infiltration.



NOTE: ONLY TWO OF SEVERAL PRECIPITATION GAGES ARE SHOWN

FIGURE 14.--SKETCH OF DRAINAGE-BASIN BOUNDARY FOR SITE 6A AND RAINFALL AMOUNTS FOR THE STORM OF OCTOBER 6, 1993.

Table 2.--Storm rainfall and estimated runoff for areas of site 6A.

Location	Drainage Area (mi^2)	Storm Rainfall (in)	Storm[a] Runoff (in)
At Scottsdale Road	4.20	1.63	0.00043
Between Scottsdale Road 56th Street	.60	1.85	.01345
At 56th St. near Dixileta Dr.	.008	1.80	.00651
At 56th St. between Dixileta Dr. and Peak View	.020	1.83	.00651
At 56th St. near Peak View	.034	1.85	.00766
Between 56th Street and 40th Street	1.42	1.78	.00073
At 40th St. and Pinnacle Vista Dr.	6.22	1.69	.00205

[a]values are computed and significant figures shown does not represent precision.

Table 3. Recorded rainfall at Maricopa County Flood Control District gages.

Time (Oct.6, 1993)	Gage number			
	4650[a]	4670[b]	4800[a]	4920[c]
1100	0.00	0.00	0.00	0.20
1115	0.00	0.00	0.00	0.00
1130	0.00	0.00	0.00	0.00
1145	0.00	0.00	0.31	0.00
1200	0.08	0.12	0.00	0.00
1215	0.00	0.24	0.08	0.00
1230	0.12	0.12	0.35	0.00
1245	0.16	0.08	0.00	0.24
1300	0.00	0.28	0.20	0.31
1315	0.00	0.20	0.67	0.20
1330	0.04	0.31	0.71	0.00
1345	1.38	0.16	0.63	0.24
1400	0.47	0.28	0.08	0.12
1415	0.08	0.20	0.00	0.00
1430	0.00	0.04	0.00	0.00
1445	0.00	0.00	0.00	0.00
1500	0.00	0.04	0.00	0.04
Total	2.33	2.07	3.03	1.35

[a]gage located few miles south of site 6A. [b]gage located to south of site 6A as shown on figure 14.
[c]gage located to north of site 6A as shown on figure 14.

With few exceptions the flow in the distributary channels was well within the channel banks. The flow level for the cross section of a distributary channel near Tatum Blvd. and Dynamite Drive (figure 15) is typical of the observed and measured flow level in the distributary channels. There was flow in all of the distributary channels and flow split at all channel forks that were inspected.

In the upper distributary-flow area above about 54th Street the channel gradient is about 2 percent and computed flow velocities were about critical. Below about 50th Street the channel gradients are less and are about 1.7 percent near 40th Street where computed flow velocities in the main channels are less than critical.

Peak discharge measurements and estimates were made of inflow and outflow for site 6A. Measured inflowing peak discharge was 62 ft^3/sec at Scottsdale Road and 48 ft^3/sec at 56th St. and Dixileta Dr.(table 4). Total outflowing peak discharge was 262 ft^3/sec at seven channels crossing 40th Street (figure 16) and 197 ft^3/sec at eight channels crossing Pinnacle Vista Drive (figure 16 and table 4). Most of the peak discharge was from the area between Scottsdale Road and 56th Street where the amount of storm rainfall was nearly 2 inches (figure 14). The flow crossing 56th Street was in 11 tributary and distributary channels with the largest discharge in the distributary channels.

Flood volume is generally related to the peak discharge of storms. Data from gaging stations in Arizona have been plotted by the U. S. Geological Survey and although data are widely scattered, there is a definite trend between flood volume and peak discharge. Relations for three groups of gaging stations have been defined. The gaging stations are in northern Arizona, southern Arizona (Aldridge and Condes, 1970) and in southeastern Arizona (Burkham, 1976). The relations are of the form

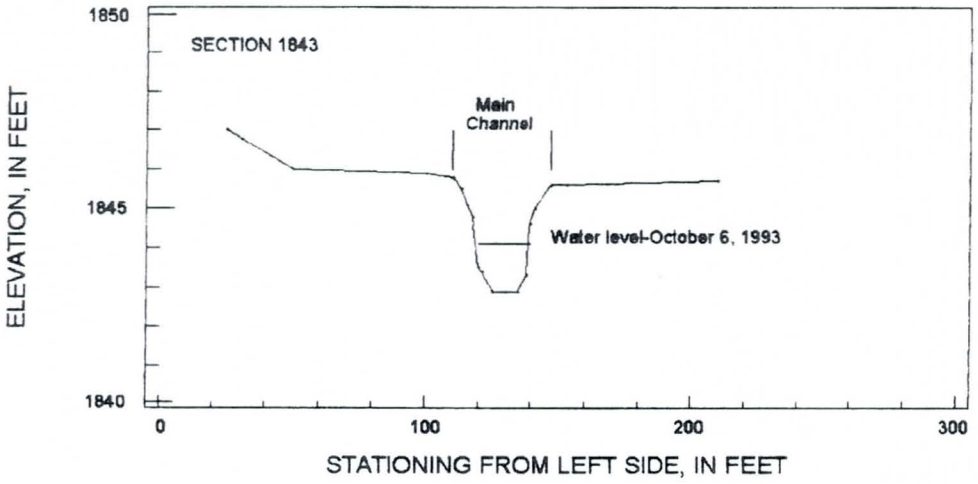
$$V = CP^a,$$

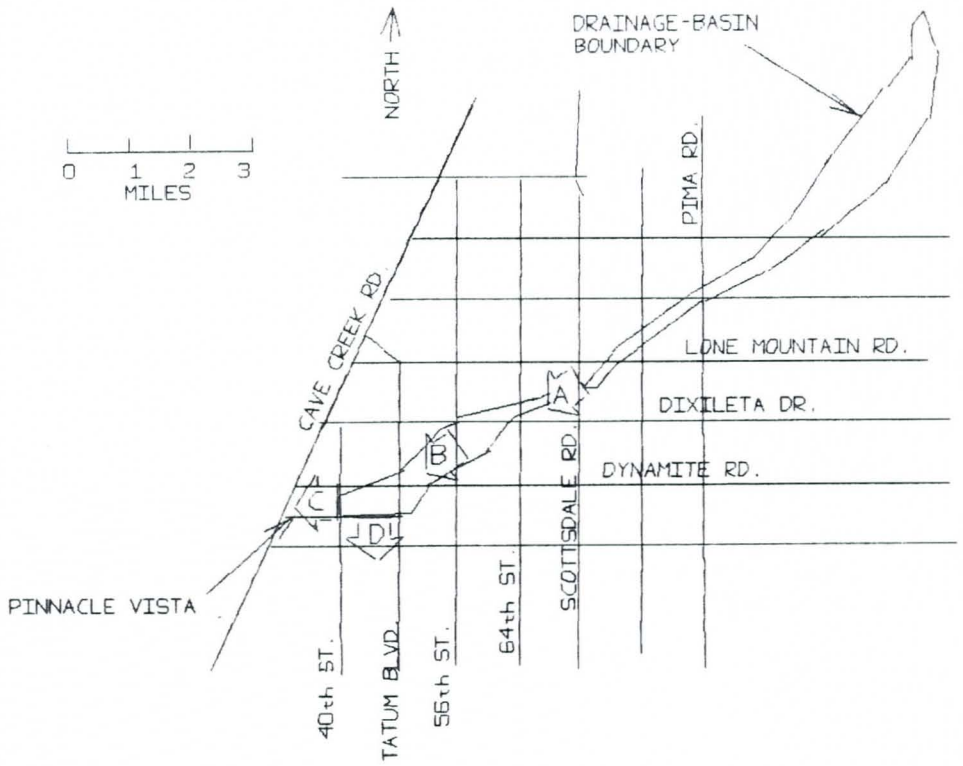
where V = volume of runoff, in acre-feet,
C = coefficient,
P = corresponding peak discharge, in ft^3/sec, and
a = exponent.

The coefficient and exponent for the three regional relations are:

Region	C	a
Northern Arizona	0.008	1.5
Southern Arizona	0.26	1.18
Southeastern Arizona	0.03	1.14

Figure 15.--Typical cross section for distributary channel and water level for storm of October 6, 1993.





A.--PEAK DISCHARGE = 62 FT^3/SEC.

B.--SUM OF PEAK DISCHARGE AT 13 SITES ALONG 56TH STREET =375 FT^3/SEC.

C.--SUM OF PEAK DISCHARGE AT 7 SITES ALONG 40TH STREET =262 FT^3/SEC.

D.--SUM OF PEAK DISCHARGE AT 8 SITES ALONG PINNACLE VISTA DRIVE =197 FT^3/SEC.

FIGURE 16.--SKETCH OF DRAINAGE-BASIN BOUNDARY FOR SITE 6A AND PEAK DISCHARGES FOR FLOOD OF OCTOBER 6, 1993.

Table 4.--Summary of flood peak discharge computations and field estimates for site 6A for Flood of October 6, 1993.

Field inspection of October 7, 1993 by H. W.Hjalmarson.

Location	Regime site	Remarks	Peak Discharge (ft^3/sec)
Scottsdale Road.	2191	slope-conveyance	62
Peak View abv. 56th	1960	slope-conveyance	224
Inflow at Dixileta Dr. and 56th St. from area to north.			
At Dixileta Dr.	1969	slope-conveyance	48
Along 56th. Street			
450 ft. south of Dixileta	--	est.	10
750 ft. south	--	est.	2
1150 ft. south	--	est.	8
1500 ft. south	--	est.	5
1850 ft. south	--	est.	2
550 ft. N. of Peak View	--	slope-conveyance	62
At Peak View	--	slope-conveyance	25
500 ft. S. of Peak View	--	est.	10
800 ft. S. of Peak View	--	slope-conveyance (north)	32
800 ft. S. of Peak View	--	slope-conveyance (south)	76
1600 ft. N. of Dynamite Rd.	--	slope-conveyance	143
Along Tatum N. of Dynamite			
1400 ft. N of Dynamite	--	est.	10
1000 ft.	--	est.	4
770 ft.	1850	slope-conveyance	144
190 ft. (blw. Tatum)	1843	slope-conveyance	97
Above Tatum S. of Dynamite			
1920 ft. abv Tatum, 200 ft. S. of Dynamite	1872	slope-conveyance	134
Below Tatum S. of Dynamite (flow within area)			
2010 ft. S & 1270 ft. W.	1808	slope-conveyance	17

Table 4.(contunued)

Location	Regime site	Remarks	Peak Discharge (ft^3/sec)
Below Tatum S. of Dynamite (flow that crosses Pinnacle Vista Dr.)			
2500 ft. S. & 630 ft. W.	1815	slope-conveyance	111
3400 ft. S. at Tatum	--	est.(rough)	50
Along 40th S. of Dynamite			
250 ft.	--	est.	2
750 ft. S. of Dynamite	1763	slope-conveyance	166
1000 ft	--	est.	2
1300 ft	--	est.	0.5
1500 ft (1400-1700)	--	est. (several)	15
1950 ft. S. of Dynamite	1755	slope-conveyance	61
2100-2600 Flow along 40th St. leaving area at Pinnacle Vista Dr.			
2640 (at Pinnacle Vista Dr.)	--	est.	15
Along Pinnacle Vista Dr. East of 40th St.			
500 ft. E.	--	est.	1
1000 ft. E.(W. of 42nd St)	--	est.	10
1320 ft at 42nd St. Flow along Pinnacle Vista Dr. with 15 cfs inflow at 42nd St. and 5cfs from East.			
2350 ft. E.	--	est.	10
2640 ft. E.	--	est. (down 44th St)	5
3100 ft. E.	--	est.	5
3500 ft. E.(at 4520 E. Pinnacle Vista Dr.)	--	est.	5

Because none of the regional relations is specifically for the area surrounding site 6A and because of the wide scatter of data about the relations, the volume of runoff corresponding to the peak discharge in the many channels of site 6A for the storm of October 6, 1993 was computed using the three relations. Runoff volume at the many sites was estimated as the average of the three computed amounts of runoff (table 5).

It is important to note that the average relation of the three relations closely agrees with the gaged peak discharge and runoff for the October 6, 1993 storm at the FCDMC gage on Indian Bend Wash at Indian Bend Road (figure 17). This gage is located to the south of site 6A in the City of Scottsdale below much of the area of storm rainfall on October 6, 1993 (Waters, 1993).

at the U.S. Geological Survey gaging station at the same site where the drainage area is 142 mi^2 and at a nearby site (figure 17). The use of the average runoff of the three relations to estimate the runoff volume for the storm of October 6, 1993 for site 6A is supported by the close agreement with this nearby site.

Rainfall and runoff

Storm runoff within the bounds of site 6A is directly related to total rainfall of the storm of October 6, 1993. Storm rainfall, peak discharge, and the corresponding runoff volume were determined for seven drainage areas of site 6A (table 2). The rainfall and runoff amounts were plotted and a definite trend was observed (figure 18). A simple linear relation was used because of the limited range of computed storm rainfall. The relation indicates that generally at least 1.65 inches of rainfall was needed to produce runoff within site 6A on October 6. The proportion of rainfall that entered the larger tributary and distributary channels as runoff increased with the amount of rainfall. The relation indicates that for 1.7 inches of rainfall only about 0.12 percent ran off but at a total storm rainfall of 1.85 inches about 0.45 percent ran off. The relation between storm rainfall and runoff (figure 18) is similar to segments of the runoff curves, especially CN 60 and CN 65, in Figure 2-1 and Table 2-1 of Technical Release 55 by the U.S. Soil Conservation Service.

The amount of storm runoff appears to be influenced only by the amount of storm rainfall of site 6A. Although the data and runoff estimates are limited, there is no indication that runoff amounts were influenced by factors such as the channel type (distributary or tributary), altitude or area drained. The estimated amount of rainfall that ran off in the larger channels is subject to considerable error but it is certain that the total amount of runoff was a small portion of the total storm rainfall. Abstractions of storm rainfall to surface and underground storage are large in site 6A.

Table 5.--Estimated volume of storm runoff for peak discharges, storm of October 6, 1993.

Peak discharge	Storm volume, in acre-ft (1)	(2)	(3)	(4)
Scottsdale Road				
62.0	4	34	3	14
Peak View above 56th street				
224.0	27	154	14	65
Along 56th Street				
48.0	3	25	2	10
10.0	0	4	0	2
2.0	0	1	0	0
8.0	0	3	0	1
5.0	0	2	0	1
2.0	0	1	0	0
62.0	4	34	3	14
25.0	1	12	1	5
10.0	0	4	0	2
32.0	1	16	2	6
76.0	5	43	4	18
143.0	14	91	9	38
Total volume				97
Along Tatum north of Dynamite road				
10.0	0	4	0	2
4.0	0	1	0	1
144.0	14	92	9	38
97.0	8	57	6	24
Total volume				65
Above Tatum south of Dynamite road				
134.0	12	84	8	35
Below Tatum south of Dynamite road				
17.0	1	7	1	3
111.0	9	67	6	28
50.0	3	26	3	11
Total volume				42

Table 5.(continued)--

Peak discharge	Storm volume, in acre-ft (1)	(2)	(3)	(4)
Along 40th street south of Dynamite road				
2.0	0	1	0	0
166.0	17	108	10	45
2.0	0	1	0	0
0.5	0	0	0	0
15.0	0	6	1	2
61.0	4	33	3	13
15.0	0	6	1	2
Total volume				62
Along Pinnacle Vista east of 40th street				
1.0	0	0	0	0
10.0	0	4	0	2
10.0	0	4	0	2
5.0	0	2	0	1
5.0	0	2	0	1
5.0	0	2	0	1
Total volume				7

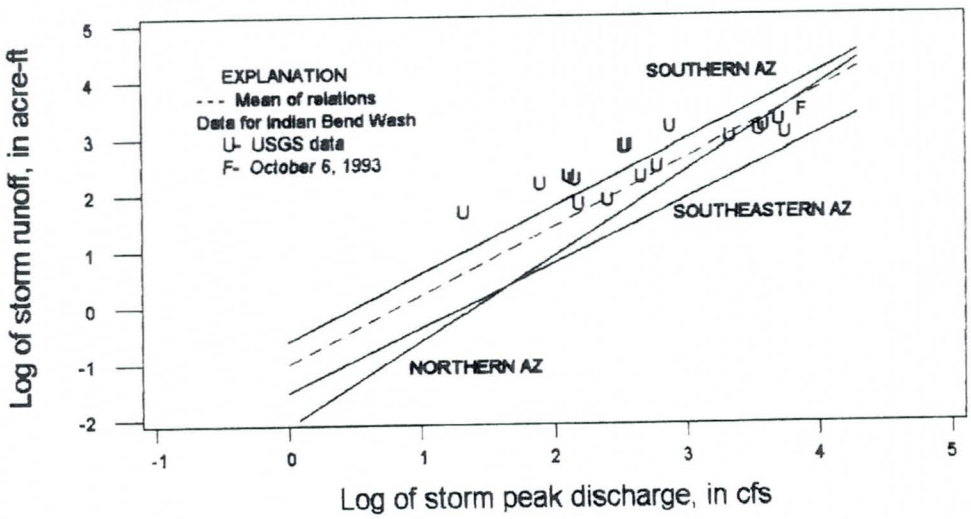
(1) Computed value from relation of runoff volume to maximum discharge for northern Arizona in unpublished U.S.Geological Survey report by B.N.Aldridge and A.Condes de la Torre entitled Flood Hydrology of small drainage areas in Arizona. May 1970.

(2) Computed value from relation of runoff volume to maximum discharge for southern Arizona in unpublished U.S.Geological Survey report by B.N.Aldridge and A.Condes de la Torre entitled Flood Hydrology of small drainage areas in Arizona. May 1970.

(3) Computed value from relation in figure 4 of Burkham, D.E., 1976, Flow from small watersheds adjacent to the study reach of the Gila River phreatophyte project, Arizona: U.S. Geological Survey Professional Paper 655-I, 19p.

(4) Value is the mean of the three values computed from the relations described in (1), (2), and (3) above.

Figure 17.--Peak discharge and runoff volume for storms in Arizona



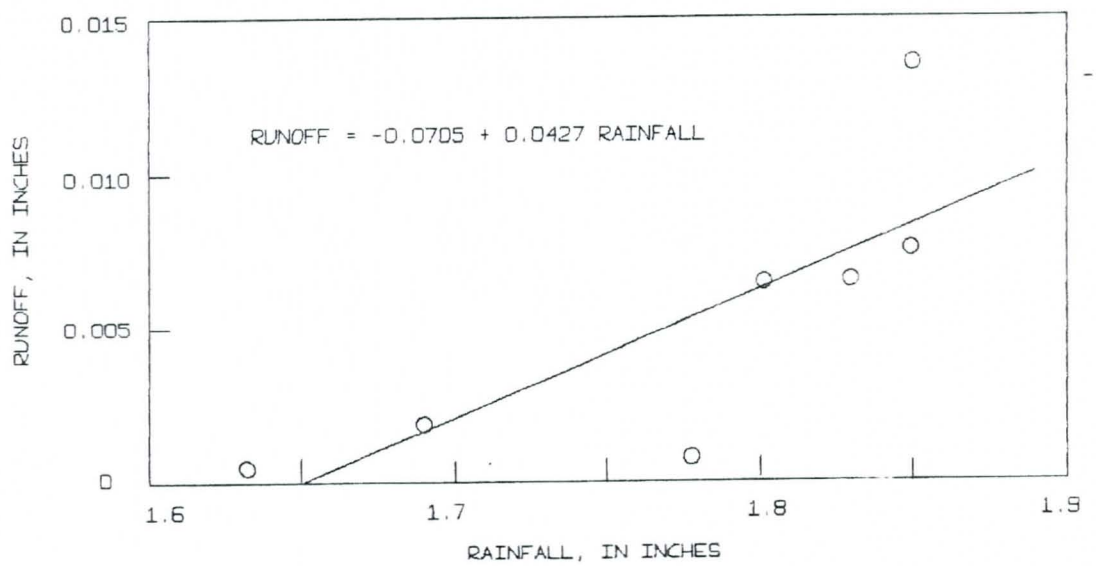


FIGURE 18.--RELATION OF STORM RUNOFF TO STORM RAINFALL FOR STORM OF OCTOBER 6, 1993 FOR SITE 6A.

MOVEMENT OF FLOW PATHS AND CHANNEL STABILITY--LEVEL 1

Reconnaissance and quantitative methods using surveyed cross sections are presented and applied in this level 1 assessment of stability of DFAs. Several methods are presented including the use of information in SCS soil surveys (Camp. 1986), hydrologic geometry relations, the observed appearance of the channels and surface of DFAs, the significance of a perched primary channel, and the comparison of stream channels depicted on old and recent aerial photographs. Additional methods and related information are given in several publications including geologic studies and documentation of flow paths for a major alluvial-fan flood (Pearthree, 1991); relations between the potential randomness of flow paths and topologic, hydrologic, and physiographic characteristics (Hjalmarson and Kemna, 1991); observations of channel location before and after large floods at several alluvial fans in California and Nevada (DMA, 1985); and the evaluation of channel stability of streams subject to erosion and sedimentation (CofE, 1990). Some of the evaluation of the stability of flow paths is subjective; the subjectivity is considered an advantage because the exclusion of a factor such as vegetation, whose effect on channel stability is not rigorously quantified in engineering literature, can influence the assessment of stability.

The flow paths of the DFA of site 6A were found to be stable for the following reasons:

1.--There are abundant large paloverde and other trees along the banks of the distributary channels and the interfluves are covered with scattered large trees. These large trees along the channel banks tend to stabilize the flow paths. Also, such trees would be washed away and not reach maturity if the flow paths were changing. In addition, few tree roots from lateral bank erosion are visible.

2.--No channel movement was observed on the DFA from a comparison of aerial photographs taken in 1940, 1953 and 1991.

3.-- The relations between channel width and discharge and mean depth and discharge for channel cross sections are typical of cross sections formed in cohesive bank material. These hydraulic geometry relations indicate the channels and flow paths are stable.

4.--The channels are eroded into the cemented Pleistocene sediments and are not perched above the adjacent land (figure 4).

5.--The soils forming the banks are well developed with dark reddish-brown sandy clay loam and clay loam textures a few inches below the surface and lime masses and may have cemented sediments. Also, the recent deposites along the distributary channels are horizontally stratified indicating the presence of hydraulic processes and not debris flows.

6.--There are areas of eroded Pleistocene sediments with triburtary drainage systems between the distributary channels (figure 2).

If the flow paths of the DFA of site 6A were unstable, it might have the following characteristics:

1.--Large trees such as paloverde would be scattered in somewhat of a random fashion over the DFA and not along the channel banks for sites in central and southwestern Arizona. Other sites with unstable flow paths in the southwestern U. S. may have little vegetation on the DFAs.

2.--Channel movement on the DFA may be depicted by comparison of aerial photographs taken before and after a major flood and spanning a few tens of years.

3.--The hydraulic geometry relations would show the channels are formed in noncohesive material.

4.--The channels and banks would be perched above the adjacent land at the same distance below the PD (figure 5).

5.--The soils of much of the DFA would not be developed except perhaps at great depths. The soils would lack lime masses and cementation at shallow depths and the soils would tend to be lighter or be more yellow and tan at shallow depths and have sandy textures. Also, the soils would lack horizontal stratification, cross-bedding, and/or imbrication usually associated with water flooding (hydraulic processes).

6.--Most of the interfluves in the upper DFA would be below the expected level of the 100-year flood.

7.--There would be little to no desert varnish on stones in the DFA. The surface of stones such as granite fragments weather easily in the desert environment of the southwestern United States and do not have desert varnish.

8.--The size of the DFA would be small relative to the size of the drainage basin above the DFA (Hjalmarson and Kemna, 1991).

9.--The computed degree of hazard would be at least 9 using regression equation 9 by Hjalmarson and Kemna (1991, p. 54). Site 6A (site 2 in Hjalmarson and Kemna, 1991) has a degree of hazard of 6 according to Hjalmarson and Kemna.

10.-The channel links would appear random using the random link model (Hjalmarson and Kemna, 1991). The random link model was not used for Site 6A because there was an insufficient number of channel links to reliably use the model.

Vegetation

The flow path stability is substantiated by the presence of abundant large paloverde and other vegetation along the banks of the distributary channels. There are no apparent alignments of large trees on the interfluves that would indicate the location of abandoned channels.

Active alluvial fans with unstable flow paths in the southwestern United States generally have little vegetation that is more than a few years old. Central and southwestern Arizona is an exception where there are few, if any, saguaro cacti on active alluvial fans but there are scattered bushes and trees except in the active channels and relatively small active depositional areas. Barring obvious differences of climate, vegetation may be disturbed less frequently on DFAs in the pediment environment of central and southwestern Arizona than in the mountain-valley environments of other regions. On aggrading fans in Arizona, vegetation may be less disturbed and therefore matures more easily than in other regions. There are few saguaro cacti, however, on actively aggrading alluvial fans in central and southwestern Arizona.

Mature saguaro cacti are found on stable land adjacent to the unstable land of aggrading alluvial fans on which there are very few saguaros. Mature saguaro cacti are also found on the stable areas (interfluves) between incised distributary channels of DFAs. In central and southwestern Arizona the presence of saguaro cacti on the DFA indicates the land is stable. There are many saguaro in the interfluves of site 6A.

Distributary-flow areas with vegetated drainage basins may be subjected to fewer debris flows than DFAs with little vegetation in the drainage basins. Basins with little vegetation and steep slopes have been known to produce debris flows. With fewer debris flows there are correspondingly fewer channel avulsions and the DFA is more stable. There is no evidence of debris flow in site 6A.

Cryptogamic crusts are soil crusts held together by algae, fungi, lichens, and moss (figure 19). These desert crusts are dark colored and typically occur on erodible land with some topographic relief (Johansen, 1993). Established cryptogamic crusts increase the shear strength of the surface as shown later in this report. These crusts may take 10 to 20 years to form starting during periods of moist-warm weather. A disturbed crust can recover within 1-5 years. In Arizona these crusts may be lichenized and are an indication of surface stability. Crusts like that shown in figure 19 are scattered throughout the DFA of site 6A.

The native riparian vegetation affords resistance to bank erosion and channel migration. The presence of abundant large paloverde trees along the banks of the distributary channels is historical evidence there is little, if any, channel migration on the DFA of site 6A. Only at a few locations are the roots of large trees exposed from lateral bank erosion or buried by deposition (figure 20).

Figure 19.--View looking across and north at cryptogamic crusts on right bank of hydraulic geometry site 1843 on distributary channel in DFA of site 6A located 130 feet west of Tatum Blvd. and 190 feet north of Dynamite Blvd. The dark soil algal crusts may take 10 to 20 years to develop.

Figure 20.--View looking downstream at channel below the alternate primary diffluence of site 6A showing deposited sediment around large trees. This scene is near the downstream edge of the pediment.

Channel movement

The stability of the paths of flow for site 6A is substantiated by the absence of channel movement depicted on aerial photographs taken in 1940, 1953 and 1991.

The comparison of stream channels depicted on aerial photographs can be a reliable means of ascertaining if flow paths are stable or unstable in engineering time. If quality aerial photographs of a DFA span a period of a few tens of years which included at least one major flood or at least one period of prolonged high flow, then a potentially reliable estimate of the frequency of channel movement on the DFA may be made. An example of such an estimate for site 6A was made using the following three sets of aerial photographs.

Set	Date taken	Identification
1	September 7, 1940	COU-2-69 Aerial glossy print 20x24 inches, Prescott area #22. Scale 1 inch to 1,000 ft. Scale for portion of site 6A covered by the photograph was 1 inch = 1,000 ft (determined using USGS topographic map).
2	March 8, 1953	Nos. 66,68 and 69. I.D. on no. 68 is: VV BE MI AMS * MAR. 53 1145 52.22 31,000 33 degrees 48 min. N 115 deg. 55 min. W. Physical size of the glossy prints was about 3.1 ft. x 3.1 ft.
3	March 30, 1991	Nos. I-17 and I-18. Taken by Landiscor Aerial Photo, Inc., 3816 North 7th St., Phoenix, Arizona 85014. Physical size of the prints was about 1.7 ft. x 1.7 ft. Physical size of the negatives was 8-1/2 x 11 inches.

The author examined two complete sets (sets 2 and 3) of aerial photographs of FEMA site 6A in the sections 5 and 6 of T. 4 N., R. 4 E., and sections 19-23, 26-32 of T. 5 N., R. 4 E.. The areal photographs were furnished by Mr. Joe Tram of the Flood Control District of Maricopa County. Both sets of photographs were of good to excellent quality. There was no cloud cover and the resolution was satisfactory for the identification of small trees and low-order stream channels. The scale of both sets of photographs was 1 inch = 1,200 feet or approximately 1:14,500. The photographs were black and white. Horizontal registration of the mylar overlays was made using road intersections and prominent trees as control points. There was some edge distortion which required frequent checking of the horizontal registration to obtain an accurate and precise comparison of the photographs.

The author examined a third aerial photograph (set 1) of site 6A in sections 19-20, 29-32 of T. 5 N., R. 4 E.. The third photograph was obtained from the National Archives. The photograph was of good quality, there was no cloud cover and the resolution was satisfactory for the identification of small trees and low-order stream channels. The scale of the black and white glossy photograph, according to the National Archives, was 1 inch = 1,100 feet. A side by side visual comparison with the other two sets of photographs was made.

The network of stream channels depicted on the three sets of aerial photographs were examined and no differences in the locations of the stream channels were found. There also were no discernible changes in channel width for streams located in the areas listed above except possibly for one 300 ft. long channel fork. The display of the negatives (set 3) over the glossy prints (set 2) when placed on a light table revealed no movement of the stream channels or the formation of new stream channels. The visual side by side comparison of photograph 1 with sets 2 and 3 also revealed no movement of stream channels. The original sets of aerial photographs(sets 2 and 3) are on file at the FCD and a copy was sent to FEMA as part of a draft of this paper in November 1993. The negative for the 1940 photograph is on file at the National Archives.

The only evidence of possible channel widening was found in a 300 ft. reach at the SW1/4NW1/4 of sec. 32, T.5 N., R. 4 E. about 1,600 ft. south of Dynamite Rd. and 800 ft, upstream of Tatum Blvd. A small channel fork that leaves the DFA of site 6A and enters the DFA to the south is apparent on the 1953 and 1991 photographs. This channel is very faint on the 1940 photograph but the contrast between the mobile bed material and the surrounding stable bank material is poor: the lighter colored channel beds are not distinct in this area on the 1940 photograph. Some recent deposits of bed material were observed along the channel banks during a recent field inspection of the site. The deposited bed material in this area is confined to the channel banks and is not on the adjacent flood plains.

Because there is no known deposited bed material on the floodplains adjacent to the distributary channels of site 6A, deposits like the above appear to be remobilized by a flow "pulse" as previously described. The channel conveyance is reduced by the deposited bed material until energy is sufficient to remobilize the material. These deposited "pulses" of bed material are well within the bounds of the 100-year flood.

Many trees shown on the 1940 and 1953 photographs were present in 1991. With few exceptions individual larger trees along the defined channels were visible on all sets of photographs. Also, the channels remained at the same position relative to the trees for the three sets of photographs. There was no evidence that channel movement destroyed trees along the channel banks or that the channels moved relative to the location of the trees.

While employed as a hydrologist with the U. S. Geological Survey (USGS) the author studied the potential flood hazards of the Cave Creek 7.5-minute quadrangle which include much of the area in the sections above. Stream channels were examined from a helicopter on several occasions in the mid 1970s. Also as part of the 1970's study and subsequent studies in the late 1980s and early 1990s, there were many on-site investigations of the stream channels and associated potential flood hazards. A major objective of these studies was to assess the potential movement of the channels (Hjalmarson, 1978, Hjalmarson, 1993a and b, Hjalmarson and Kemna, 1991). The potential flood hazards, stream channels, topography, physiography, soils, and geology that the author has observed, studied and reviewed as part of these studies are sufficient to enable the author to make the following comments and draw the following conclusions:

1.--To a degree of reasonable engineering certainty, the author does not believe that the stream channels emanating from the south channel of site 2 (Hjalmarson and Kemna, 1991) otherwise known as FEMA site 6A will change location significantly under natural processes during engineering time or approximately 100 years. If the distribution of annual flood peaks was time invariant for the 38 year period spanned by photograph sets 2 and 3, the probability is 54 percent that a 50-year flood was exceeded. For the 51 year period, 1940-91, the probability is 50 percent that a 75-year flood was exceeded. There was ample opportunity for the channels to move during the 51 years.

2.--The systems of both tributary and distributary channels are considered relatively stable unless manmade obstructions to floodflow are constructed in the channels and adjacent flood plains. The distributary channels are incised in old-fan remnants and the old-fan remnants are slowly eroding.

3.--The relative amounts of floodflow in distributary channels downstream of forks will change some from one flood to the next because of small amounts of scour and fill in the defined channels. Precise estimates of the distribution of floodflow in the system of distributary channels cannot be made because of the scour and fill but scour in all the incised distributary channels is likely during major floods. Even during small floods there is enough kinetic energy to move sediment deposited on the channel beds (Hjalmarson, 1994, in press). Small differences of scour and fill in the relatively small entrenched channels will have little affect on total conveyance differences of the forked channels. Even for the unlikely event that there was scour in one entrenched channel and fill in the other channel at a fork, a relative change in the bed levels of even one foot would result in an average change in the distribution of discharge of less than about 10 percent at the 100-year discharge.

4.--The construction of homes, buildings, roadways, impervious areas and other obstructions in the distributary channels and adjacent flood plains can cause lateral migration of the channels. If such disturbances of the natural system of channels are large, new channels may form and existing channels may be abandoned. There presently (June 9,1993) are a few homes and roadways scattered throughout the DFA of site 6A that form obstructions to runoff and floodflow.

5.--Small amounts of lateral movement of channels caused both naturally and by man occur throughout the area. Observed scour and fill is local and commonly on the order of a few feet laterally and less then about 1 ft. vertically. The outcrops of cemented Pleistocene sediments act as erosion-resistant anchor blocks and restrict general channel movement.

Hydraulic geometry

The relations between channel width and discharge and mean depth and discharge for channel cross sections of site 6A substantiate that the cross sections were formed in cohesive bank material. The hydraulic geometry relations indicate the channels and flow paths are stable.

The cross section of the incised channels of DFAs depends on many factors such as the channel gradient, sediment load, underlying material, vegetation along the banks, and the magnitude, frequency, and duration of floodflow. The change of cross-section shape along a channel depends on many factors such as if the cross section is on a bend or a straight reach of the channel. For example, the shape of cross sections in straight-uniform reaches of cohesive material exhibit certain preferred characteristics. These characteristics can be described by hydraulic geometry (geometry-discharge relations). The continuity equation for the instantaneous discharge (Q) is:

$$Q = WDV$$

where

W = width of the channel,
D = mean depth of the channel, and
V = mean velocity of the discharge that formed the channel.

To represent the geometry of the uniform-channel section:

$$Q = kQ^bQ^fQ^m$$

where the coefficient, k, is the product of the coefficients Cw, Cb, and Cv defined below, and is equal to one, and the sum of the exponents b, f, and m is equal to one.

The hydraulic geometry relations at a given cross section along a stream for channel width, depth, and velocity are:

$$W = CwQ^b$$

where

Cw = constant related to the size of the channel,
Q = peak discharge, in cubic feet per second, that formed the channel, and
b = constant exponent.

$D = CbQ^f$

where

Cb = constant related to the size of the channel, and

f = constant exponent.

$V = CvQ^m$

where

Cv = constant, and

m = constant exponent.

The empirical exponents (b, f and m) for a cross section in a straight-uniform reach with cohesive bank material are 0.25, 0.43, and 0.32, respectively (Appendix D, table D1). For non-cohesive bank material at a cross section the corresponding empirical exponents are 0.50, 0.27 and 0.23.

The exponents for 15 surveyed cross sections in the DFA of site 6A were computed (table 6 and figure 21) and compared to the empirical values (table D1). These cross sections were surveyed during June 1993. The exponents were defined for the range of stage where the cross section shape changed uniformly with elevation. The mean of the exponents for the cross sections indicates the cross sections were formed in cohesive bank material. The standard deviation of the exponents of the surveyed sections is small and indicates the network of distributary channels is formed in uniform cohesive sediments; all of the empirical exponents for cohesive bank material are within one standard deviation of the mean values but two of the empirical exponents for non-cohesive bank material are more than one standard deviation from the mean values for the 15 sites (table 6). Some of the variation of the exponents is the result of the stabilizing affects of trees and bushes along the channels and channel bends above and below the straight reaches where the cross sections were surveyed.

Following the flooding of October 6, 1993 the cross sections at 11 sites were resurveyed and the exponents were computed (table 6). The mean exponent for channel width was 13 percent less following the floodflow. The mean exponent for mean depth increased 5 percent. The largest change at a site was a 55 percent decrease in the width exponent at site 1866 and a corresponding 36 percent increase in the depth exponent. The mean of the exponents remained similar to the empirical exponents for channels with cohesive bank material.

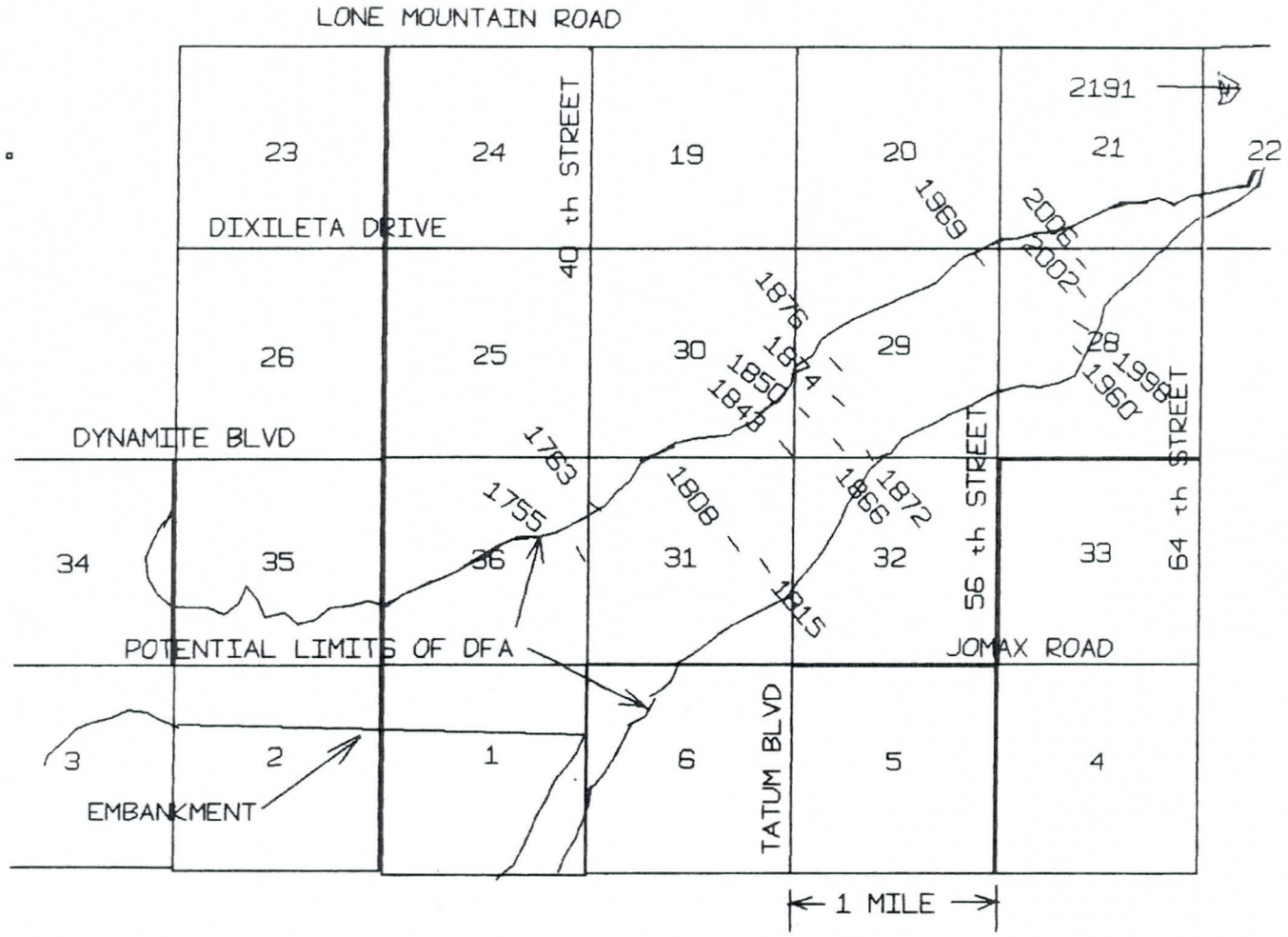
Measurements of channel geometry at several cross sections within a DFA are needed for a reliable estimate of the mean exponents. The hydraulic geometry characteristics can be reliable indicators of channel stability if "steady state" flow conditions have formed the channels. Large floods can alter the shape of the channels, especially channels with unstable boundaries, and many years may be needed for the channels to reform to "steady state" conditions (Osterkamp and Harrold, 1981). Hydraulic geometry measurements are more reliable for stable than unstable channels because the scour and fill effects of large floods are small. A large computed standard deviation for the mean exponents may indicate the "unsteady state" imprint of a recent large flood. The change of the mean of the exponents following the small flood of October 6, 1993 is small and indicates the channels are stable.

Two of the channels where the cross sections were surveyed are shown in figures 22 and 23. The stabilizing effects of the riparian vegetation is evident for all flows. No evidence of a recent large flood was found along the channels of the DFA when the sections were surveyed during the summer of 1993.

Table 6.--Computed hydraulic-geometry exponents and soil type for channels cross sections in site 6A

Site (elevation, in ft.)	Exponents						Soil* unit
	Before October 6, 1993			After October 6, 1993			
	Width	Depth	Velocity	Width	Depth	Velocity	
1843	.20	.48	.32	.14	.54	.32	3
1850	.25	.45	.30	.14	.50	.36	3
1866	.31	.44	.25	.14	.60	.26	3
1872	.40	.49	.11	.18	.50	.32	3
1874	.16	.51	.33	.21	.48	.31	3
1960	.39	.35	.26	.33	.41	.26	3
1998	.38	.37	.25				3
2191	.22	.47	.31	.23	.46	.31	6
1755	.20	.47	.33	.24	.48	.28	90
1808	.44	.37	.19	.47	.34	.19	90
1876	.30	.47	.23				90
1969	.29	.44	.27	.37	.37	.26	90
2002	.30	.42	.28				96
2006	.41	.34	.25				96
1763	.21	.50	.29	.24	.50	.26	98
Mean	.30	.44	.26	.26	.46	.28	
Standard deviation	.084	.053	.055	.11	.083	.044	

* From maps of soil types in Camp (1986).



EXPLANATION: 1808- ELEVATION AT INDICATED CROSS SECTION

FIGURE 21.--LOCATION OF CROSS-SECTIONS FOR HYDRAULIC GEOMETRY.

Figure 22.--View looking upstream at hydraulic geometry site 1876 on distributary channel in DFA of site 6A. The channel is lined with scattered Palo Verde trees and dense brush and bushes. Because of above normal precipitation during the past winter the ground is covered with dense grass.

Figure 23.--View looking downstream at hydraulic geometry site 1969 on distributary channel in DFA of site 6A. The channel is lined with Palo Verde trees and bushes and is within the landform. The ground is covered with dense grass.

Appearance of channels

The channels of site 6A are eroded into cemented sediments and are not perched above the adjacent land. The incision of the channels into the landform substantiates the flow paths are stable.

The following observations were made during reconnaissance of the DFA and channels of site 6A during the beginning of this study. These observations are characteristic of initial visual observations of an area under study.

1. The 1/2 to 3 ft. deep banks of the small-incised channels of site 6A appear stable. There is insignificant caving of banks and no evidence of meander migration that would be indicated by exposed roots, sluff areas, and abrupt transitions at tributary points.

2.--In many places the potential movement of channel beds and banks is constrained by cemented sand and gravel. The channels and adjacent flood plains of streams emanating from the PDs are composed of sandy loam and gravely-sandy loam. The stream channels are composed of more granitic type coarse sand and gravel than the flood plains. The channel beds can easily erode and the channel banks are susceptible to erosion in places unprotected by vegetation and cementation. The banks generally are calcareous sandy loam from a few inches below the surface. The amount of cementation by the calcium - carbonate varies along the channel banks and generally affords slight to moderate resistance to erosion except in some places where cemented Pleistocene sediments resist downcutting and lateral movement of the channels (See figures 24 and 25). Some minor channeling, deposition and streambank erosion is common during infrequent flooding but there is no evidence of flow path movement throughout the DFA.

The frame of the square grid shown in figures 24 and 25 and several other photographs is 1.5 ft. outside dimension on a side. The internal square of the square grid is 1 ft. on a side with a grid spacing of 1 inch.

The incision of the distributary channels into the cemented sediments is evidence that the channels are stable or eroding. The cemented sediments like those shown in figures 24 and 25 control the local grade, with slope above and below the cemented sediments similar, with the drop caused by resistance to erosion (David Dawdy, consulting hydrologist, written communication, following a field inspection of site 6A with the author during June 1993). The exposed deposits of cemented sediments in the channel banks also indicates an erosional environment. The cemented sediments of the B soil horizon form at the depth of maximum water penetration, where it deposits dissolved constituents. A B horizon can form on active alluvial fans where the surface is aggrading but where there is incision, material is removed from abandoned fan surfaces (Lattman, 1973). At site 6a, channels are downcutting through those earlier deposits (David Dawdy, written communication, June 1993).

Figure 24.--View looking upstream from hydraulic geometry site 1960 on distributary channel in DFA of site 6A. The channel is lined with scattered Palo Verde trees and dense bushes. The abrupt rise in the streambed above the backpack in the center of the scene is at an outcrop of erosion resistant Pleistocene sediments that is resisting the incision of the channel (See figure 25 for closeup view of the cemented sediments).

Figure 25.--Closeup view looking upstream and down at cemented sediment from 80 feet upstream of hydraulic geometry site 1960 on distributary channel in DFA of site 6A. The cemented block of old sediment is resisting channel entrenchment and controlling the channel grade (See figure 24 for view of the cemented sediments from below).

3.--The soils adjacent to the major streams in the DFA are developed on fan terraces (Camp, 1986) that have been eroding slightly during the past thousand years. The soils of these terraces are well developed and commonly are oxidized to depths of 1-1/2 to 2 feet. There is a distinct B horizon with a build up of limy clay from leaching of clay minerals from near the surface to the lower part of the soil. The old material contains calcareous gravelly loam to a depth of a few feet and strongly cemented gravelly material was observed in road cuts and in many places where the channel had downcut. There are systems of tributary channels developed in these eroding areas between the several distributary channels that emanate from the primary diffluence. The calcareous gravely sandy loam is resistant to erosion along the washes and the hazard to runoff erosion is slight (Camp, 1986, p.71).

4.--There is some sediment deposition where floodflow is locally unconfined at some diffluences. Sediment appears to have deposited at some diffluences during large floods because the flow is unconfined and spreads laterally. The laterial spreading is within the confines of defined ridges of old-cemented material. Subsequent small floods appear to erode the deposited sediment from the steepened face of the small deposited mounds as shown by low-flow channels cut into these deposits. In fact, throughout the DFA the low flows appear to erode sediment deposited at these hydraulic expansions. This observation was made by Joe Tram, Hydrologist, FCD and the author during a field inspection of the channels during June, 1993.

5.--There is degradation at the diffluences as evidenced by the general channel entrenchment in the surrounding Pleistocene sediments.

6.--The many large paloverde trees and bushes along the banks of the distributary channels appear to protect the channel banks from erosion (figures 22, 23 and 24).

7.--The ridges of the interfluves separating the distributary channels generally are from 2 1/2 to 4 feet above the channel beds (plate 1 and Appendix F). The distributary channels and the adjacent flood plains between the ridges convey floodflows in separated wide-flat distributary channels. The potential conveyance between most of the ridges is a few times more than the conveyance needed to convey the 100-year flood (Appendix F, table F1). The combined capacity of the small distributary channels at bankful stage is a small portion of the 100-year flood but the capacity of the defined channels between the stable ridges is a few times more than the 100-year flood (Appendix F). The land adjacent to the incised channels generally slopes gradually upward to the ridges between the incised channels while a few ridges are fairly flat between the channel banks. The width of the distributary-channel beds generally is from 6 to 20 feet, the width between the top of the banks is from about 20 to 50 feet, and the width between defined ridges generally is more than 50 feet and less than 500 feet. The ridges of interfluves have well developed old soils (Camp, 1986).

8.--The channels are eroded into the old cemented sediments and are not perched above the adjacent land. The channels of site 6A are incised into the landform (figure 4) and no perched principal channels were observed on the DFA (figure 5). DFAs with perched principal channels have given alluvial fans the valid reputation of unstable-highly hazardous landforms where channels can suddenly avulse. DFAs with channels entrenched in old cemented sediments should not inherit the same reputation.

In central and southwestern Arizona only the most active alluvial fans have perched principal channels or elongated depositional tongues of perched debris-flow deposits. The fan of Lost Dog Wash located near the southwest end of the McDowell Mountains in Maricopa County has a perched principal channel. Floodwater of major floods in Lost Dog Wash is unconfined about 1,100 ft. below the PD and spills over the perched banks (Hjalmarson, 1994, in press). A fan on the north side of Picacho Peak (Hjalmarson and Kemna, 1991, site 4) in Pinal County has a mound of debris-flow deposits that is perched above adjacent land equidistant from the PD. Both of these fans are below steep mountainous basins and like other similar fans in central and southwestern Arizona, have unpredictable paths of flow (high degree of flood hazard) based on a progressive rating system by Hjalmarson and Kemna (1991).

Soil characteristics

Soil surveys are useful for assessing the stability of the channels and surface of DFAs and where available, should be routinely consulted for flood studies of DFAs. The soils of stable surfaces, like those for site 6A, are well developed with dark reddish-brown clay loam and sandy clay loam textures, lime accumulations and may have cemented sediments near the surface.

Soil survey reports of the SCS with 7.5-minute orthophoto maps depicting types of soils are a major source of information on the stability of DFAs. For example, the soil map units for most of the DFA of site 6A are fan terraces (Camp, 1986) with well developed soil profiles. Within these cemented Pleistocene sediments are soil map units of the Antho or Carrizo series that have been recently (Holocene Epoch) deposited by runoff and commonly are aggrading or subject to periodic erosion and deposition by floodflow. These map units commonly correspond to areas along stream channels subject to erosion and deposition by floodflow. The Antho and Carrizo soils are stratified in the sedimentary sense and have no horizon development. Soils like the Antho are layered with sorted material deposited by different flood events at site 6A (figure 26).

Deposits like that shown in figure 26 are horizontally stratified along the distributary channels throughout site 6A. The individual beds within the deposits are thin and very loose except for occasional thin-cemented plates. Also, sediment tends to be deposited on the inside of meander bends throughout site 6A. These characteristics usually are associated with water flooding and not debris flows.

Figure 26.--View looking down and across at alternating layers (right side of scene) of silt, sand and small gravel on left bank of distributary channel near center of cross section 2090. The material is slightly oxidized about 2 inches behind the bank where it was removed in the center of the scene.

Soil survey maps are produced at five standard levels of detail by the SCS. The maps are produced to standards for such factors as the density of augured soil samples and the map scale. The SCS also publishes an assessment of the frequency of flooding for soil types which is independent of the common definition of flood frequency for flood studies. A 3rd order soil survey is commonly shown at a 1:24,000 scale. A first order soil survey is shown to much more detail at a map scale of 1:15,840 or larger (table 7). The order of the soil survey depends on the users needs.

More detailed soil surveys may be especially useful for defining distributary channels and small-stable interfluves. Recently mapped soil units for site 6A on aerial photographs, scale approximately 1:5,000 (Cathy E. McGuire, soil scientist, SCS) provided useful detail for definition of active watercourses and assessment of flow path stability. Such detailed soil surveys by the SCS are not readily available.

As noted previously, topographic maps and aerial photographs are used to delineate the PD and boundaries of DFAs and maps of soil surveys are used to substantiate these boundaries and to further assess if the DFA is degrading or aggrading and has stable or unstable paths of flow. Degrading areas with old-developed soils which are traversed by incised distributary channels may be considered stable because the channel location does not change over periods of many years and the channel geometry is fairly stable. For example, the location of the channels of site 6A did not appear to change for a period of 51 years which includes at least one major flood and thus, the flow paths, which are entrenched into cemented material, are considered stable.

Soil surveys

Soil survey reports with maps of a large scale (1:20,000 and 1:24,000) cover more than one-half of Arizona (See Camp, 1986, for example). These soil survey reports with maps delineate soils characteristic of flooding and active deposition. Some examples of soils characteristic of aggrading DFA's include the Anthony soil and the mixed alluvial units (Richardson, 1971). The following are general characteristics of soils that are subject to flooding and are commonly found on aggrading DFA's or along the active channels of eroding DFAs. The color of soils on aggrading DFA's is typically more yellow and tan (7.5 YR to 10 YR on the Munsel Color Chart) than the redder Pleistocene soils of eroding DFAs (2 YR to 5 YR). The soils of aggrading DFA's generally lack lime masses and concretions near the surface that are found in the Pleistocene soils of degrading DFAs. Any lime present in aggrading DFAs generally is disseminated, but the soil may still effervesce slightly. Lastly, the texture of soils on aggrading DFA's generally is loam and loamy sand to sandy loam and sand.

Soils on degrading DFAs like site 6A commonly have three distinct zones or horizons. The top or A horizon is where soluble constituents have been removed by downward percolating water. Below the top zone are the B horizons where the leached constituents and particles washed down from the A horizon are deposited. Calcium carbonate accumulations in the C horizon are strongly effervescent and fine soft lime masses are common in some areas(Camp, 1986). Soils on "old fan" deposits or fan terraces commonly have B horizons that extend to a depth of at least 2 feet and are a reddish brown. Soils with this amount of development have been stable for

Table 7.--Levels of U. S. Soil Conservation Service soil surveys.

Source: National Soil Survey Center, Lincoln, NE.

Level of data (order)	Data needs	Land area represented (hectares)	Kinds of map units	approx. map scale
1st.	Very intensive. For experimental plots.	1.0 or less	Consociations and some complexes	1:15,840 or larger
2nd.	Intensive. For general agriculture and urban planning.	0.6 to 4	Consociations and complexes	1:12,000 to 1:31:680
3rd.	Extensive. For rangeland, forest land and community planning.	1.6 to 16	Associations or complexes	1:20,000 to 1:63,360
4th.	Extensive. For regional planning.	16 to 252	Associations, some consociations, complexes, and undifferentiated groups.	1:63,360 to 1:250,000
5th	Very extensive.	252 to 4,000	Associations, some consociations and undifferentiated groups	1:250,000 to 1:1,000,000

thousands of years (Philip D. Camp, Acting State Soil Scientist, SCS, oral communication in field at site 6A during June, 1993). According to Machette(1985), calcic soils in this region can represent millions of years of formation.

Soil map units of the Pinamt and Pinaleno series commonly have horizons that have developed thousands of years. These soils are found on fan terraces (Camp, 1986, p. 74, and oral communication at site 6A during June, 1993) of the Pleistocene Epoch and are older than soils like the Antho and Carrizo series. The sediments in the B horizon generally are weakly cemented with calcium carbonate. In places the sediments are strongly cemented by calcium carbonate that act as erosion resistant anchor points. The surfaces of soils like the Pinaleno are stable or eroding slightly and the cemented sediments resist lateral movement of the incised channels that drain or traverse these areas.

Soil survey reports can be confusing to engineers and hydrologists studying the nature and extent of flooding on DFAs. The reports are written for a wide variety of potential users such

as engineers, farmers and home builders. Mapped units of a particular soil series can include areas of other soil series which are too small to be defined. These unmapped inclusions, which are described in the soil survey reports, can be important and confusing. For example, a map unit of Antho-Carrizo-Maripo complex associated with active channels incised in older Pleistocene sediments (parent material of Pinaleno soil) may not show small-stable interfluves of Pinaleno soil that are readily observed in the field. Inclusions like these stable interfluves are important for the assessment of channel stability and type of flood hazard of a particular DFA. The author has experienced excellent assistance from SCS soil scientists in the interpretation of soil survey reports. For additional information about soil surveys consult the following publications by the SCS: National soil survey interpretations handbook, (430-VI-NSH, Draft, September 1992) and National Soil Handbook, (NSH Parts 600-606, July 1983).

Soil properties related to the stability of flow paths and channel geometry and the frequency of flooding are given in sections 618.03-11 to 618.03-19 of the National soil survey interpretations handbook. Soil characteristics and the criteria for defining characteristics of soil erodibility, soil loss tolerance and flooding of soils are described in these sections of the handbook and have been used in assessing site 6A. The glossary of landform and geologic terms (part 629) of the handbook can be useful for the interpretation of soil surveys.

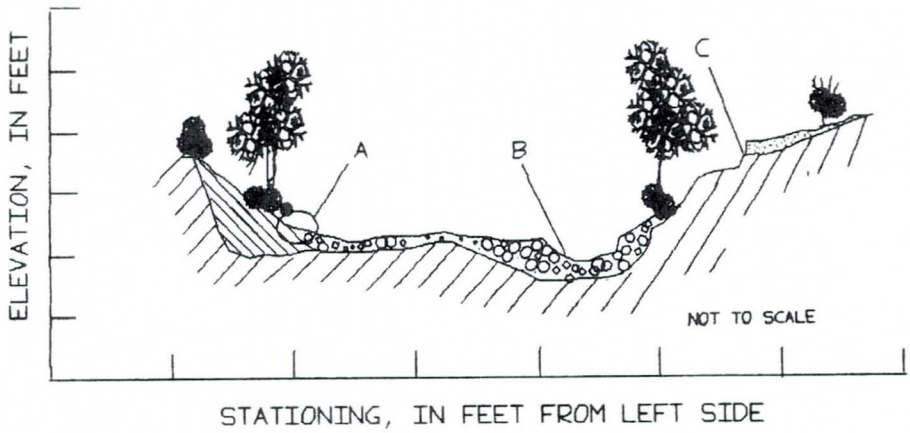
A potential source of confusion to engineers and hydrologists is the changing of map units primarily on the basis of climate. In southern Arizona, for example, the map units can change at an elevation of about 2,000 ft. based on the temperature, annual precipitation, and the major resource land area. Antho soils change to Anthony soils mostly for this reason. Except for the climate characteristics, Antho and Anthony soils can be considered the same when assessing flood hazard characteristics of DFAs. Other soils in central and southern Arizona that can be considered the same are the Carrizo and Arizo soils and the Pinamt and Pinaleno soils.

Another potential source of confusion is the difference between the traditional and SCS use of the term alluvial fan. Alluvial cone as described by the SCS is similar to alluvial fans described by hydrologists (See glossary). The SCS has also used alluvial fan for aggrading areas near the toe of piedmonts far downslope of areas with distributary channels and alluvial fans (Camp, 1986).

Younger soils

The young soils (Holocene Epoch) of site 6A generally have light colors (figure 24), stratification (figure 26), irregular decrease of organic matter with depth, none to weak structure, and none to little clay or calcium carbonate ($CaCO^3$) accumulations. Some of the younger soils have developed soils structure with a weakly developed (cemented) B horizon and Munsel color of 7.5 YR. These Agustin soils (figure 27) are hundreds or perhaps a few thousand years old and commonly are along the more recent Arizo soils which are moved about by floodflow. The younger Arizo, Anthony and Agustin soils overlay the older Tres Hermanos, Pinaleno and Soledad units (figure 28). These younger soils are along the distributary channels and at the toe of site 6A where flow spreads out as sheetflow.

Figure 27.--View looking down at augered soil sample on interfluve between incised channels near center of cross section 2090. The developed soil is brown from about 2 inches below the surface(deposit located a few inches above the bottle) and, although not readily visible in the photograph, reddish-brown below a depth of 18 inches(deposit below and to right of hole). There are clay coats on the rocks below a depth of 18 inches.



EXPLANATION

SAND AND GRAVEL DEPOSIT WITH ARIZO AND ANTHONY SOILS

FLOOD DEPOSIT

HOLOCENE SEDIMENTS WITH AGUSTIN SOIL

PLEISTOCENE SEDIMENTS WITH SOLEDAD SOIL

A ANTHONY SANDY LOAM ON FLOOD PLAIN

ALTERNATING LAYERS OF SILT, SAND, GRAVEL AND ORGANIC DEBRIS DEPOSITED BY RECENT FLOODS. THERE COMMONLY ARE WEAKLY CEMENTED "PLATES" OF SILTY MATERIAL.

B GRAVELLY ARIZO SOIL IN CHANNEL

C EROSIONAL SCAR OF FLOOD DEPOSIT(UNCOMMON)

FIGURE 28 --SCHEMATIC DIAGRAM OF HOLOCENE AND PLEISTOCENE SEDIMENTS ALONG DISTRIBUTARY CHANNELS OF FAN 6A.

Older soils

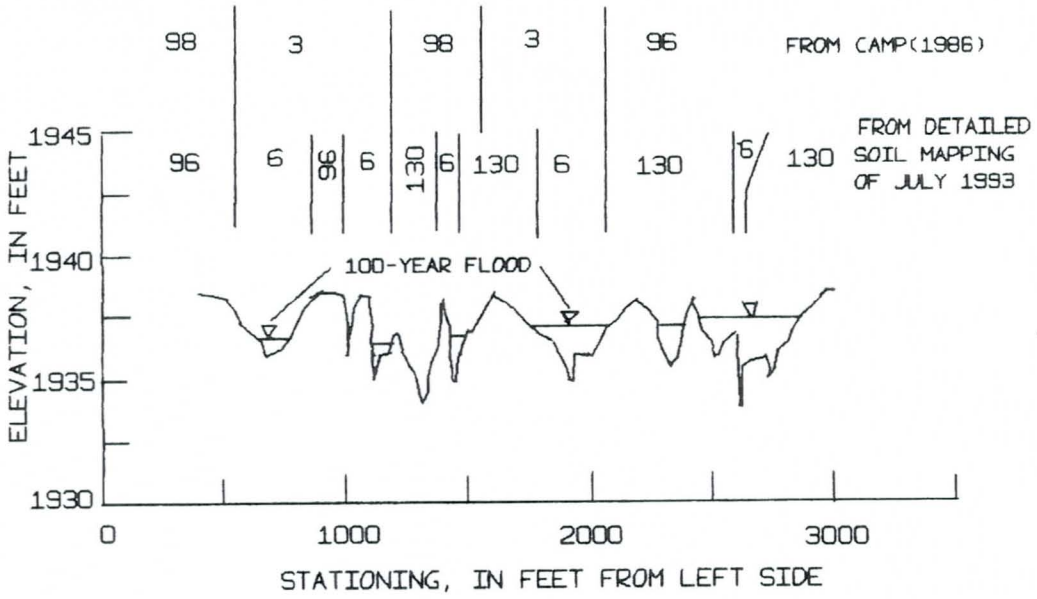
Older soils of site 6A have developed argillic horizons (clay minerals), strong structure, calcium carbonate movement with a well cemented B horizon, and shiny clay coats on the ped faces and rocks generally at higher positions on the interfluves. The Soledad series is coarse-loamy and contains less than 35 percent rock fragments. The texture of the Tres Hermanos unit is fine-loamy with a brown-reddish color (5 YR) at 2 to 6 inches deep.

Detailed soil survey

During July 1993 a detailed survey of soils along the DFA of site 6A was made by Cathy E. McGuire, soil scientist, SCS. While the published soils maps on 7.5-minute orthophoto quads (Camp. 1986) were very useful for substantiating the stability and extent of the DFA, a detailed survey was made to evaluate the usefulness of the less detailed published maps (7.5-minute Quads) and to determine if the detailed maps provided needed information.

The soil map units for the published maps and the unpublished detailed survey are shown on three cross sections (figures 29, 30, and 31). Soil map units 3 and 6 are the younger unstructured mapped units and are essentially the same soil except for climate features, soil unit 130 is the younger unit (Holocene Epoch) with developed soils and some development (cementation) in the B horizon, and soil units 96 and 98 are older-well developed soils (Pleistocene Epoch) which are essentially the same soil except for climate features. All of the channels shown in figure 29 and most of the channels shown in figures 30 and 31 that convey the 100-year flood correspond to the younger units of the detailed survey. Only one channel with younger soil (figure 30) was shown not to convey much 100-year floodflow. A field examination of this small channel revealed that some distributary flow may overtop stable banks upstream and enter this small channel. The detailed soil survey clearly shows the interfluves are composed of older developed soils that have been stable for many years. Some of the channels that are tributary and drain areas within the DFA have younger soils (figures 29, 30, and 31). The less detailed survey (Camp, 1986) also shows a general stability of flow paths but with much less precise agreement with the flooded areas. The area of least agreement is on the right side of section 2000 (figure 30) where the active flood channels were too small to be published on the older less detailed soil survey.

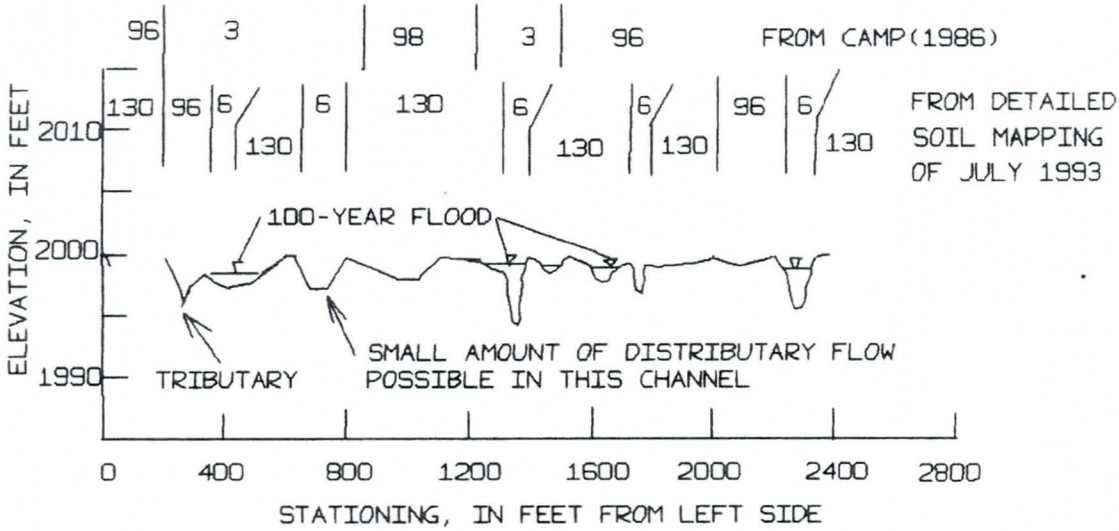
Although not shown for the entire DFA of site 6A, the detailed soil survey substantiates the active watercourses of the distributary system of channels that emanate from the PD (plate 1). The published soil maps on the 7.5-minute Quads generally coincide with the area of distributary-flow but potentially useful detail is missing. Both soil surveys depict the younger soils along the distributary channels as lying within the older Pleistocene sediments. Thus, both surveys are useful for assessing if the DFA is subject to active deposition or is an abandoned depositional surface that is eroding.



EXPLANATION

SOIL UNIT	NAME OF UNIT	SCS FREQUENCY OF FLOODING	REMARKS
3	ANTHO, CARRIZO	RARE	SAME AS UNIT 6.
6	ANTHONY, ARIZO	RARE, OCCASIONAL	SAME AS UNIT 3.
96	PINALENO	NONE	WELL DEVELOPED GRAVELY CLAY LOAM
98	PINANT-TREMANT	NONE	SIMILAR TO UNIT 96
130	AGUSTIN	NONE	SOME DEVELOPMENT-GRAVELY

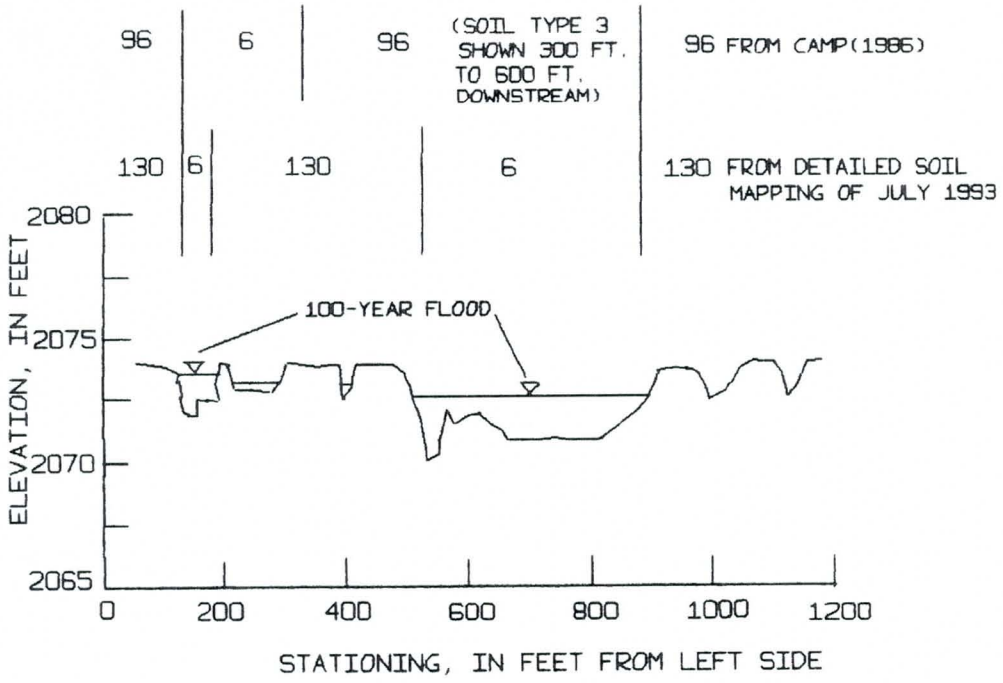
FIGURE 29.--CROSS SECTION 1938 SHOWING LEVEL OF 100-YEAR FLOOD AND MAPPED SOIL UNITS.



EXPLANATION

SOIL UNIT	NAME OF UNIT	SCS FREQUENCY OF FLOODING	REMARKS
3	ANTHO, CARRIZO	RARE	SAME AS UNIT 6.
6	ANTHONY, ARIZO	RARE, OCCASIONAL	SAME AS UNIT 3.
96	PINALENO	NONE	WELL DEVELOPED GRAVELY CLAY LOAM
98	PINANT-TREMANT	NONE	SIMILAR TO UNIT 96
130	AGUSTIN	NONE	SOME DEVELOPMENT-GRAVELY

FIGURE 30.--CROSS SECTION 2000 SHOWING LEVEL OF 100-YEAR FLOOD AND MAPPED SOIL UNITS.



EXPLANATION

SOIL UNIT	NAME OF UNIT	SCS FREQUENCY OF FLOODING	REMARKS
3	ANTHO, CARRIZO	RARE	SAME AS UNIT 6.
6	ANTHONY, ARIZO	RARE, OCCASIONAL	SAME AS UNIT 3.
96	PINALENO	NONE	WELL DEVELOPED GRAVELY CLAY LOAM
130	AGUSTIN	NONE	SOME DEVELOPMENT-GRAVELY

FIGURE 31.--CROSS SECTION 2074 SHOWING LEVEL OF 100-YEAR FLOOD AND MAPPED SOIL UNITS.

Use of soil surveys

Soil surveys are useful for assessing the stability of DFAs and where available, should be routinely consulted for flood studies of DFAs. Soil surveys provide valuable clues as to the length of time since land last received deposits (Bull, 1977, p. 252). For example, the degree of soil development associated with the stages of fan development, and thus the stability of the flow paths depicted in figures 3 and 4 or the instability depicted in figure 5, can be readily assessed using soil characteristics given in most published soil surveys. When used with detailed topographic maps, geology, vegetation and quality aerial photographs, published soil surveys with mapped soils on 7.5-minute orthophoto Quads provide information essential to characterizing flood hazards of DFAs in central and southwestern Arizona . Detailed soil surveys, which may depict small-stable interfluves between distributary channels, also provide useful information on flow path characteristics and should be considered if the additional detail is needed.

Discussion

The abundance of large paloverde trees and other vegetation along the distributary channels, the absence of flow path movement gleaned from the recent and past aerial photographs, the cohesive bank material gleaned from the analysis of hydraulic geometry, the degrading and stable appearance of the distributary channels observed during field reconnaissance, and the developed and stable soils depicted on maps of soil types throughout much of the DFA especially along the ridges separating the distributary channels are considerable evidence pointing to the stability of the flow paths of site 6A. There is little, if any, evidence of flow path movement and there is no evidence of movement past ridges on interfluves of Pleistocene material. The distribution of floodflow in the distributary channels at the several diffluences may change because of variable scour and fill of the channel beds at and below the diffluences. Because the floodflow in the distributary channels is generally wide and shallow, obstructions such as a fallen saguaro cactus and fallen trees can also change the distribution of flow at the diffluences. The unchanging paths of flow are considered a much more significant flood hazard characteristic than the ability to define precisely the amount of flow in each of the distributary channels. The stable paths of flow point to the presence of hydraulic processes at work on site 6A and not alluvial fan processes with associated debris flows.

This reconnaisanse-quantitative analysis of stability (level 1) shows the channel banks and the paths of flow are stable and the bed material of the distributary channels is mobile. Some scour and fill occurs along the distributary channels but the degradation is restricted by cemented blocks of old material. To demonstrate the use of methods by Federal agencies, a level 2 assessment is next performed.

ENGINEERING ASSESSMENT OF SYSTEM STABILITY--LEVEL 2

This section is a continuing stability assessment of the distributary channels of site 6A. Techniques recommended or published by the USGS, CofE, SCS, FHWA, USFS and ASCE are applied to the channels of site 6A. Numerous technical specialists, mostly with the CofE, USGS and SCS, were consulted in regard to recommended engineering methods of stability assessment. The specific techniques presented in this section form a comprehensive quantitative assessment of system stability. An initial reconnaissance level assessment that identified stability differences among DFAs in Arizona was made by Hjalmarson and Kemna(1992). Differences among DFAs in Maricopa County were next described by Hjalmarson(1994, in press). The stability assessment of site 6A was then extended to a detailed reconnaissance-quantitative stage described in the previous sections of this report. The following level 2 assessment of channel stability is based mostly on detailed channel and bed material characteristics and engineering methods.

Also contained in this section are data on soil and vegetation characteristics of site 6A that are used in one or more of the recommended methods by Federal Agencies. These data are presented in detail for the critical inspection and use by FEMA, scientists and engineers.

The channels and flow paths of site 6A were found to be stable for the following reasons:

1.--Measurements of the proportion of silt and clay in the channel banks show that large amounts of sediment suspended by floodwater have been deposited along the wetted perimeter of the channel banks. The fine material is filtered by the sandy parent bank material as floodwater infiltrates stable banks.
2.--Measurements of the particle size of the bed material at many sites along the DFA show that the mobile bed material entering the DFA is conveyed through the system of defined distributary channels. This transport of the bed material through the DFA is shown by the uniform distribution of particle size along the channels. The decrease of particle size, which is characteristic of aggrading systems where the finer material is deposited downslope, was not shown by the measurements.
3.--Data from measurements of channel geometry and material samples at several cross sections were plotted on the relation between channel width-depth ratio and percent silt-clay along the wetted perimeter published in U. S. Geological Survey Professional Paper 352C. The data for site 6A plotted consistantly in the stable region of the relation.
4.--Data from measurements of vegetation size and channel geometry show the stream power at nearly all cross sections is insufficient to lay over the trees along the channel banks. The relation of the effect of the 100-year flood on vegetation is from an unpublished paper approved by the U. S. Geological Survey.
5. Measurements of vane shear corresponding to computed tractive power at many cross sections show the channel banks are non-erosive or stable. The data consistantly plotted in the non-erosive region of the relation of tractive power and unconfined compressive strength published in TR-25 by the U. S. Soil Conservation Service.

6.--The channels are considered stable because depths of floodflow at this site are less than the computed depths of floodflow based on measurements and computations at several cross sections. These computations were made in accordance with the "Maximum discharge design procedure" of HEC 15 published by the Federal Highway Administration.

7.--Relations of bankfull width, mean depth and channel slope versus channel-forming discharge at several cross sections show the DFA is not aggrading. This assessment was in accordance with procedures published in "Stability of flood control channels" by the U. S. Army Corp of Engineers.

8.--Measured vegetation cover along the banks at many transects show the banks are stable using procedures in "Methods for evaluating riparian habitats with applications to management" by the U. S. Department of Agriculture.

9.--The critical shear stress associated with banks coated with silt and clay and covered with grass and cryptogamic crusts is at least a few times the critical shear stress of bare soil. This measure of channel stability is from a relation between critical shear stress and sediment size published in "Sediment engineering" by the American Society of Civil Engineers.

Collection of field data

The overall objective of the sampling of bed and bank material is to characterize the stability attribute of the system of distributary channels. Longitudinal sampling was done at several cross sections from upstream of the PD to near the toe of the DFA of site 6A. Vertical and lateral sampling was done at selected cross sections at rather uniform longitudinal distances. Samples were collected to enable assessment of material size and strength variations along the channels, within the channel bed and banks, between banks, and between the bed and banks. Two main objectives are (1) to distinguish the changes or variations of the truely mobile sediment that is moved around by flow events and (2) to define what the substrata is which represents the stored material and what the soil processes are in the riparian environment.

The measurements of shear stress, sediment size and distribution, vegetation type and size, and channel shape were made during February-April, 1994 by the author, Mr. Joe Tram of the Flood Control District of Maricopa County, and SHB AGRA, Inc. Engineering and Environmental Services of Phoenix, Arizona (SHB). Data were collected at several sites along the stream channels between Pima Road and 40th. Street (figure 32). A description of the methods and much of the data follows:

Sediment size

Sixty seven samples of bank and bed material were collected during March 1994 at 22 sites (figure 32 and table 8). Sieve analyses were performed in accordance with ASTM D422 by SHB. The grain size for which 10, 50, 64, 75, 84 and 90 percent (D10, D50, D64, D75, D84, and D90), by weight, of the sediment is finer was determined for the samples.

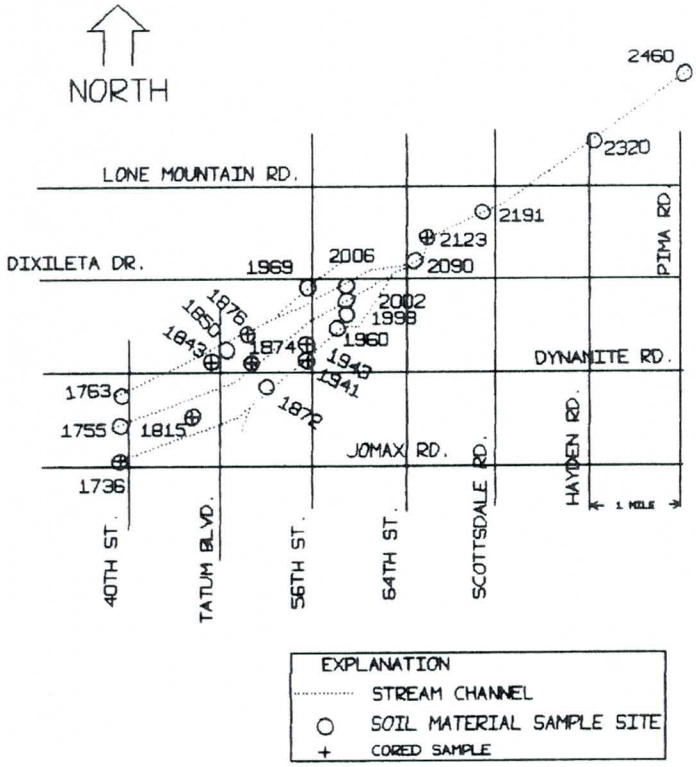


FIGURE 32.--LOCATION OF BED AND BANK MATERIAL SAMPLE SITES.

Table 8.--Grain sizes of the channel banks and bed in site 6A.

I.D.	Site[a] no.	Grain size, in millimeters, at indicated percent of material finer than size given					
		D10	D50	D64	D75	D84	D90
1	1815	--	0 .07	0.17	0.42	0.93	1.58
2	1815	--	.37	.81	1.62	2.69	3.98
3	1815	--	.11	.38	1.00	1.78	2.82
4	1815	--	.68	1.17	1.78	2.69	3.98
6	1815	0.21	1.17	1.66	2.40	3.39	4.36
5	1815	.25	1.00	1.44	1.86	2.63	3.72
1	1969	--	.71	1.35	1.99	3.16	4.17
2	1969	--	.72	1.55	3.16	3.98	5.37
3	1969	--	1.12	1.99	3.16	3.98	5.37
4	1969	--	.74	1.41	2.51	3.98	5.62
5	1969	.21	1.36	2.12	3.16	4.27	5.62
6	1969	.10	1.39	2.15	3.31	4.47	5.65
1	1755	--	.06	.17	.52	1.48	2.88
2	1755	--	.27	1.26	2.34	3.55	4.79
3	1755	--	.06	.11	.16	.28	.60
4	1755	--	.08	.17	.50	1.41	2.63
6	1755	.22	1.99	3.31	4.57	5.89	7.41
5	1755	.16	1.20	1.66	2.29	3.55	4.79
1	1843	--	.31	.95	1.69	2.95	4.17
2	1843	--	.50	1.17	1.77	3.09	4.16
3	1843	--	.10	.21	.59	1.58	3.39
4	1843	--	.74	2.51	4.16	6.02	7.58
5	1843	.35	1.77	2.63	3.54	4.46	5.62
6	1843	.19	1.65	2.63	3.54	4.46	5.62
1	1874	--	.07	.16	.41	.93	1.58
2	1874	--	.37	.81	1.62	2.69	3.98
3	1874	--	.11	.38	1.00	1.77	2.81
4	1874	--	.67	1.17	1.77	2.69	3.98
6	1874	.25	1.17	1.65	2.39	3.38	4.36
5	1874	.21	1.00	1.54	1.86	2.63	3.71
1	2090	--	.06	.12	.25	.75	1.62
2	2090	--	.28	1.07	2.29	3.71	4.78
4	2090	--	.42	1.34	2.34	3.71	4.67
5	2090	.28	1.41	1.77	2.39	3.63	4.70
9	2090	.18	.49	.76	1.05	1.45	1.80
6	2090	.20	1.47	1.86	2.45	3.71	4.67

Table 8.--continued

5	2460	.31	1.62	2.51	3.54	5.01	6.02
6	2460	.38	2.04	3.16	4.16	5.24	6.30
5	2320	.35	1.77	3.01	4.16	5.49	7.07
6	2320	.35	2.04	3.16	4.16	5.37	6.91
5	2190	.35	1.62	2.39	3.31	4.07	5.01
6	2190	.48	2.34	3.46	5.01	6.02	8.31
5	1960	.24	1.02	1.44	1.81	2.75	3.54
6	1960	.31	1.47	1.77	2.88	3.98	5.01
5	2006	.20	.87	1.23	1.62	2.34	3.16
6	2006	.17	1.23	1.58	2.23	2.95	3.54
5	1872	.33	1.51	2.04	3.01	4.07	5.01
6	1872	.10	1.99	2.51	3.38	5.88	7.94
5	2002	.20	1.04	1.47	1.99	2.95	3.98
6	2002	.15	.50	.79	1.12	1.58	2.08
5	1998	.16	.79	1.28	1.81	2.75	3.63
6	1998	.25	1.34	2.18	2.95	3.80	4.16
7	1874	.01	.61	1.51	2.52	4.75	6.71
8	1874	.21	1.29	1.84	2.48	3.50	4.50
8	1876	--	1.21	1.60	2.64	4.19	5.50
7	1876	.05	1.60	2.36	3.30	4.60	5.50
8	1815	--	.98	1.82	3.01	4.67	5.82
7	1815	--	.78	1.75	3.01	4.66	5.80
8	1736	--	.10	.45	1.43	3.11	4.78
7	1736	--	.11	.45	1.42	3.14	4.75
8	1843	--	1.0	1.75	2.82	4.20	5.50
7	1843	--	1.35	2.38	3.37	4.72	5.80
8	2123	--	1.30	2.40	3.64	5.09	6.20
8	1943	--	.77	1.41	2.30	3.43	4.80
7	1943	--	.76	1.27	2.03	2.92	4.04
8	1941	--	.45	1.19	1.92	3.27	4.78
7	1941	.18	1.44	2.21	3.00	4.10	5.00

I.D. 1.--Left bank at 0-1/4 in. depth perpendicular to bank(composited sample).
2.--Right bank at 0-1/4 in. depth perpendicular to bank(composited sample).
3.--Left bank at 1-4 in. depth perpendicular to bank(composited sample).
4.--Right bank at 1-4 in. depth perpendicular to bank(composited sample).
5.--Channel bed at 0-1 in. depth(composited sample).
6.--Channel bed at 3-4 in. depth(composited sample).
7.--Cored sample(drilled) on right bank side 18-36 in. depth.
8.--Cored sample(drilled) on right bank side 18-36 in. depth.
9.--Magnitite layer of channel bed at 2-3 in. depth.

[a]Approximate elevation of channel bed at cross section of site.

Bed.--The samples of bed material (I.Ds. 5,6 and 9 of table 8) at uniform depths across the stream channels were collected and composited. Compositing of the samples at the same depths is needed because the bed material commonly is highly stocastic in nature and individual samples may be meaningless. Pairs of samples were collected at 0-1 in. depths and at 3-4 in. depths typically at ten locations across the channel bed at cross sections located in straight reaches (figure 33). The near-surface samples are an indication of the material presently in transport by recent flows while the deeper samples indicate the material at larger less-frequent floods such as a 5- or 10-year flood. A single composited sample of a layer of dense magnitite at 2-3 in. depth across the channel was collected at site 2090. Magnitite, which is common in streambeds composed of quartz material, occurs in layers that may influence hydraulic and sediment processes.

Banks.-- Samples of the bank material (I.Ds. 1-4 of table 8) were collected along the banks between the toe and top and also at 18-36 in. depths typically about 20 ft. shoreward of the edge of the main channel (figure 34). The deep samples were collected using a truck mounted CME-75 drill rig (figure 35). Standard penetration testing was performed continuously to a depth of 5 to 9 ft. in each of the borings using a 2-in. outside diameter, 1 3/8-in. inside diameter sampler. The sampler was advanced by a free-falling sliding drop hammer weighing 140 pounds. The number of blows required to advance each 6-in. interval was recorded. In addition to the 15 borings (I.Ds. 7 and 8 of table 8) an attempt was made to obtain "undisturbed" samples of the shallow subsurface material using an 8-in. diameter hollow-stem auger with a CME sampler in the auger stem. Because of the friable nature of these relatively dry soils, the CME samples were not of adequate quality for soil mechanics tests. The classification and logging was performed in accordance with the procedures of ASTM D2487 and D2488 by Mr. Thomas H. Walker, P.G. of SHB.

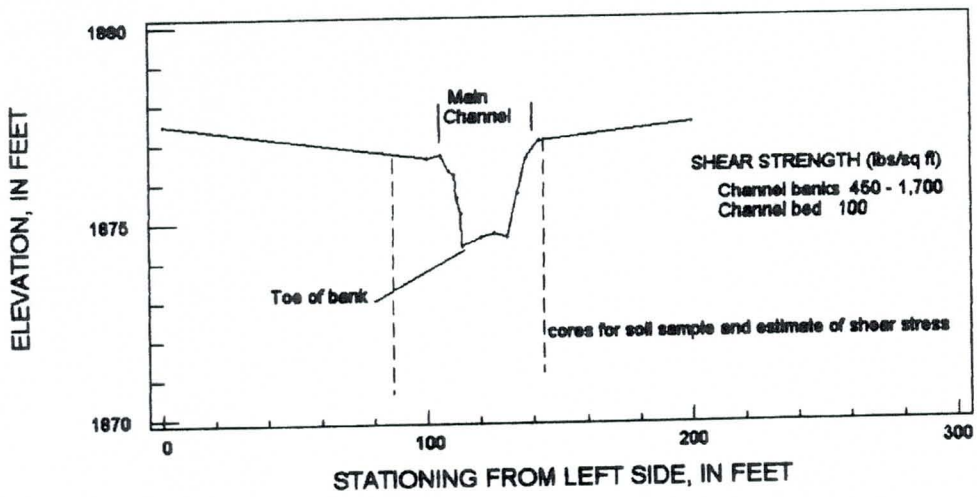
Samples of the material along the channel banks were collected at 0-1/4 in. and 1-4 in. depths along and perpendicular to the wetted perimeter of both banks over about a 3-4 ft. distance between the toe and top of the banks. Samples were collected with a trowel and composited for each depth along each bank (figure 36). The presence of fine cohesive sediment sizes at shallow depths along the wetted perimeter of the banks is indicative of stable channels (figure 37) (Osterkamp and Harrold, 1982 and Osterkamp, oral communication, 1994). The typically granular soil is weakly cemented at the surface with a thin layer of fines deposited at the surface by infiltrating floodwater (figure 38).

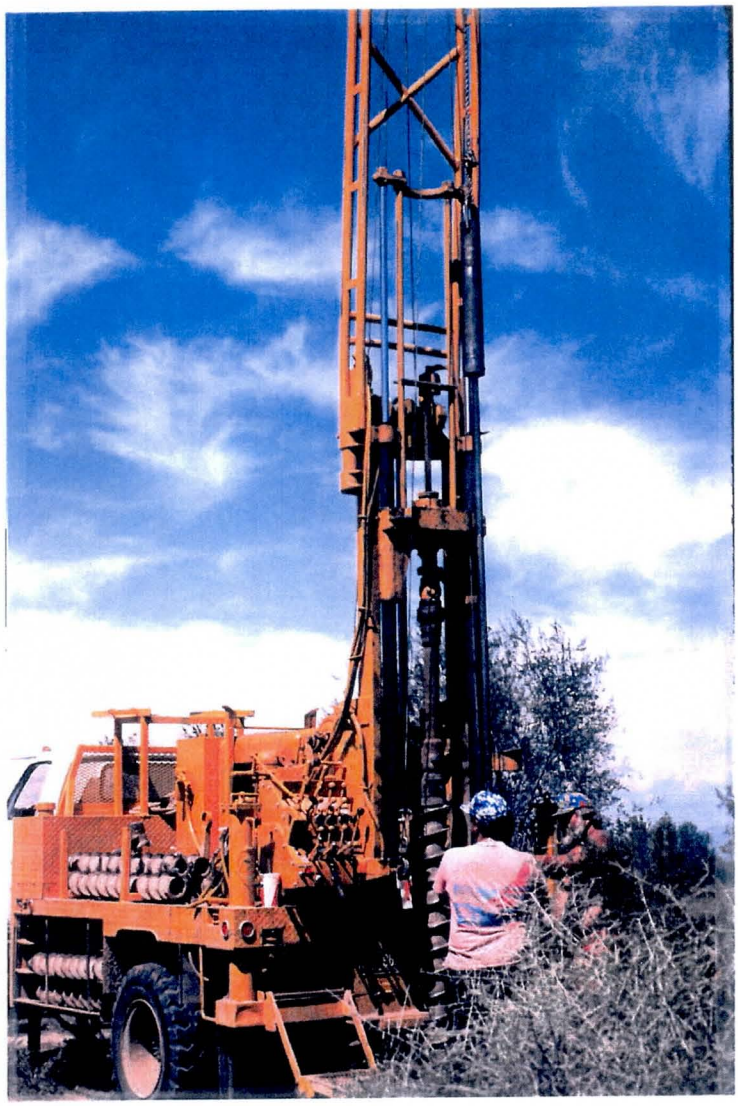
The silt-clay forming the perimeter of channels is related to channel stability. Thus, the silt-clay, in percent, for sections where bank samples were collected is given in table 9. For convenience, the classes of particles are given in table 10.

Samples of the bed material were taken from the surface to 1 in. depth at 10 locations across the channel and composited. A second composited sample was collected at the same locations at a depth of 3-4 in. The bank material was sampled at the trench to the left of the scene where the trowel is located. The coarse quartz bed and soil material is typical of arid soil where physical forces instead of chemical processes dominate the weathering of rock.

Figure 33.--View looking east and upstream at bed and right bank of cross section at site 1843 where samples of bed and bank material were collected.

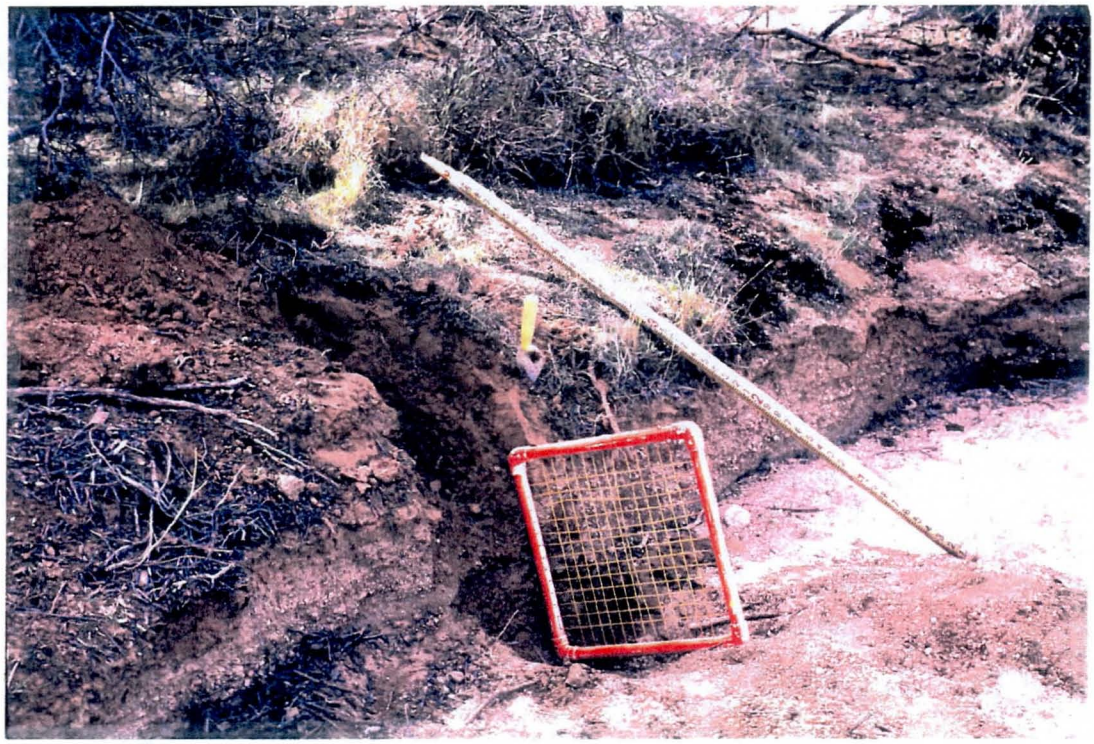
Figure 34.--Soil borings for grain size, shear and compressive strength at section 1874.





Sample of soil on right bank collected with auger to a depth below the bank toe.
Photograph taken tooking across channel from left bank during March 1994.

Figure 35.--View looking north at drill rig on right bank at site 1843.



Scene is approximately 1,000 ft. downstream of the primary diffluence where most of the flow is confined to the main channel and floodplain. Samples of bank material were collected from near the toe through the steep portion over a distance (along the wetted perimeter) of about 3 ft. One sample was collected at depths of 1-4 inches perpendicular to the bank surface. A second sample was collected of the surface material to a depth of about 1/8 to 1/4 in. using the trowel. The dark reddish-brown soil (Agustin unit 130) in the bank is at least a few thousand years old. The absence of light colored recently deposited soil on the surface indicates the surface is not aggrading.

Figure 36.--View looking southwest and downstream at left bank of distributary channel located 200 ft. upstream of 64th street.

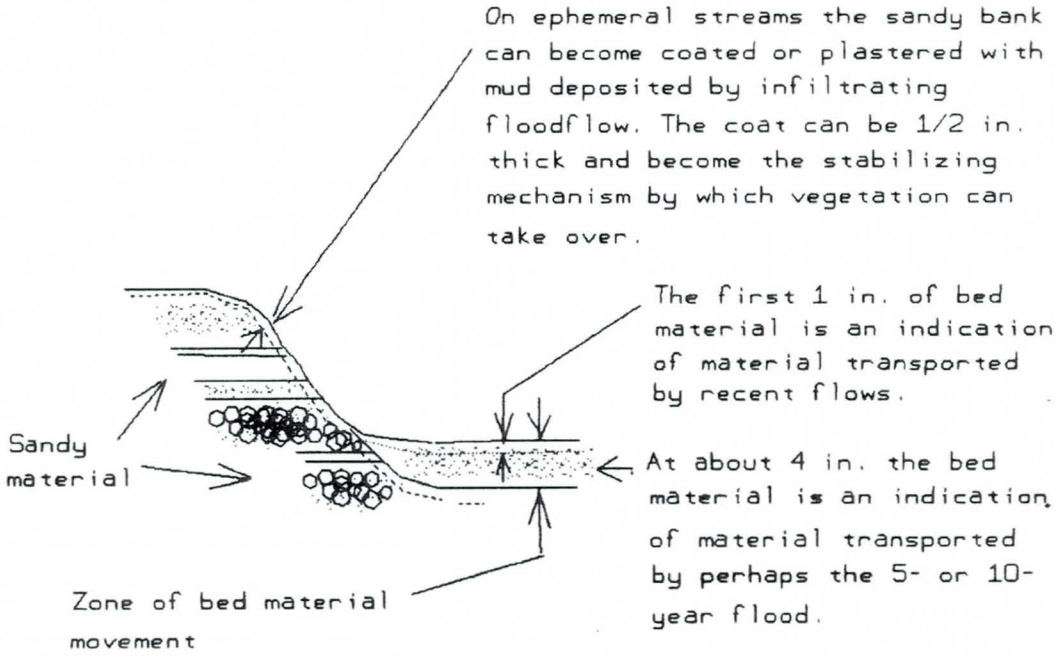


FIGURE 37.--CROSS SECTION OF CHANNEL SHOWING BED AND BANK MATERIAL.

Closeup view of soil profile about 3/4 in. thick. The coarse quartz grains are typical for the banks throughout the distributary-flow area. There are more fine particles in the top 1/4 in. of the soil profile. The thin surface layer of stored fine cohesive sediment sizes permits the formation of stable alluvial banks that can resist relatively high shear stresses. Moisture is retained in the silt and clay that permits seed germination and growth of grasses and other plants along the channel banks. Photograph was taken during March 1994.

Figure 38.--View of cohesive piece of surface material removed from top of left bank of distributary channel at site 1969.

Table 9.--Silt-clay in channel bed and banks.

Site no.	Silt-clay, in percent				
	Bed		Bank		
	0-1in.	1-4in.	0-1/4in.	1-4in.	18-36in.
1736	2.4[e]	4.4[e]	--	--	46
1755	5.1	4.1	52.5	42	--
1815	1.8	2.9	43.5	31.5	32
1843	1.5	4.0	34.5	27.5	20
1874	1.7	2.3	46.5	21	15
1876	2.4[e]	4.4[e]	--	--	22.5
1969	1.9	8.6	22.5	24	--

[e]Estimated using average value.

Table 10.--Classes of particles.

Class and subclass	Metric		English
	Millimeters	Microns	Inches
Boulders	**4096-256**		**160-10**
Very large	4096-2048	----	160-80
large	2048-1024	----	80-40
Medium	1024-512	----	40-20
Small	512-256		20-10
Cobbles	**256-64**		**10-2.5**
Large	256-128	----	10-5
Small	128-64	----	5-2.5
Gravel	**64-2**		**2.5-0.78**
Very coarse	64-32	----	2.5-1.3
Coarse	32-16	----	1.3-0.6
Medium	16-8	----	.6-.3
Fine	8-4	----	.3-.16
Very fine	4-2	----	.16-.078
Sand	**2-.062**		**.078-.0024**
Very coarse	2.000-1.000	2,000-1,000	.078-.039
Coarse	1.000- .500	1,000- 500	.039-.020
Medium (most rivers)	.500-.250	500-250	.020-.0098
Fine(most beaches and deserts)	.250-.125	250-125	.0098-.0049
Very fine	.125-.062	125-62	.0049-.0024

Silt and clay pass through the smallest sieve size of 0.062mm. This is the approximate upper limit of particle sizes which are found in wash load or suspension. This is also the upper limiting size of quartze sphere which will obey Stokes Law.

Silt	**.062-.004**		**.0024-.00015**
Coarse	.062-.031	62-31	.0024-.0012
Medium	.031-.016	31-16	.0012-00061
Fine	.016-.008	16-8	.00061-.00030
Very fine	.008-.004	8-4	.00030-.00015
Clay	**.004-.00024**		**.00015-.000010**
Coarse	.004-.002	4-2	.00015-.000076
Medium	.0020-.0010	2.0-1.0	.000076-.000038
Fine	.0010-.0005	1.0-0.5	.000038-.000019
Very fine	.0005-.00024	0.5-0.24	.000019-.000010

Shear strength

Estimates of shear strength of the surface soils adjacent to the borings, on the channel banks, and of the channel bed were obtained using a vane meter. A Torvane Shear Device (CL-600A) by Soil Test, Lake Bluff, Ill.(figure 39) was used to measure the strength of the in situ bed and bank material. The Torvane meter is a torsional shear device with small vanes which are inserted in the soil and subjected to a torque until the surrounding soil shears. Many measurements of shear were made on both banks and also across the channel bed at 18 sites (table 11). Several measurements of shear stress on grasses and cryptogamic crusts were made using the Torvane meter (table 11). Following some of these measurements about 1/4 inch of the vegetation and surface material was removed and measurements of the underlying bare soil were made. Additional comparative measurements of shear stress were made on adjacent bare surface material. These "paired" measurements of bare and covered soil are discussed later in this report.

Paired measurements of dry and wetted soil also were made at a few locations. Floodflow conditions were crudely simulated by pouring water on the bare-flat soil adjacent to the location of a dry-soil measurement. After periodically pouring water for at least 5 minutes the wetted front in the soil was from 1/4 to 1/2in. deep and a shear stress measurement was made. These measurements, which are discussed later, are listed in table 11 but are not specifically identified.

Driving resistance

Measurements of penetration resistance were made while the 2 in. diameter tube sampler was driven (figure 40). The number of blows of the 140-pound 30-inch free fall hammer required to advance the sample in 6-in. increment was recorded (table 12). This "driving resistance" is related to the compressive strength, compactness and cementation of the soil.

Soil characteristics

Soils at the borings were classified and characterized by measurements and visual examination by Mr. Thomas H. Walker, P.G. of SHB. Soils were classified in accordance with the Unified Soil Classification System at various depths for all borings. The plasticity, color, degree of cementation were defined by visual examination and field tests (table 13). Plasticity indexes of 2, 5, and 15 were used for the SW, SM and SC classes, respectively based partly on Camp (1985, table 13) and partly on communication with Thomas H. Walker, P.G. during the collection of the data. These plasticity indexes typically are for soils 96 (Pinaleno-Tres Hermanos) and 98 (Pinamt-Tremant) soils at distances several feet shoreward of the channel banks. The upper soil typically to a depth of less than 4 ft. is brown with an underlying light brown strongly cemented layer (figure 41).

Note: Scene is typical of many banks. Crusts typically cover areas in a blotchy pattern interspersed among grasses. A vane shear measurement was made in the disturbed area located between the vane meter and pen. The cryptogamic crust covers much of the ground in the lower-right quadrant of the scene.

Figure 39.--View looking down at bank and vane meter adjacent to area covered with cryptogamic crust.

Table 11.--Torvane shear stress for sites.

Site no.	Shear Stress, in psf			
	Damp or wet soil	Dry soil	Cryptogamic crust	Grass
1736	800	1120	1600	300
	800	1240		400
	800	2320		400
		1700		
		1200		
		800		
		1220		
		L580		
		L620		
		R680		
		R680		
1755	1000	1200		400
	1200	1200		440
	1000	1900		
		1800		
		1500		
		1760		
1763	1600	1600		300
	1000	1980		
	1100	1300		
		800		
1808	1100	1200		300
	1500	1520		400
		1720		
		1400		
		1700		
1815	1300	1600	1300	300
	1300	1100	1200	300
		1200		
		1300		
		1400		
		1800		
		L780		
		L620		
		R680		
		R700		

Table 11.--cont.

1843	R680	1800	300
	R620	1600	200
	R700	1500	
		1500	
		600	
		900	
		1500	
		800	
		1300	
		1300	
		1800	
		L750	
		L600	
		L820	
1850	1000	1100	100
	900	1200	
		1260	
		1300	
1866	1200	800	300
	1100	1100	
		1400	
		1400	
		1300	
1872	1100	1200	400
	1260	1400	300
		1400	
		1200	
		1500	
1874		1140	100
		1000	100
		1700	
		800	
		600	
		500	
		800	
		1500	
	L950		
		R680	
		R450	

Table 11.--cont.

1876	1700	1500		200
	1600	1900		160
	1000	1500		
		L550		
		L550		
		L750		
		R900		
1941	1000	1200	1060	260
	920	1000	1200	300
		800	1300	
		1400		
		1000		
		L650		
		L570		
		R500		
		R550		
1943		840	1400	220
		900		200
		1960		220
		1900		200
		1440		
		1400		
		760		
		700		
		1700		
		1740		
		L550		
		L600		
		R500		
		R700		
1960	700	1200		100
	900	1200		
		1100		
		1200		
		1600		
2002	800	800		300
	700	1100		
		1400		
		800		
		1000		

Table 11.--cont.

2006		1100	100
		1300	100
		1300	
		1400	
2123		1500	
		1500	
		1300	
		1500	
		[L]600	
		[L]700	
2191	1000	1000	200
		1100	
		1300	
		1100	
		1200	

[L]Denotes measurement made on left bank near boring.
[R]Denotes measurement made on right bank near boring.

Split spoon sampler being driven with a 140 pound weight falling 30 in. The number of blows needed to drive the sampler a unit distance is related to the compactness and permissable shear stress of cohesive soils. Photograph was taken during March 1994.

Figure 40.--View looking north at drill rig on right bank of distributary channel near toe of of the distributary-flow are near 40th Street and Jomax Road.

Table 12. Log of blow counts for penetration resistance.

Depth (ft.)	Number of blows at indicated site no. (lb = left bank side. rb = right bank side)														
	1736		1815		1843		1874		1876		1941		1943		2123
	lb	rb	lb	rb	lb	rb	lb	rb	lb	rb	lb	rb	lb	rb	rb
0.5	3	2	4	2	5	3	4	1	3	6	1	2	1	1	9
1.0	4	3	4	3	5	4	3	2	4	6	2	2	4	3	9
1.5	5	4	4	4	5	6	3	2	7	8	4	4	6	3	10
2.0	5	3	5	5	5	9	9	3	6	9	5	4	4	2	15
2.5	6	4	6	5	5	6	11	4	7	11	3	4	5	2	16
3.0	8	6	13	7	6	5	16	7	5	13	2	7	4	3	17
3.5	9	9	22	9	7	8	10	17	4	27	3	6	3	4	17
4.0	11	12	36	11	8	8	12	[g]50	5	[i]50	5	5	4	7	26
4.5	16	43	40	19	9	[e]50	22		16		6	11	4	7	[e]50
5.0	27	[b]50	30	12	6		[f]50		10		5	19	8	5	
5.5	47		30	18	7				16		6	32	15	5	
6.0	[a]50		[c]30	[c]23	8				17		13	35	[k]45	4	
6.5					7				17		18	35		4	
7.0					9				23		23	45		5	
7.5					[d]50				[h]23		[h]25	[j]50		11	
8.0														15	
8.5														23	
9.0														[l]26	

[a]Sampler refused at 5ft. 11in..
[b]Sampler refused at 4ft. 9in..
[c]Sampler stopped at 6ft..
[d]Sampler refused at 7ft. 5 1/2in..
[e]Sampler refused at 4ft. 4in..
[f]Sampler refused at 4ft. 11in..
[g]Sampler refused at 3ft. 10 1/2in..
[h]Sampler stopped at 7ft. 6in..
[i]Sampler refused at 3ft. 11 1/2in..
[j]Sampler refused at 7ft. 5in..
[k]Sampler refused at 6ft. 1 1/4in..
[l]Sampler stopped at 9ft..

Table 13.--Soil classification and characteristics at borings.

Site no.	Bank	Universal soil class-ification	Depth (ft.)	Plas-ticity	Color	Cemen-tation	Comments
1736	left	SM-SC	0-4.5	low	brown	moderate	lime cemented
		SC	4.5-6	low	light b	strong	
	right	SC	0-3.5	low	brown	moderate	lime cemented
		SC	3.5-5	low	light b	mod-strong	
1815	left	SW-SC	0-6	low	brown	weak-mod.	light brown beolw. 3.5 ft.
	right	SM	0-6	low	brown light b	weakly to strongly	fine grained gravel from 3.5-6 ft.
1843	left	SM	0-7	low	brown light b	weak-mod	Strongly cemented below 6 ft.
	right	SC	0-5	low	brown	weakly to strongly	
1874	left	SC-SM	0-5	low	brown	weak-mod below 2 ft.	strongly cemented
	right	SW-SM	0-5	NP-low	light b	at 4.5 ft.	strongly cemented
1876	left	SM-SC	0-7.5	low	brown	weak-mod	brown to light b to reddish brown
	right	SW-SC	0-5	low	brown	mod from 3.5-4 ft.	strongly cemented
1941	left	SW-SM	0-6.5	NP	brown		
		SC	6.5-7.5	low	brown	mod.	brown to reddish brown
	right	SM-SC	0-4.8	low	brown		
		SC	4.8-7.4	low	brown		
1943	left	SM-SC	0-5	low	brown		
		SC	5-6.1	low	light b	mod. to strong	
	right	SM-SC	0-8.3	low	brown		
		SC	8.3-9		light b	mod.	
2123	right	SC	0-5	low to medium	brown	mod. to strong	also reddish brown

The reddish-brown soil extends to a depth of about 2 ft. The underlying light-colored horizon is accumulated calcium carbonate at least 3 ft. thick (trench is 5 ft. deep). The cemented pieces of light-colored soil were deposited to the right of the surveying rod by a backhoe. The soil is well developed gravely clay loam (Pinant-Tremant unit 98) that has taken thousands of years to form. The absence of light colored soil at the surface indicates no recent deposition and the surface is not aggrading.

Figure 41.--View looking down at soil exposed in dug trench near site 1850 on west side of Tatum Blvd.

Vegetation

The height and percent cover of vegetation along the channel banks was estimated at 16 sites. Tree and large brush size was measured with a surveying rod projected vertically through the foliage and around the perimeter of the foliage. The height of the small brush was also measured using a surveying rod and the area covered by the canopy was determined by visual examination. The average height of the trees and brush for about a 100 ft. reach was estimated based on scattered height measurements at each site and visual examination (table 14).

The trees along the distributary channels generally appear larger and greener than the same species of trees in the interfluves and along the tributary channels. The larger size and healthy appearance may be the result of more frequent recharge moisture along the distributary channels which drain larger drainage basins. Also, there may be more moisture retained in the silt and clay material along the distributary channels.

The percent vegetation cover of the banks at transects across the channels was estimated using methods of the USFS (USDA, 1987). The vegetation cover under a transect line(channel cross section) from the shoreline to within 5 ft. shoreward or to the top of the bank, whichever is larger, was defined and rated. The horizontal distance to the top of the bank typically was more than 5 ft. The streambank stability rating takes the vegetation cover, bedrock, boulders and rubble into account and is in four classes as explained in the bottom portion of table 14. All of the transects were rated as unit 4 or 3 based mostly on the vegetation cover. There was no bedrock but some of the banks were highly cemented. The cementation effects were excluded for this technique to yield a conservative stability rating.

Channel characteristics

The width, depth, and width-depth ratio for the hydraulic geometry cross sections (table 6 and figures 21 and 32) were determined for bank-full stage (table 15). The discharge at bank-full stage was assumed to be the dominant discharge that forms the channels. The channel gradient and average slope of the channels banks for these sections located in rather straight-uniform reaches were also determined (table 15). The gradient was measured on topographic maps (scale 1in.=200ft.) and with a hand level at most locations. The average slope of the channel banks is from the toe to the top of the banks (figure 34). The bank slope was measured on detailed plots of the surveyed cross sections.

Table 14.--Vegetation characteristics along channel banks.

Site no.	Estimated average height of vegetation (ft)		Percent of streambanks covered by vegetation	Units[a]	Grass
	Trees	Brush			
1755	11.0	5.0	70	3	scattered
1763	15.0	5.0	80	4	scattered and thick in places
1808	10.0	5.0	90	4	generally thick
1815	10.0	5.0	70	3	very thick on left bank
1843	15.0	5.0	70	3	scattered and thick in places
1850	15.0	5.0	80	4	scattered
1866	12.0	5.0	60	3	scattered
1872	12.0	6.0	90	4	generally thick
1874	12.0	5.0	60	3	scattered and thick in places
1876	10.0	6.0	70	3	scattered and thick in places
1960	12.0	4.0	60	3	scattered
1969	13.0	3.0	80	4	generally thick
1998	10.0	3.0	50	3	scattered in places
2002	10.0	3.0	60	3	scattered
2006	12.0	4.0	70	3	scattered and thick
2191	12.0	3.0	50	3	scattered, thick at tops

[a]USFS Method follows:

STREAMBANK STABILITY RATING
(From: U.S. Department of Agriculture, 1987)

Rating		Description
Units	Percent	
4	75-100	Over 75 percent of the streambank surface is covered by vegetation in vigorous condition or by boulders and rubble. If the streambank is not covered by vegetation. it is protected by materials that do not allow bank erosion.
3	50-74	Between 50 and 74 percent of the streambank surface is covered by vegetation or by gravel or larger material. Those areas not covered by vegetation are protected by materials that allow only minor erosion.
2	25-49	Between 25 and 49 percent of the streambank surface is covered by vegetation or by gravel or larger material. The area not covered by vegetation is covered by materials that give limited protection.
1	0-24	Less than 25 percent of the streambank is covered by vegetation or by gravel or larger material. That area not covered by vegetation provides little or no control over erosion and the banks are usually eroded each year by high water flows.

Table 15.--Channel characteristics at hydraulic geometry sites.

Site number	Width, in feet (W)	Depth, in feet (D)	Width-depth ratio (F)	Gradient (S)	Bank slope(horizontal distance, in feet, corresponding to 1 ft vertical rise) (Z)	
					left bank	right bank
1736	31	2.30	13	0.013	2.4	5.6
1755	31	1.90	16	.017	5.3	5.3
1763	33	2.90	11	.016	2.1	5.1
1808	25	1.70	10	.017	6.9	3.7
1815	22	1.90	11	.017	1.9	8.0
1843	35	2.70	13	.017	4.0	4.3
1850	57	2.20	7	.017	8.8	9.9
1866	25	2.60	9	.016	2.7	4.3
1872	20	1.40	14	.016	3.5	8.5
1874	30	2.10	14	.018	3.7	3.5
1876	21	1.30	16	.018	5.3	8.5
1960	30	3.10	10	.020	1.3	6.1
1969	22	1.55	14	.020	5.1	2.7
1998	23	3.20	7	.020	0.8	3.2
2002	23	2.20	10	.020	2.7	6.4
2006	14	1.70	8	.020	0.8	5.3
2191	51	4.50	11	.020	3.4	4.8
Average	29.1	2.31	11.4	0.018	3.57	5.60

U.S. Geological Survey

Of the numerous publications by the U. S. Geological Survey related to stability of ephemeral stream channels one important publication (Schumn, 1961) and the recent work of Phillips and Hjalmarson (1994, in press) specifically on the stability of vegetation along the ephemeral streams in Maricopa County, Arizona were used for quantitative characteristics of this section. Also, much of the advice and suggestions of Mr. Waite Osterkamp (U. S. Geological Survey, Denver, Colorado) are included in this section.

Channel and DFA characteristics

The average median (D50) grain size of the channel bed (0-4 in. depth) is 1.42 mm or very coarse quartz sand (table 16). The median size of the shallow bed material (0-1in. depth) is less than the median size of the deeper bed material and may be the result of (1) more of the finer material being transported through the DFA by larger flows that mobilize the deeper material or (2) recent flows that included local runoff with finer bed material that mixed with the shallow bed material to produce the smaller median grain size. The only recent flow was on October 6, 1993 where, as discussed previously, much of the runoff that entered the distributary channels was from the DFA. The smaller median size of immobile material of the DFA is indicated by the deep bank material (18-36in.) which is finer than the median size of the deep bed material (table 16).

Table 16.--Average grain sizes of the channel banks and bed for sites in site 6A.

Percent of material fine than size given	Grain size, in millimeters					
	Bank			Bed		
	0-1/4 in[a]	1-4 in[a]	18-36 in[b]	0-4 in[c]	0-1 in[d]	3-4 in.[d]
D10	--	--	0.11	0.25	0.26	0.24
D50	0.25	0.49	0.87	1.42	1.28	1.56
D64	0.54	1.20	1.57	2.08	1.90	2.27
D75	1.02	2.16	2.51	2.89	2.60	3.18
D84	1.78	3.35	3.91	3.95	3.61	4.29
D90	2.81	4.63	5.22	5.07	4.68	5.45

[a]Depth perpendicular to bank of composited sample for each bank at each site.

[b]Vertical depth typically about 20 ft. shoreward of main channel.

[c]Vertical depth of composited sample for each site. Samples at 0-1/4 in. and 3-4 in. combined to yield these values.

[d]Vertical depth of composited sample for each site. About ten samples taken across channel bed and composited.

The generally uniform relation between the shallow and deep bed material along the distributary channels is shown in figures 42 and 43. The site number is the elevation of the streambed at the channel cross sections and because the channel gradient is rather uniform, the relations generally show the longitudinal and vertical distribution of the bed material along the DFA. The patterns of the D50 and D90 amounts are very similar. Because the bed material at the upper and lower ends of the DFA is similar, the material has the appearance of being transported through the DFA without deposition. The landform is not aggrading because the particle sizes are not decreasing downstream.

The small measured decrease of bed material particle size for sites 2090 to 1874 may be the result of fine material deposited in the distributary channels during the storm of October 6, 1993. Much of the runoff for the storm was below site 2090 (figures 16 and 32). Because large amounts of the storm runoff were lost to infiltration, it follows that fine wash load from local runoff was deposited along the distributary channels. The small possible change of particle size is unknown but does not appear significant because the measured particle size increases at the lower sections.

The grain size distribution of the bank material (table 16) indicates plastering of the banks with fine sediments (Schumn, 1961, p. 53). This plastering of the channel banks indicates a stability that might not be expected in the normally sandy environment of the DFA. For more stable channels in sandy immobile material the channel banks typically are much finer material (Waite Osterkamp, oral communication, 1994). During rising hydrographs water seeps into the sand banks and the inflowing water with the suspended sediment particles of silt and clay will plaster the sandy bank with a mud cake (see figure 37). This donoring process is clearly indicated by the uniform progression with depth of the D50 to D 90 values toward the deeper "parent" material (18-36in. depth) as shown by data in table 16. The sand banks have become plastered with silt and clay that is a stabilizing mechanism by which the paloverde trees and other vegetation took over. The resulting mud-caked vegetation covered banks have "aged" to create an overall stability of the DFA.

The generally finer shallow bank material is apparent down the DFA (figures 44 and 45). With only one exception at the right bank side of site 1969, the shallow bank material is finer than the parent material. Only at the lower elevations does the material appear to be finer indicating aggradation if the drainage system was similar to the present drainage system. The similar D84 and D90 grain sizes (table 16) for the deep bank material of the Pleistocene Epoch and for the mobile bed material (0-4in. depth) may indicate similar material sources in the headwaters. The general relation between site number and the D84 grain size shows the similarity of the bed and deep bank material. The large difference between the shallow bank material and the bed and deeper bank material also is shown (figure 46). The D50 particles of the bed material are much larger than the bank material at the lowest sites (figure 47).

The data and relations indicate the parent material of the DFA is immobile and the bed material is transported from the upstream drainage basin through the DFA. The present system of distributary channels appears stable.

Figure 42.--Bed material size (D50) at sites

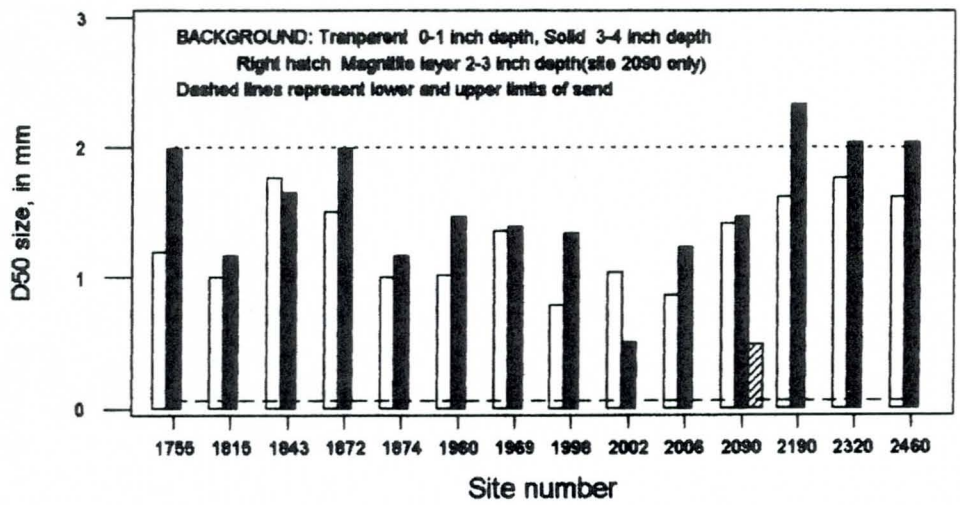


Figure 43.--Bed material size (D84) at sites

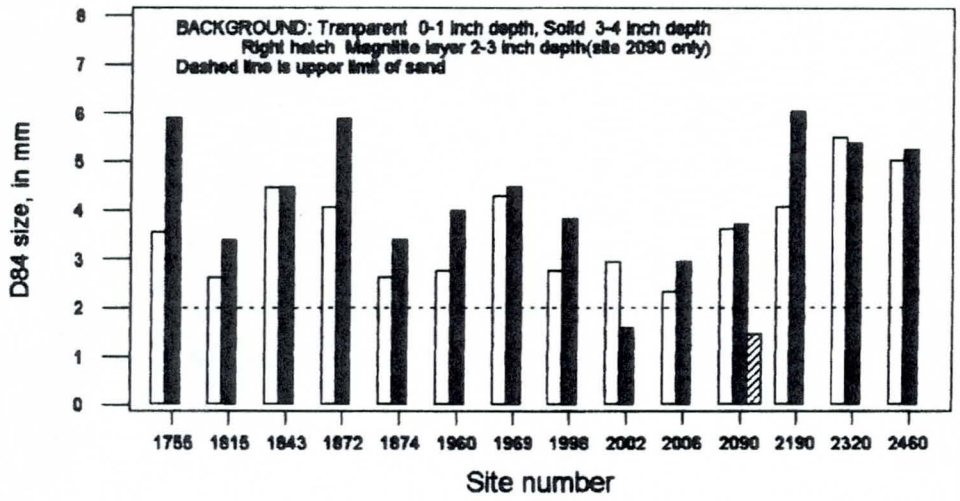


Figure 44.--Bank material size (D50) at sites

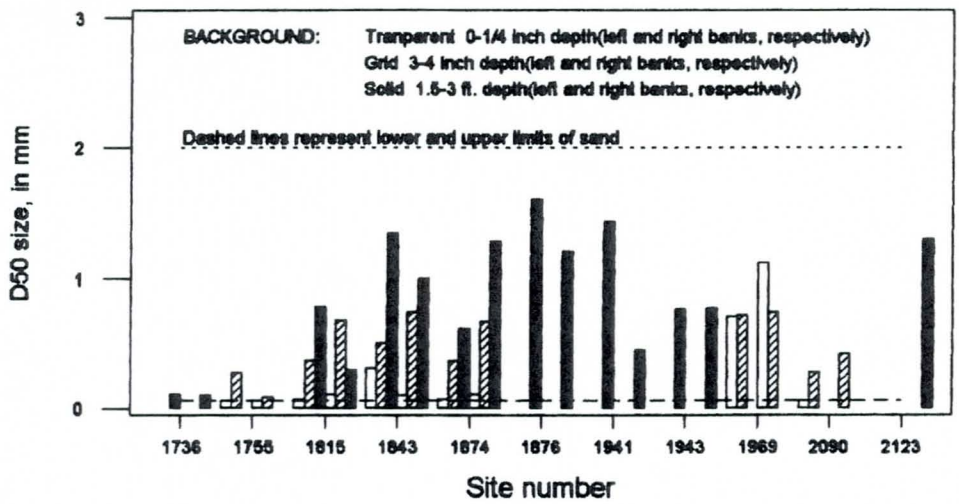


Figure 45.--Bank material size (d84) at sites

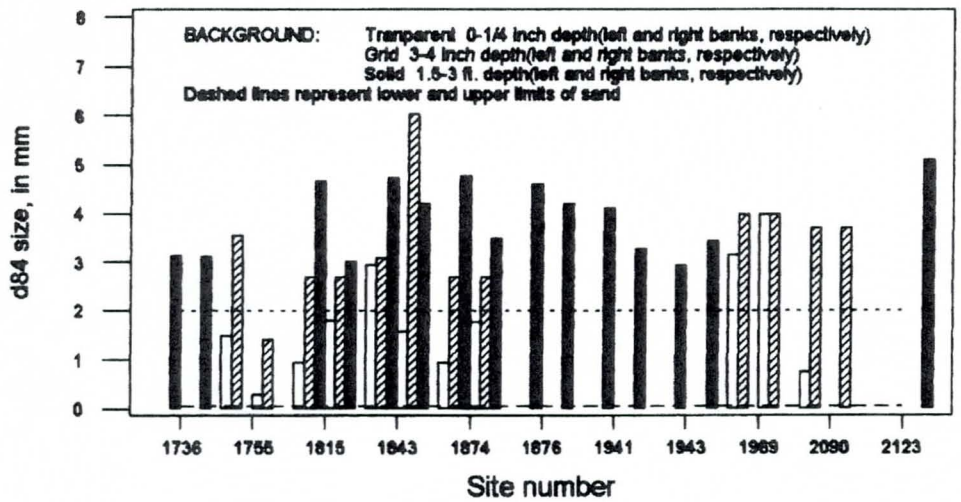


Figure 46.--Relation of D84 and site elevation.

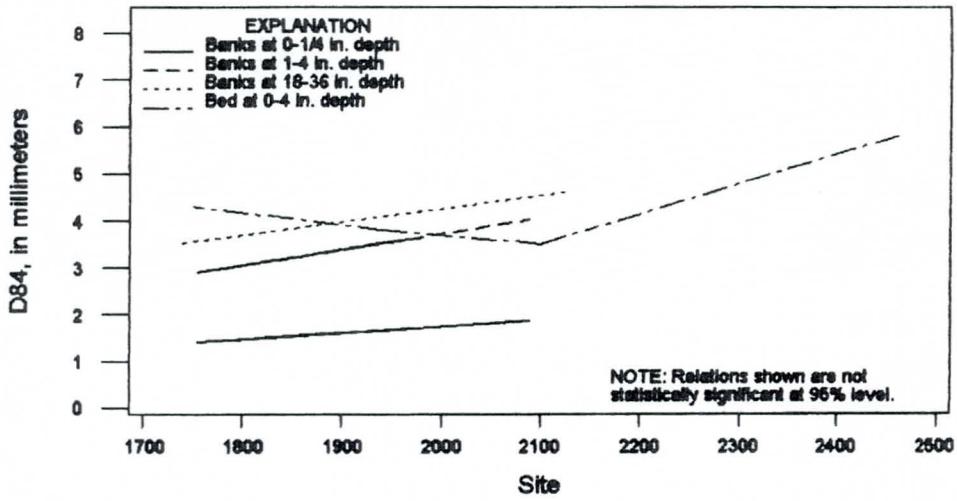
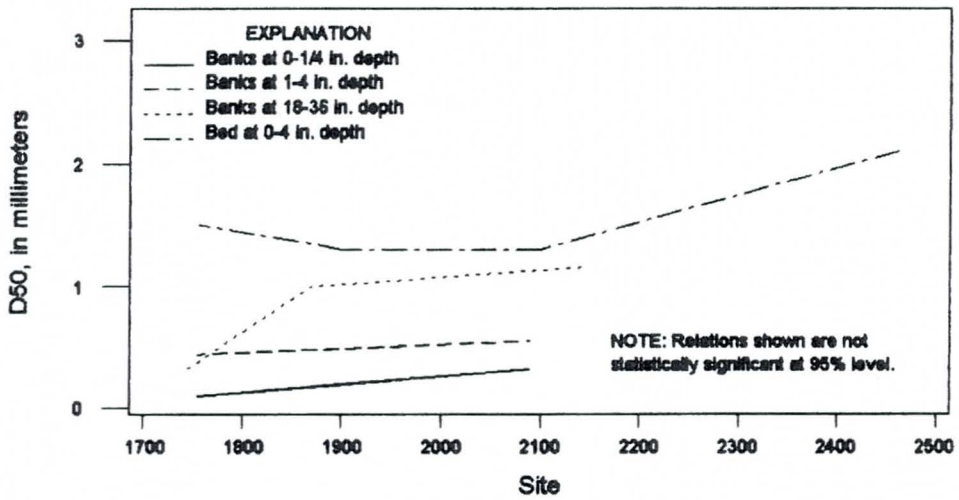


Figure 47.--Relation of D50 and site elevation.



Vegetation commonly is established on fine-stable alluvium and not on predominantly sandy material. Seeds germinate along ephemeral streams where there occasionally is sufficient moisture at the surface for extended periods (perhaps 2 weeks) at a particular time of year. Vegetation will establish after coarse deposits are covered with a veneer of finer sediment (Zimmermann, 1969). On many ephemeral streams with a high bed movement the seeds and plants will be washed away preventing development of permanent vegetation like the paloverde trees along the banks in site 6A. Vegetation aids deposition only after deposition has begun. Thus, the channel banks in site 6A were stable for a sufficient period for the riparian vegetation to establish and form the present system of stable flow paths.

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Two major techniques of distinguishing between stable and unstable ephemeral-channel cross sections and the corresponding instability of flow paths associated with aggrading channels are given by Schumm (1960 and 1961). First, the stability of channel cross sections is related to the width-depth ratio and the proportion of silt-clay composing the perimeter of the channel. Channels with a small width-depth ratio and a small proportional amount of silt-clay in the channel bed and banks are classified as stable. Second, aggrading channels have a marked variation in channel character and sediment type downstream (Schumm, 1961, p. 66). The generally assumed ability of a stream to adjust to changed conditions does not apply to ephemeral streams in channels that are being rapidly aggraded. The aggrading ephemeral streams, when attempts to adjust fail, follow a pattern of alternate deposition and erosion (Schumm and Hadley, 1957). Stable channels exhibit an orderly relation between (1) width-depth ratio and the proportion of silt-clay and (2) the proportion of silt-clay and channel gradient.

Application

Both techniques require measurements of channel width, depth and gradient (table 15) and samples of channel bed and bank material (table 9) with the computed weighted mean percent silt-clay at cross sections along the stream channel. The percent silt-clay is taken as that part of the sample smaller than the 200-mesh sieve of 0.074 mm. Cross sections should be located in uniform reaches that represent the channel gradient, width and depth along the stream.

Channel depth can be difficult to measure precisely because there may be recent scour or fill of the channel bed. Where there is recent scour along the banks the depth is the height above the channel profile to the top of the scour or deposited floodmarks, whichever is higher. No such scour of the banks was found in straight channel reaches of site 6A. Where there is recent fill along the channel the depth is the height above the channel profile (thalweg) to the first permanent surface or bank. Thus, the depth generally represents the distance from the thalweg to the height of the active channel within which the bed material is mobile. For site 6A this height was from the thalweg to the top of the banks at locations corresponding to the measurement of channel width. The stage of the channel-forming discharge (dominant discharge) is assumed to be at the top of the lowest bank. Channel width is the distance

between the top of the banks determined previously (table 15). The width-depth ratio (F) is for the bank-full stage.

The percent silt-clay along the channel perimeter is determined as follows (Schumn, 1960, p. 18):

$$M = \frac{Sc(W) + Sb(2D)}{W + 2D}$$

where M = weighted mean percent silt-clay,
Sc= percentage silt-clay in channel bed (table 9),
Sb= percentage silt-clay in banks,
W= channel width(table 15), and
D = channel depth.

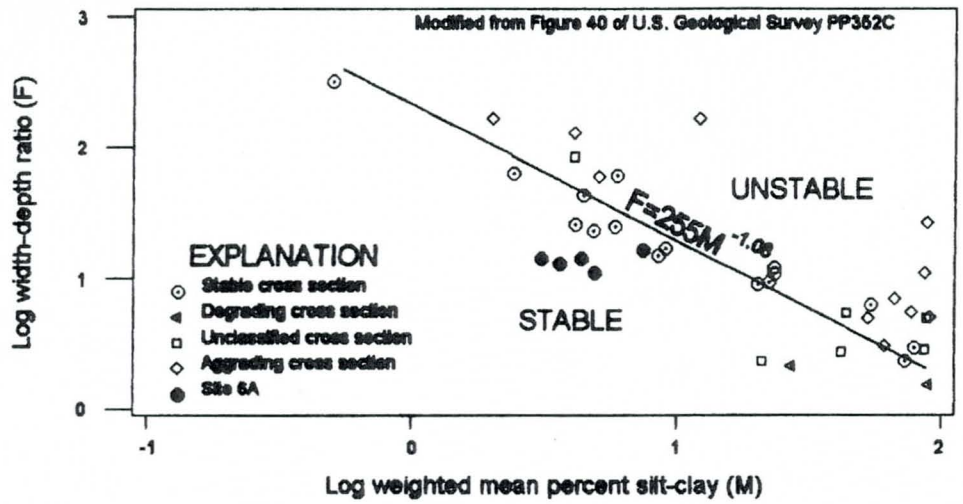
The computed values width-depth ratio (F) and weighted mean percent silt-clay (M) plot well to the left of the relation for stable cross sections (Schumn, 1961, p.63) as shown in figure 48. The orderly plotting of the points well on the "stable cross section" side of the relation indicates the channels are stable.

The weighted mean percent silt-clay (M) is based on a mix of geologic processes. The bed material is actively being transported through the DFA while the bank material is not mobile and was deposited a long time ago. Thus, the relation in figure 48 is empirical and might not be supported by process theory.

Discussion

Several examples of channel depth and width for cross sections from Schumm (1961) are shown in figure 49. Cross section sketches B and F represent many cross sections of site 6A (for example figure 34). Following the storm of October 6, 1993 there was some fill in a few reaches of the distributary channels and minor scour along the toe of some banks. The upper portion of the channel banks in site 6A typically appear permanent and are not moved except possibly by major floodflow. The bed is formed in cemented sediments as evidenced by highly cemented blocks exposed at an average of about 400 ft. intervals along the distributary channels. The immoble bed material is covered with coarse-grained mobile material that moves from the upstream basin over the immobile bed. There was some evidence of small amounts of local scour at the toes of the immobile banks following the flow of October 6, 1993. It is interesting that the shape of the distributary channels (figure 34 and B & F of figure 49) are similar to the shape of channels with cohesive banks and restricted bed scour discussed by Thorne (1988, p. 143).

Figure 48.--Relation between percent silt-clay and width-depth ratio at sites in straight reaches of distributary channels.



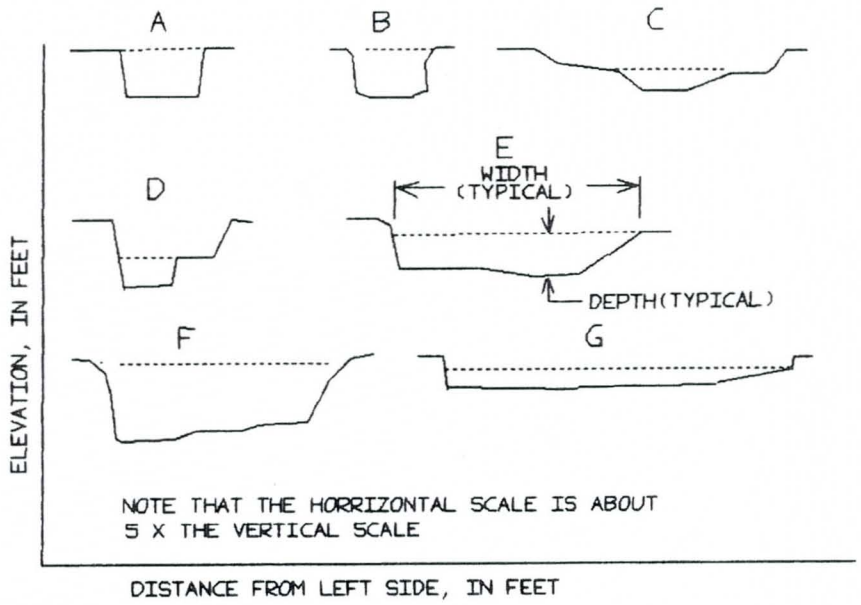


FIGURE 49.--CROSS SECTIONS SHOWING MEASURED DEPTH AND WIDTH.

Stream power

Vegetation along channel banks has a significant effect on bank stability. The vegetation has effects on both the hydraulics along the banks and on the bank material properties (Osman and Thorne, 1988). Vegetation along the banks commonly increases the resistance to flow and lowers flow velocities. Grasses act to reinforce the bank soil by increasing the resistance to the shear stresses of floodflow (Urban Land Institute, 1975). The stability of streambanks is also increased by trees and brush especially where the roots extend below the toe of the banks. The effects of vegetation on bank stability is difficult to define because the changes in the soil properties cannot easily be accounted for (Thorne and Osman,1988). Phillips and Hjalmarson (1994, in press) have found that changes of the condition of riparian vegetation during floodflow is related to the stream power. More stream power is needed to lay over or remove larger trees and thereby destabilize the channels banks. For this study, stream power is:

$$SP = 62RSV$$

where 62= is the specific weight of water, in lbs/ft^3,
R = hydraulic radius, in feet,
S = slope, in ft/ft, and
V = velocity of flow, in ft/sec.

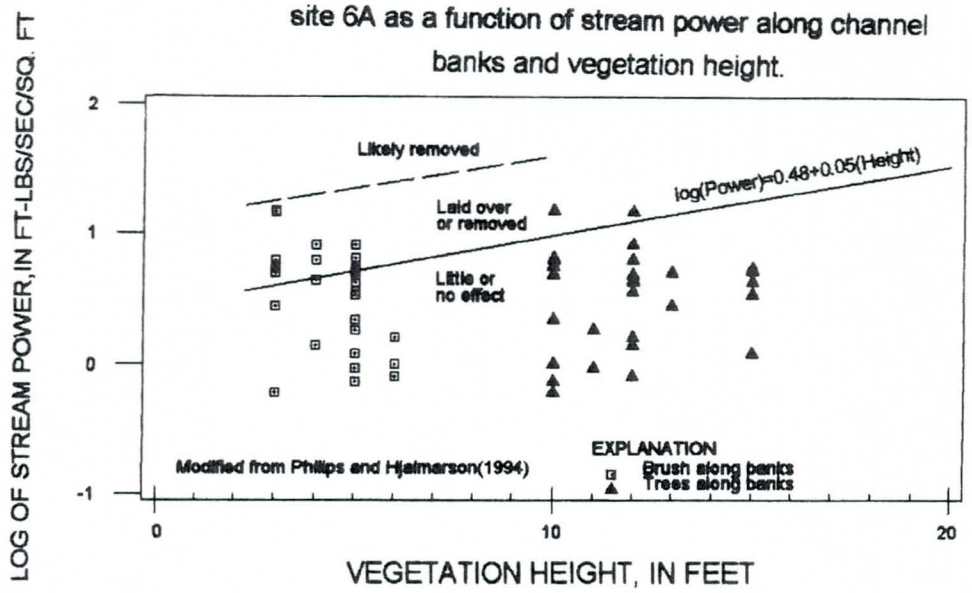
For many ephemeral streams in central Arizona with mobile cobble and small boulder bed material , changes in vegetation condition resulting from floodflows is a function of stream power and vegetation height (Philips and Hjalmarson,1994, in press). The allowable stream power (at the flood peak discharge), which will have little or no affect on the riparian vegetation, is estimated as a function of the height of trees and bushes along the channel banks (figure 50). Riparian vegetation is susceptible to damage or removal where the stream power for an average height of vegetation along a reach of channel is described by the following preliminary relation:

$$\log SP > 0.48 + 0.05VH$$

where SP = Stream power, in ft-lbs/sec/ft^2 = power at the peak discharge per unit area of streambed, and
VH = height of the vegetation in the floodflow, in ft. The minimum value is about 2 ft.

Although only partial indicators of bank stability, the height of riparian vegetation and the power of the peak discharge are significant factors. The effects of other factors such as the total stream power of a flood, the type and character of the bed material, the alignment of the trees along the channel and the distribution of trees and brush along the channel and banks are presently being studied. For streams in central Arizona, the ability of streambank vegetation to withstand the forces of floodflow as defined by Phillips and Hjalmarson is considered a useful indicator of bank stability especially when used in conjunction with other criteria.

Figure 50.--Estimated effect of peak floodflow on vegetation in site 6A as a function of stream power along channel banks and vegetation height.



Stream power and the height of vegetation along both of the channel banks was determined at 16 reaches defined by cross sections in site 6A (figure 21). The stream power for the width of 100-year floodflow along the channel banks where the vegetation is located (See figure 51) was computed using the velocity distribution option of WSPRO (Shearman, 1990). According to the computations, the bushes may be laid over or removed at about 1/3 of the sites (figure 50). Thus, some damage and removal of the bushes is expected. The 100-year flood does not appear to have sufficient power to damage or remove most of the trees along the banks of the distributary channels of site 6A (figure 50). Because the roots of the mature paloverde trees, the predominant species along the banks, are below the toe of the banks and commonly in the cemented soil, little damage to most of the trees and little movement of the channel banks associated with bank scour is expected .

Soil Conservation Service

The U. S. Soil Conservation Service developed a procedure to evaluate the stability of channels in cohesive soils in the western United States (USDA, 1977). This procedure, known as the tractive power approach, is specifically for channels in cohesive or partially cohesive lithified soils. In the tractive power approach the aggregate stability of soils related to erosion by floodwater is assessed by use of the unconfined compression test. The compressive strength of a soil sample is determined along with a computation of the tractive power of the floodflow and plotted on figure 52 (USDA, 1977, figure 6-15). Soils with a large compression strength relative to the tractive power of the streamflow can be expected to resist the erosive effects of the streamflow.

For this study, vane shear tests were used to obtain the in place shear strength of the bed and bank soils of the distributary channels. In place field tests are useful where it is difficult to obtain and transport undisturbed samples of the soils (USDA, 1977, p. 3-29). According to the USDA (1977, p.3-30) and Vanoni (1977,p. 109 and 112) the in situ shear strength can be determined using vane shear meters. A potential advantage of vane shear strength is that it is determined in the plane of the erosional forces as opposed to compression measurements that are made perpendicular to the shear forces exerted by floodflow. The shear strength is related to the unconfined compressive strength of the soil.

Tractive Power Approach

The tractive power approach is the result of limitations of tractive stress methods based on simple index properties determined for disturbed soils. Natural undisturbed soils have additional erosional resistance related to geological processes such as cementation in the B-horizon of developed soils and the presence of tree roots, grasses and cryptogamic crusts. According the U. S. Soil Conservation Service, the tractive power approach overcomes some of the limitations of the tractive stress methods.

The tractive force on a stream channel is the force of the water on the wetted perimeter. The unit tractive force is the average tractive force per unit of wetted area. In a uniform flow the tractive force is equal to the component of gravity acting on the body of water in the direction parallel to the stream channel. Briefly, the total tractive force is as follows:

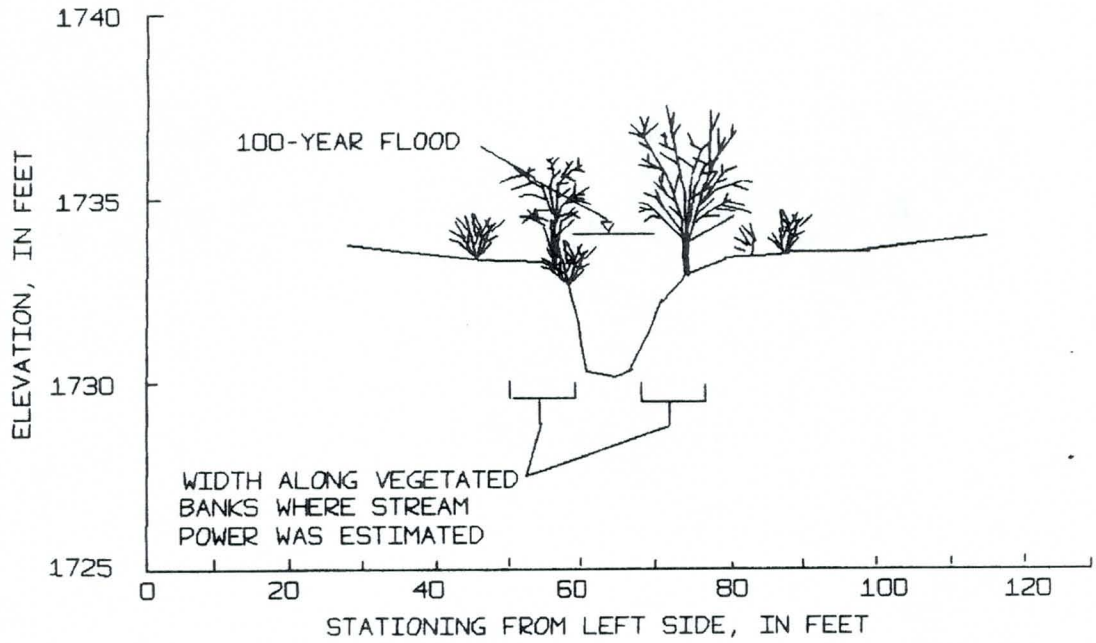


FIGURE 51--CROSS SECTION OF CHANNEL AT SITE 1736 SHOWING LOCATION OF STREAM POWER COMPUTATIONS.

Tractive force = $wALS$ = lb/ft^3(ft^2)(ft)(ft/ft) = lb

where w = unit weight of water, in lbs/ft^3,
A = wetted area, in ft^2,
L = length of channel reach, in ft, and
S = channel slope.

Unit tractive force = τ_o = $wALS/PL$ = wRS = lb/ft^3(ft)(ft/ft) = lb/ft^2

where R = hydraulic radius, in feet = A/P.

The unit tractive force is also the tractive stress. The product of the mean velocity and the tractive stress is the tractive power. It is important to note that the tractive power is for a unit area(1 ft^2) of the wetted perimeter as shown by the following units.

TP = $\tau_o V$ = lb/ft^2(ft/sec) = ft-lbs/sec/ft^2

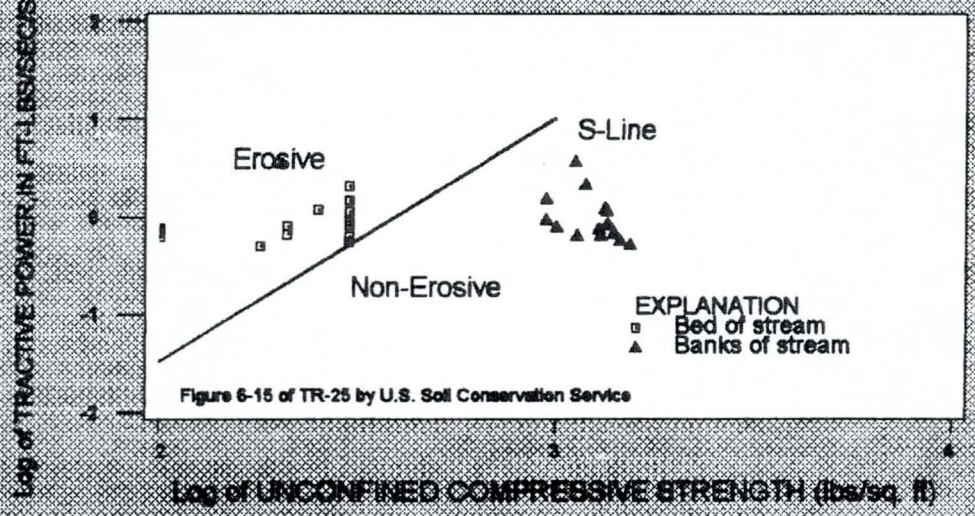
where V = mean velocity, in ft/sec.

The tractive power for cross sections was determined using methods in TR-25 (U. S. Department of Agriculture, 1977, p.6-33). A kinematic viscosity of 1.42 x 10^{-5} (water temperature of 50°F) was used. The average side slopes at bank-full stage of the approximate trapezoidal channel sections ranged from 1.3:1 to 9.9:1 (Table 15) with average side slopes of about 4.8:1.

The compressive strength of the in situ bed and bank material was estimated using measured shear strength by a Torvane meter (Soiltest, Lake Bluff, Ill.) (See figure 39). Several measurements of shear were made on both banks and on the channel bed at each site (table 11). The average shear strength for bare soil at each site was used for this analysis. According to two U.S. Soil Conservation Engineers (oral communication with Gary Conoway, Portland, Oregon and John Harrington, Phoenix, Arizona) the use of unconfined shear strength in place of unconfined compression strength for the relation given in figure 53 (USDA, 1977, figure 6-15) adds a factor of safety of about 2 (based on the Mohr's circle diagram for vertical and lateral pressures) which is useful for design purposes. Because shear strength, which is half the value of the compression strength (Hey and Thorne, 1987, p. 675), was used for the analysis the conclusion that the banks are stable is considered reliable and very conservative.

All of the data for the stream banks at the cross sections in site 6A plot to the right of the S-line (figure 52) indicating the channel banks are stable. Conversely, all of the data for the channel bed at the sections indicate the bed will erode. Observations of the soft sand channel

Figure 52.--Unconfined compressive strength and tractive power as related to channel stability



beds which overlay the immobile Pleistocene material clearly indicate the beds are subject to scour and fill. Thus, the mobile beds of the distributary channels can erode during flow but the channel banks are stable.

Observed stratification of the Pleistocene bank material is minor and layers of weak material such as unconsolidated gravel that are much weaker than the surrounding material are uncommon. Sediment fines in weak layers can be washed out during major flooding and lead to total failure of banks. The lack of observed bank stratification in site 6 indicates the distribution of shear strength is rather uniform. The observations of uniform bank material are supported by a computed coefficient of variation for the many measurements of bare-soil shear stress of only 27 percent.

The predominant nonuniform bank material that is visible in places throughout the DFA is the underlying cemented sediments that will withstand very large shear stresses (the shear strength of this material is much greater than the upper limit of one ton per square foot for the Torvane meter that was used for the measurements). Cemented bank and bed material is visible at 4 of the 16 hydraulic geometry sections. This occurrence of cementation, assuming an average visible reach of 100 ft. at each cross section, indicates the presence of visible cemented material an average of once every 400 ft. along the distributary channels. These outcrops of highly cemented material, which often are hidden under vegetation, act as anchor points which resist the downward cutting of the channels and the lateral movement of flow paths.

Effect of grass and cryptogamic crusts

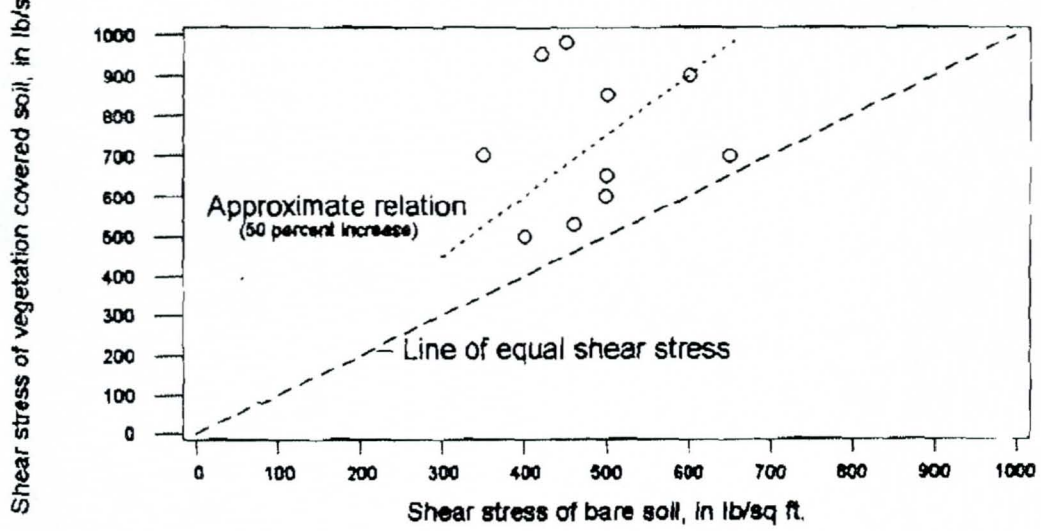
A comparison of the Torvane shear stress measurements of vegetated and bare soil (figure 53) indicates the vegetation increases the shear stress about 50 percent (figure 54). The increase of shear stress indicates the grasses and cryptogamic crusts have a stabilizing effect on the channel banks. The overall effect is unknown partly because the grasses and crusts are not uniformly distributed along the channel banks. However, because the floodflow typically is from thunderstorms and is short lived, any soil cover that affords some degree of protection against the flashy erosive forces probably is an important factor. Some of the apparent increase of shear may also be the result of the layer of silt and clay which accumulates near the soil surface as sediment laden floodwater is "filtered" as it infiltrates stable channel banks.

The apparent increase of shear strength from the vegetation adds a factor of safety in the stability assessment which is not included in the measurements plotted in figure 52. Also not included in this analysis is the stabilizing effect associated with the root mass of the many paloverde and other trees. According to Frank Reckendorf of the U.S. Soil Conservation Service, Portland Oregon (oral communication, April 11, 1994), the additional stabilizing effect of tree roots above any measured physical properties of the bank material is not precisely known. The typical velocities of overbank flow in site 6A are much less than the velocities that vegetation covered banks can withstand as discussed later in this report.

Note: Scene is typical of left banks under tree canopies. Grasses typically cover shaded banks and the left banks typically are steeper than the right banks for the generally westward flowing ephemeral streams.

Figure 53.--View looking down at bank and vane meter adjacent to area cleared of grass cover.

Figure 54.– Relation between measured shear stress for vegetation covered soil and bare soil at same locations.



Effect of wetting soil

The shear stress of the bank material appears to decrease about 19 percent as a result of the wetting previously described in the data section (figure 55). It is unknown if Torvane shear is best correlated to erosive factors for these dry or saturated conditions. Perhaps the measurements should be made at field capacity or perhaps after a longer period of saturation to more closely approximate the flow-duration of flash floods and the wetting of associated rainfall. There are several unanswered questions like these concerning the use of the Torvane meter to represent erosive shear stresses. An apparent advantage of the Torvane meter is that it measures in situ shear stress parallel to the erosive forces. Unconfined compressive strength, for example, commonly is measured perpendicular to the erosive forces. For this study, because the measured shear stress of the wet soil decreased only about 20 percent and was still well to the right of the S-Line (figure 52), the effect of wetting does not appear to significantly effect the channel stability along the flow paths for site 6A.

Measured shear stress

There is no apparent change of shear stress of the banks and bed of the channels along the distributary streams (figure 56). The shear stress at the sites in figure 56 is indicative of shear stress along the DFA of site 6A because the sites are distributed along the DFA (the site numbers correspond to the bed elevation at the surveyed cross section). Site 1736 is near the toe of the DFA and site 2123 is at the PD. The presence of grass or cryptogamic crust appears to increase the shear stress 50 percent and the wetting of the banks appears to decrease the shear stress of bare soil about 20 percent. The average of all the shear stress measurements of the wet and dry bank material is 1,080 lbs/ft^2 and 1,300 lbs/ft^2, respectively. The average shear stress at the undisturbed surface of the channel bed is about 250 lbs/ft^2.

Summary

There is a marked difference in the shear stress of the channel beds and banks and the measurements indicate the shear stress is uniform along the channels of the DFA. The shear stress of the channel banks at and upstream of the primary diffluence to Scottsdale Road is approximately the same as the shear stress of the channel banks near the toe of the DFA near 40 th Street. According to the latest published Flood Insurance Rate Map (Panel 820 of 4350, December 3, 1993) the channel at Scottsdale Road is considered to be a stable flow path. It follows that the flow paths also are stable near 40th Street.

The shear strength of the channel bed is about 1/5 the shear strength of the banks. The bed of the distributary channels is considered erosive but scour is restricted at the underlying cemented sediments. The Torvane shear stress of grassed bank soil is about 50 percent more than the shear stress of dry soil. The increased shear strength associated with the grass is partially offset by the decrease of shear strength associated with soil wetting. Using the procedures in TR25, the relation in figure 52, and the Torvane shear stress of dry soil (field condition), the bed material is mobile and the natural banks are stable.

Figure 55.--Relation between measured shear stress for wet and dry soil at nearby locations.

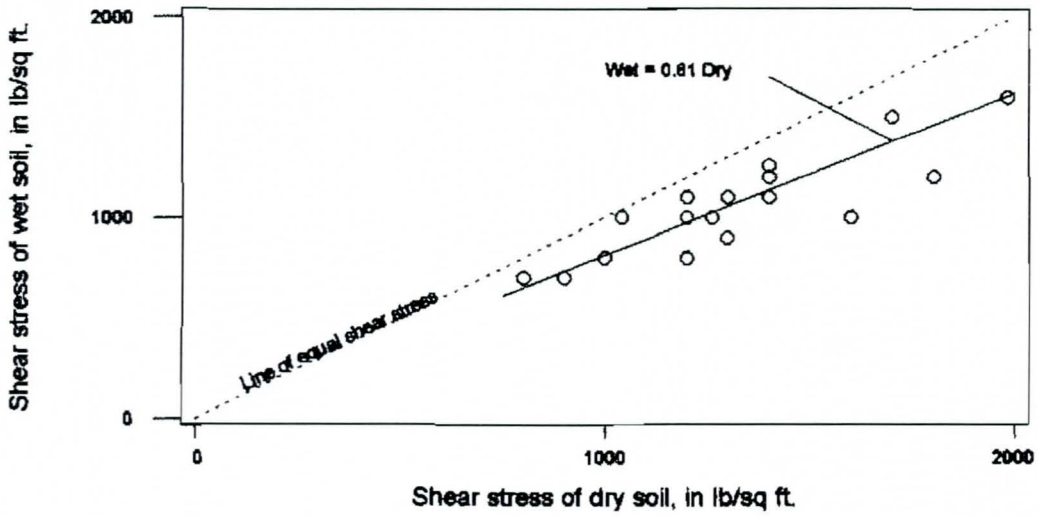
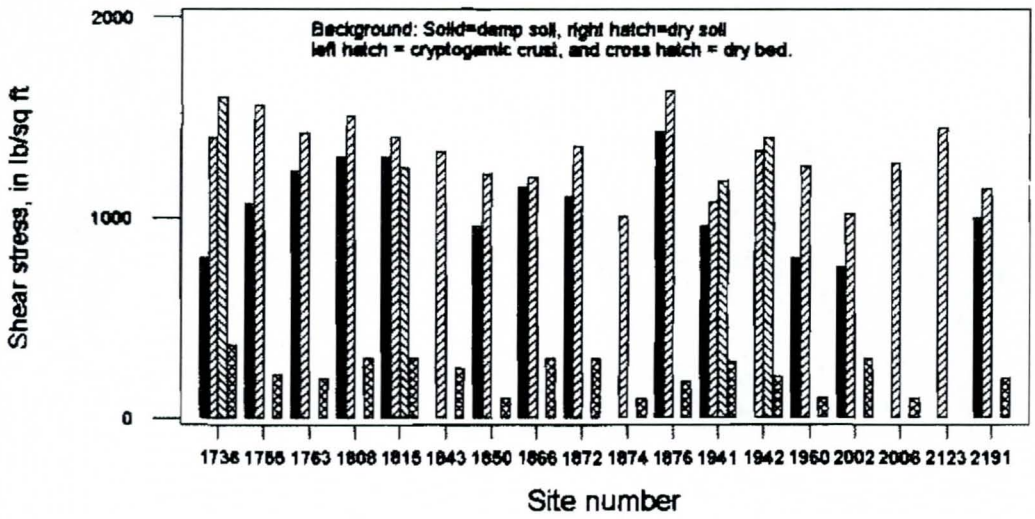


Figure 56.--Torvane shear stress for damp and dry bank soil, bank soil covered with cryptogamic crust, and dry bed material.



Federal Highway Administration

Two publications by the Federal Highway Administration related to stream channel stability are discussed in this section. The procedures presented in the publications indirectly apply to the stability assessment of site 6A. The permissible shear stress approach is first described followed by an empirical assessment of channel pattern. The classification of channel pattern using an overly simplified relation illustrates a pitfall of classifying complex channel systems. The permissible shear stress approach illustrates the need to define shear strength attributes of various types of bushes and trees.

Hydraulic Engineering Circular No. 15

The permissible tractive force (shear stress) approach has been developed based on research by the U. S. Bureau of Reclamation and is commonly applied to determine if a channel is stable in the sense that the boundaries are basically immobile or in static equilibrium (Chen and Cotton, 1986, p. 12). The approach focuses on the stresses developed at the interface between flowing water and materials forming the channel boundary. The permissible shear stress (PSS) is the maximum unit tractive force that will not cause serious erosion of the channel bed material from a level channel bed (Chow, 1959). Associated with the PSS is the allowable depth (Da) below which there will be no serious erosion. The values of PSS are conservative and appropriate for design use where the channel gradient is mild.

The procedures in HEC15 (Chen and Cotton, 1986) are a means for stabilizing roadside channels and are specifically for rock rip rap and flexible linings but include the stabilizing effects of vegetation. These procedures are similar to the procedures in Chow (1959, p.168-188) for the design of channels for uniform flow. Because procedures for vegetation lined natural channels are few, the results of the HEC 15 procedure are presented in this section. The reader is cautioned that the procedures may not reflect the channel conditions of site 6A where the vegetation includes many trees, the size of the bed and bank is much smaller than rip rap, and the banks are cemented at depth with calcium carbonate.

The permissible shear stress for non-cohesive channel material with a mean diameter less than 100mm is defined by single relation (Chart 1) in HEC 15. For stone sizes larger that D_{50}=100mm the permissible shear stress is given as

$$T_p = 4D_{50}$$

where D_{50} = mean diameter of stones, in feet.

The D50 of the bed and banks of channels in site 6A is much smaller than 100 mm (table 8). Thus, HEC 15 is used for this study only as a rough guide.

For cohesive soil the plasticity index appears to provide a good guide to the permissible shear stress as shown in chart 2 of HEC 15. Chart 2 is a relation between plasticity index and permissible shear stress with loose, medium compact, and compact soil indexes defined by the no. of blows required to penetrate a 2 in. split-spoon sampler 12 in (figure 40). For the more than 30 blows the cohesive soil is considered compact and the PSS corresponding to a plasticity index of 10 is 0.1 lb/ft^2. For site 6A, the blow count for penetration increments of 1 ft. commonly exceeded 10 (See table 12) at depths corresponding to the channel banks just above the toe. At some sites the blow count exceeded 30 at depths less than 4 ft. Thus, the soils forming the banks are medium compact to compact according to chart 2 of HEC 15. The corresponding maximum permissible shear stress (at an average plasticity index of 10) is between 0.05 and 0.1 psf. This permissible shear stress is considered much too low for the bank material in site 6A because the vegetation cover and reinforcing root system is not considered, there is a large amount of coarse grained material in the banks, and there is considerable cementation at depth.

The vegetative linings in tables 1 and 2 of HEC 15 and in charts 5 to 10 more closely match the channel conditions of site 6A. The class A vegetation type composed of tall grasses appears to most closely describe the vegetation in site 6A. There is a significant difference between the tall grasses of class A and the shorter grasses with the brush and trees along the distributary channels but the class A is judged to be the best match of classes A-E in the manual. The PSS for the class A vegetation is 3.70 psf (Table 2 of HEC 15 manual).

Only the check that the depth at bankfull stage (d) is less than the allowable depth (Da) is needed for this study (step 1 of the "Maximim discharge design procedure" on p. 21 of HEC 15). The Da, average Z, B/d (see chart 13 of HEC 15), and Rc/B (see chart 10 of HEC 15) values are computed for the cross sections (table 17). The coefficients K_1 and K_b corresponding to the channel banks and bends were determined from charts 13 and 10, respectively (table 17). A radius of bend (Rc) of 100 ft. was used for this study. The resulting allowable depths for stable banks in straight reaches and at bends are shown on columns Da/K_1 and Da/K_1K_b, respectively.

The allowable depths for straight reaches and for bends with a radius of 100 ft. are greater than the maximum depth in the channels at all sites but sites 1960 and 2191. Site 1960 is located just below a large block of cemented material that controls the channel grade (figures 24 and 25). Site 2191 is located upstream of the PD at Scottsdale Road where downcutting and lateral movement is restricted by many blocks of highly cemented material. The remaining 15 sites are on the distributary channels where there are fewer outcrops of highly cemented material. Because the allowable flow depths are more than the flow depths at bank full stage, the permissible shear stress is also more than the shear stress at bank full stage and the channels are considered stable. The allowable flow depths (table 17) are more than the flow depths of the 100-year flood, which are about 1/2 to 1 ft. above the bankfull stage, at nearly all sites.

Table 17.--Computed allowable depths using HEC 15 procedure.

Site no.	d[1]	Da[2]	Z	B/d	Rc/B	K_1	K_b	Da/K_1	Da/K_1K_b
1736	2.30	4.56	4.00	5.65	7.69	0.94	1.2	4.85	4.04
1755	1.90	3.48	5.30	5.79	9.09	.94	1.1	3.70	3.37
1763	2.90	3.70	3.60	4.12	8.33	.90	1.2	4.11	3.42
1808	1.70	3.48	5.30	4.12	14.3	.94	1.0	3.70	3.70
1815	2.00	3.48	4.95	2.00	25.0	1.0	1.2	3.48	2.90
1843	2.70	3.48	4.15	4.81	7.69	.94	1.2	3.70	3.09
1850	2.20	3.48	9.35	7.27	6.25	.94	1.4	3.70	3.64
1866	2.60	3.70	3.50	2.69	14.3	.93	1.0	3.98	3.98
1872	1.40	3.70	6.00	2.14	33.3	.98	1.0	3.78	3.78
1874	2.10	3.29	3.60	7.14	6.67	.90	1.3	3.66	2.81
1876	1.30	3.29	6.90	2.31	33.3	.98	1.0	3.36	3.36
1960	3.10	2.96	3.70	2.26	14.3	.97	1.0	3.05	3.05
1969	1.55	2.96	3.90	6.45	10.0	.94	1.0	3.15	3.15
1998	3.20	2.96	2.00	3.12	10.0	.82	1.0	3.61	3.61
2002	2.20	2.96	4.55	1.36	33.3	.78	1.0	3.79	3.79
2006	1.70	2.96	3.05	2.35	25.0	.91	1.0	3.25	3.25
2191	4.40	2.96	4.10	3.41	6.66	.95	1.3	3.12	2.40

[1]Depth at bankfull stage.
[2]Allowable depth.

Hydraulic Engineering Circular No. 20

A geomorphic relation in HEC 20 entitled "Stream stability at highway structures" (Lagasse, P.F., and others, 1991) illustrates the danger of using a relation with incomplete information. The procedures in HEC 20 were examined for use in this study but the information generally is found in the other publications. Also, a relation between channel gradient (S) and the channel forming or dominant discharge is considered misleading. The relation between hydraulic and geomorphologic factors is defined using the Lane relation and other geomorphic concepts. The meandering and braiding of streams is related to the following relation by Lane (1957):

$$SQ_m^{1/4} \leq 0.0017$$

where S = slope of channel bed, in ft./ft. and

Q_m = mean discharge, in ft^3/sec. The mean annual discharge is used to represent this mean or dominant discharge. For ephemeral channels the 10-year peak discharge commonly is considered the channel forming discharge.

Also, a sand bed channel is braided where:

$$SQ_m^{1/4} \geq 0.010$$

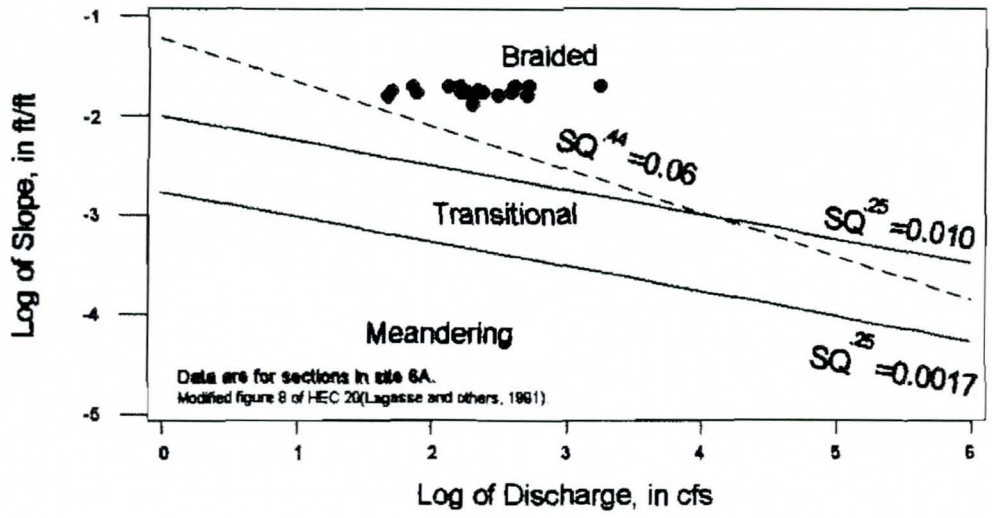
The area between the above relations is the transition zone between meandering and braided channels (figure 8 of HEC20). A line separating meandering and braided streams based on plotted slope and discharge for a variety of natural streams is (Leopold and Wolman, 1960):

$$SQ_m^{.44} = 0.06$$

Braided streams are characterized by two or more interweaving channels that change pattern, high floodflow velocities and large quantities of sediment. A braided stream has multiple channels that interweave as a result of repeated bifurcation and convergence of flow around interchannel bars and islands.

The Lane and Leopold and Wolman relations are shown in figure 57. Data for the sites in site 6A plot in the braided region but there is no evidence of braided channels in site 6A. Leopold and Wolman(1960) discuss that other factors such as sediment size and load and channel width influence the formation of braiding streams but these and other factors are ignored in HEC 20. For example, channels with braided patterns have large width-depth ratios (>40) but the channels in site 6A have relatively small width-depth ratios (table 15). Also, braided channels have many small channels within the main channel but there commonly is only one small channel within the channels of site 6A. There is general agreement that braided channels are associated with steeper slopes but the identification of the braided channel systems in HEC 20 is incomplete and not used for this study. This example illustrates (1) the need to use several independent techniques to evaluate channel stability and (2) that simple relations should be carefully examined.

Figure 57.--Relation of channel slope and dominant discharge



U.S. Army Corps of Engineers

A draft entitled "Stability of flood control channels" by the CofE is used for this section of the report. Many guidelines and techniques used in this study and other studies by the author are similar to the guidelines and techniques in the CofE report (1990). Information, which is general and mostly qualitative, that is pertinent to site 6A is presented in this section. One quantitative technique of stability assessment is presented in this section.

According to the CofE report, guidelines applicable to channel stability include velocity, shear stress, stream power, hydraulic geometry relationships, sediment transport functions, and bank slope stability. Factors related to channel stability are complex. For example, adequate resistance to erosion does not necessarily produce stability if the channel has substantial inflows of bed sediment. Also, simple criteria like allowable velocity and shear stress basically indicate what hydraulic conditions will initiate erosion in the absence of significant sediment inflows. Both the erosion resistance of channels and the bed-sediment inflows are important factors of the stability of channels. In other words, both hydraulic and geomorphologic factors should be evaluated. Also, according to the CofE report, several factors should be considered in a comprehensive evaluation of channel stability.

Hydraulic geometry relationships

Hydraulic geometry relations for a channel forming discharge along channels provide rough guidance to assessing channel stability. Values of bankfull width, bankfull depth and channel slope are plotted against the bankfull discharge. The bankfull discharge is considered the channel forming discharge. Relations given in figures 58-60 are used in the absence of locally defined relations. The CofE (1990, section 5.3.3) cautions that the relations may not suit the particular channel in question. The relations, which generally apply to channels with a low bed-sediment transport, are used for the following conditions:

Condition 1.--High bed sediment transport.

Characteristics: Plotted slope may be many times higher than indicated in figure 60. Plotted depth is likely to be correspondingly low in figure 59. Plotted width(figure 58) is likely to be much above the relations unless the stream is multi-channeled.

Comments: The data for site 6A indicate the DFA behaves like a typical multi-channel system with a high bed sediment transport.

Condition 2.--Aggrading channels.

Characteristics: Plotted width are likely to plot higher than indicated in figure 58. Plotted depth is likely to correspondingly plot lower than indicated in figure 59. Slope can plot either way depending on the aggradation process. It might be high as a result of increased sediment supply from upstream.

Comments: The widths for site 6A do not plot higher than the relations in figure 58. The data do not indicate the system is aggrading.

Figure 58.--Bankfull width and channel-forming discharge

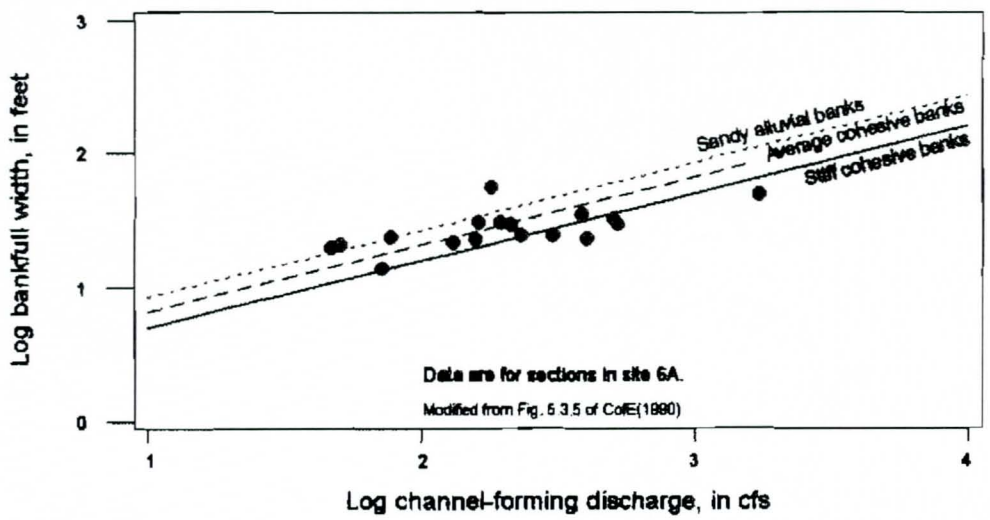


Figure 59.--Mean depth at bankfull stage and channel-forming discharge

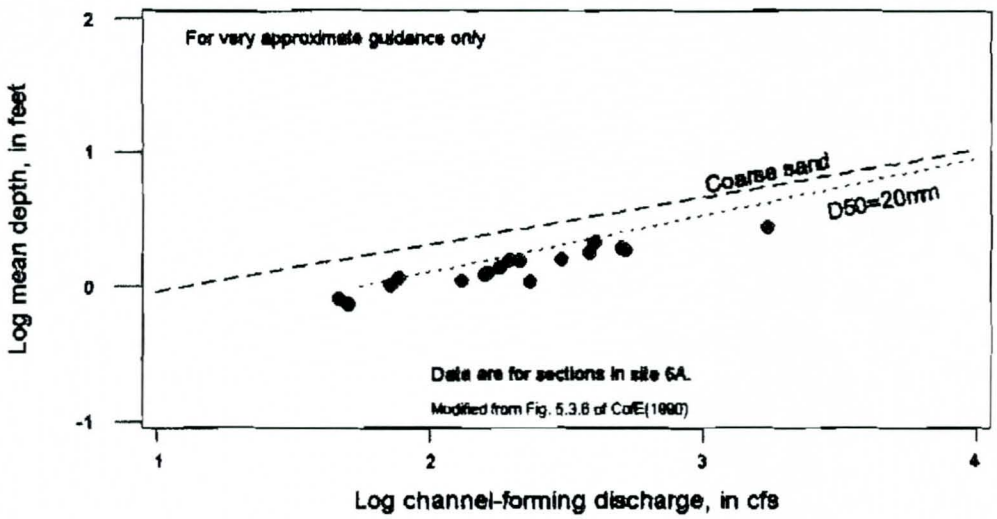
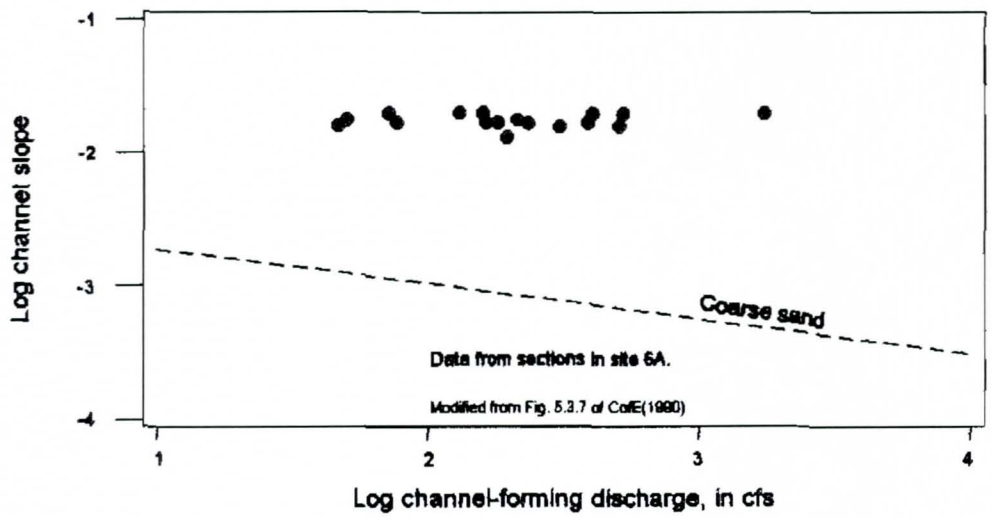


Figure 60.—Channel slope and channel-forming discharge



General information

Bank materials and vegetation are factors that may affect channel width, flowpath stability and rates of channel migration. Vegetation is an independent factor that should be considered as independently affecting channel characteristics. Instability is often triggered by the clearing of vegetation from streambanks. The role of vegetation varies greatly with region and type of vegetation. Vegetation recently has been treated as a variable in hydraulic geometry relationships (Hey and Thorne, 1986).

The stability of channel cross-section and profile requires not only that the channel resist erosion, but also that the bed sediment should be transported through the channel without deposition and loss of hydraulic capacity. It is generally agreed that "blind" computation of sediment transport without calibration against independent data may give unreliable results. The amount of sediment transported is not determined for this study but there is considerable evidence that the bed sediment is transported through the DFA in the distributary channels. The stability of channels in cohesive materials may vary widely, but it is generally greater than in alluvial materials.

Wash load consists of finer grain sizes not found on the bed- usually very fine sand, silt and clay- and is all transported in suspension. Most channels can transport all the wash load received from basin erosion, so that the transport is determined by supply. Increased wash load may increase channel stability because the silt and clay are deposited on banks during flood recessions, which tends to increase erosion resistance and promote vegetation growth. The increased channel stability associated with the deposition of silt and clay on the banks was discussed previously. The transport of bed and probably wash load in the channels of site 6A is not supply limited but rather flow limited. There is a large amount of weather quartz material in the drainage basin of site 6A that could be delivered as bed load to the DFA if there were sufficient flow. Because the flow is highly ephemeral (flow less than 1 percent of the time) there is little runoff to transport the available sediment.

Generally, increased bed-material load tends to reduce channel stability, because it forms local deposits which divert flow against the banks and so on. There is some local deposition of bed material in site 6A where there are small obstructions such as overhanging tree branches or fallen trees and cactii. There is also local deposition associated with the pulse nature of small floodflows that loose volume to infiltration and temporarily deposit sediment in channels. These deposits are remobilized, as shown by no change in flow paths between the 1940, 1953 and 1991
aerial photographs, by subsequent floodflows and eventually transported to the toe of the DFA of site 6A.

The effect of geotechnical bank stability on channel characteristics is important in some environments. River engineers have tended to regard bank instability more as a consequence than a cause of bank failure, the reasoning being that collapse of the upper bank is initiated by hydraulic scour at the toe. Geotechnical mechanisms, however, appear to be significant primary

causes of alluvial bank failures within several large drainage basins. According to Thorne and Osman(1988), bank stability characteristics affect hydraulic geometry in both straight and meandering channels. The hydraulic geometry relations defined previously for sections in site 6A are for stable channels.

A simple method of assessing alluvial fan stability is given that is in agreement with methods described in this report and in previous work(Hjalmarson, 1994, in press). According to the CofE "If the fan is generally unvegetated and the principal channel is perched in relation to ground at equal distances from the apex, the fan is likely to be actively aggrading. On the other hand, if the fan is generally vegetated and the main channel is somewhat entrenched, it may be stable or degrading." The author has observed that desert trees occur along the banks of entrenched channels while desert trees are scattered over areas with perched channels.

U. S. Department of Agriculture

Vegetation along channel banks resists channel movement and reduces floodflow velocities. Vegetated channel banks resist instability from other factors such as meandering and channel braiding. The establishment of vegetation along ephemeral streams in the arid and semiarid United States is promoted when there is sufficient stability for accumulation of deposited fine sand, silt and clay. The moisture retained in the fine sediments promotes seed germination and establishment of young plants. The permissible velocities for open channels are increased by the establishment of grasses (ULI, 1975). The overall stabilizing affect of vegetation is difficult to quantify but bank stability generally is related to vegetation density along the channel banks. Such a relation has been defined by the Forest Service (USDA, 1987).

Streambank stability has been successfully evaluated according to the Forest Service by using measured vegetative cover along channel transects perpendicular to streamflow. The vegetation cover along streambanks helps to stabilize the channels and reduce water velocity. The vegetation cover under a transect line (channel cross section) from the shoreline to within 5 ft. shoreward or to the top of the bank, whichever is larger, is defined and rated. The streambank stability rating takes the vegetation cover, bedrock, boulders and rubble into account and is in four classes as shown at the bottom of table 14.

The Forest Service bank stability rating was applied at several transects in site 6A including the cross sections used for the hydraulic geometry computations (figure 21). All of the transects were rated a unit 4 or 3 based solely on the vegetation cover (table 14). There was no bedrock but some of the banks were highly cemented. The cementation effects were excluded for this study to yield a conservative stability rating. There clearly was no evidence the banks were usually eroded each year (unit 1) except below road crossings and where roadways altered the natural flowpaths. Along the channels where there is little bank alteration by man there is much vegetation cover with little bank erosion and the banks are rated as stable (units 4 and 3).

Deeply rooted natural vegetation, like the paloverde trees of site 6A, along streams helps prevent erosion by mechanically reinforcing the bank soil with roots (USDA, 1992). The dense root system binds and restrains soil particles in place like reinforcing steel in concrete. The erosion of vegetated banks is less controlled by bank stratigraphy because the removal of soil fines from noncohesive layers of gravels is minimized. Although the stratigraphy of the bank material in site 6A appears rather uniform with no observed erosion of weak layered deposits at locations unprotected by root masses, the root mass is assumed to provide bank protection in this manner. Root systems, like those of the paloverde and other desert trees, afford some and possibly a very large degree of protection to the bank toe (Hey and Thorne, 1988). The degree of bank stabilization is greatest where the banks have a similar vegetation. The distribution of large desert trees (about 10 to 25 ft. high) along both banks of the distributary channels of site 6A is similar.

The rather dense desert grasses with lateral roots afford some degree of channel stability (See figures 36, 39 and 53 for example). The fine roots of the grasses and other plants spread laterally to available soil moisture and bind the soil into more stable aggregates (USDA, 1980). The grasses are more dense on the left banks than on the right banks because there is more available moisture in the soil. Shade is afforded by the tree canopies on the north-facing left banks and the angle of incidence of sunlight is less on the left banks. The protected left banks are steeper than the right banks (table 15) which are more susceptible to both lateral (rills) and downstream erosion. Although difficult to quantify the overall stabilizing effect of the grasses along the channel banks, the stabilizing effect is shown by the general difference in bank slope. A photograph of the rather steep left bank of the cross section at site 1815 shows dense grass over 1 ft. high and brush (figure 61).

The slope of both banks is gentle and commonly less than 2:1 (table 15). The channels are fairly wide for the height of the banks. The total depth of flow at bankful stage typically is less than 3 feet with an average of only about 2.3 ft. The width-depth ratio typically is more than 10 with an average of 11.4. Wide natural channels with flat side slopes lined with grass and other vegetation usually will be free of erosion (Urban Land Institute, 1975). Permissible velocities for open channels are greatly increased by grass covers (table 18).

Scene is of rather steep bank (average slope 1.9:1) that is partially shaded by tree located a few feet downstream (note shadows of branches on streambed). The bank is covered with thick grass and scattered brush. Photograph was taken during March 1994.

Figure 61.--View looking southeast and across from center of channel at grass on left bank of distributary channel at site 1815.

Table 18.--Permissible velocities for swales, open channels and ditches with uniform stands of various well maintained grass covers.

Cover	Slope Range Percent	Permissible Velocity on:[a] Erosion-Resistant Soils(ft/sec)[b]	Easily Eroded Soils(ft/sec)[c]
Bermudagrass	0-5	8	6
	5-10	7	5
	Over 10	6	4
Buffalograss	0-5	7	5
Kentucky bluegress	5-10	6	4
Smooth brone	Over 10	5	
Grass mixture	0-5	5	4
Lespedeza Weeping lovegrass Yellow bluestem Kudzu Alfalfa Crabgrass	0-5	3.5	2.5
Common lespedeza[d] Sundandrass[d]	0-5	3.5	2.5

From: Residential strom water management-Objectives, principles and design considerations, 1975, published jointly by the Urban Land Institute, American Society of Civil Engineers, and National Association of Home Builders.

[a] Velocities in excess of 5 ft/sec to be used only where good cover and proper maintenance can be assured.

[b] Defined as CL, CH, OH, GM, GP, GC, and GW (Unified Soil Classification System Designation).

[c] Defined as ML, SM, SC, MH, and OL (Unified Soil Classification System Designation).

[d] Annuals, used on mild slopes or as temporary protection until permanent cover is established.

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This section is a brief discussion of the effect of adding silt and clay to an otherwise sandy sediment as described in Sediment Engineering (ASCE Manual No. 54, Vanoni, editor, 1975). The filtering of suspended sediment as floodwater infiltrates the sandy banks of the distributary channels of site 6A is like adding silt and clay to sandy sediment. Also briefly discussed is the effect of duration of floodflow on erosion.

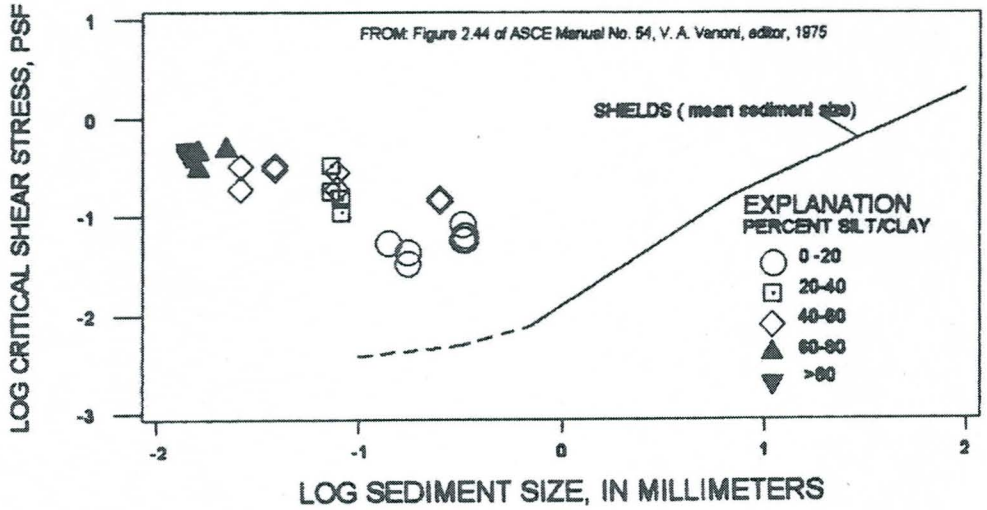
The relation between critical shear stress and grain size of noncohesive quartz sediment given in figure 2.44 of the ASCE manual on sediment engineering (Vanoni, 1975) is approximately shown in figure 62. The data from table 2.11 of the same manual for cohesive channel sediment are plotted on figure 62. The effect of adding silt and clay to the sandy sediment is clearly shown. Based on the plotting of the data far above the relation, the critical shear stress potentially can increase nearly 100 times when large portions of silt and clay are added to sandy sediment. The donoring process of adding fine sediment to the channel banks of site 6A (figures 37 and 38) results in a similar but lesser increase in erosion resistance.

The percent silt-clay along the wetted perimeter of the channel banks of site 6A is about 50 percent more than the percent silt-clay of the deep bank material (table 9). The average percent silt-clay near the surface of the banks and at depth is about 40 and 27, respectively. The effect of the added silt and clay can be estimated, at least qualitatively, using the relation in figure 62. The estimated increase of critical shear stress corresponding to this increase of fine material is about 3-6 times corresponding to the median grain size of 0.87 mm for the deep bank material (table 16).

As previously discussed, the grasses and cryptogamic crusts along the banks may increase the erosion resistance partly because the floods are short lived. It was argued that even spotty covers of vegetation effectively resist erosion because the potential amount of erosion was a function of duration of flow. According to Vanoni (1975, p. 112) the erosion is proportional to the duration of flow and potential rate of erosion is greatest at the onset of flow. Thus, the grasses and cryptogamic crusts appear to be very important factors.

The resistance to erosion of cohesive sediments varies greatly (Vanoni, 1975, p. 114). Shear stresses measured by different investigators vary almost 200 fold. The shear stress is proportional to the shearing strength of sediment as determined with a vane meter or in standard soil tests (Vanoni, p. 108). Cohesive soils have a greater shear strength than noncohesive soil and the addition of silt and clay to sandy material increases the critical shear stress of the material.

Figure 62.--Effect of fine material on critical shear stress



Comments

According to Chen and Anderson (1987) the erosion of cohesive soil is complex because many controlling parameters act interdependently. Principal factors involved are the physical and chemical properties of the soil itself, its behavior when partly and fully saturated, and the hydraulic properties of the flow.

The permissible shear stress and velocity are defined as the largest shear stress and velocity of flow that will not cause erosion. For noncohesive soils the following equation can be used to determine shear stress where the Reynolds number is greater than 70:

$$\tau_c = 0.05\ (\gamma_s - \gamma)\ d_{50}$$

where γ_s and γ are the unit weights of soil and water, respectively, and d_{50} is the median particle size of the soil.

Several relations for permissible shear stress have been developed for cohesive soil. Critical tractive force of cohesive soil has been found to correlate well with plasticity index. The relation for 11 uncompacted Missouri soils , ranging from silty loam with little cohesion to a highly cohesive clay soil, was

$$\tau_c = (PI)^{0.84}$$

where PI is the plasticity index.

Because the erosion of cohesive soil is complicated by several controlling parameters which act interdependently, general relations of permissible or critical tractive force or permissible or critical velocity may be of limited value and subject to large error. Controlling factors are the physical and chemical properties of the soil itself, its behavior when partly and fully saturated, and the hydraulic properties of the flow.

Bank stability is derived from the shearing strength of the layer of soil along the wetted perimeter. The bank material of the ephemeral streams becomes partly or fully saturated for short periods of floodflow. As the normally dry bank material is wetted the shear strength changes and the resistance to erosion can be weakened by a decrease of shearing strength. When cohesive soils in Arizona are wet they can become noncohesive (Oral communication, John Harrington, U.S. Soil Conservation Service, Phoenix, Arizona). For the bank material of site 6A there is some reduction of shear strength from wetting at the surface as previously discussed (figure 55). The shallow soils may, however, be more cohesive because of greater clay content.

For entrenched ephemeral channels the resistance to erosion may be from the considerable shearing strength of the cemented B horizon of well developed soil. A B soil horizon composed of gravelly sand that is highly cemented by calcium carbonate may have no plasticity but is

highly resistant to erosion by floodwater. Well developed B soil horizons of Pleistocene soils commonly are a few feet thick in central Arizona.

Another complicating factor for sand-bed channels where the bed form changes is that the Shield's diagram may have limited value. A much larger shear stress than indicated by the Shield's diagram is needed for erosion where the beds are covered with ripples and dunes.

An additional complicating factor is the effect of vegetation along the channel banks. According to Osman and Thorne(1988) and Thorne and Osman(1988) bank vegetation has a significant effect on near-bank flow hydraulics and on bank material properties. Bank vegetation does not necessarily have a stabilizing influence on bank movement. For example (although not applicable to site 6A), large trees on steep slopes are additional weights to the bank that decrease the stability (Thorne and Osman, 1988). The roots of small trees and plants act to reinforce the bank material and are a stabilizing influence where the vegetation is similar along both banks. Rooting systems can protect against bank undercutting at the bank toe and also prevent mass failure of the upper bank (Hey and Thorne, 1988). The roots of the paloverde trees are a few feet below the bank toe. The channel width also is influenced by the density and distribution of bank vegetation and all other factors being equal, the channel width can decrease by 1/2 with increasing vegetation density (Neill, 1988).

FLOOD BOUNDARIES OF SITE 6A

The proposed method used to define areas flooded by the 100-year flood for site 6A (a DFA with stable flow paths) is similar to the riverine method in the Guidelines and Specifications for Study Contractors for flood insurance studies (FEMA, 1985 and1993). This proposed method is a form of the "limited detail analysis" described in the guidelines and specifications. The procedures given in the guidelines should be followed but because these standard procedures were written for tributary stream channels, the application of the standard procedures to DFAs with a stable network of distributary channels may be unclear. The following is a brief description of a proposed modification to the application of the riverine procedures to define flood boundaries of DFAs. The flood boundaries were not defined for this study.

The procedures for defining flood boundaries of DFAs like site 6A are unique because the hydrology cannot be completed until the PD, boundaries of the DFA, and drainage-basin divide are defined and there normally are more channel forks than channel joins and there may be several separated channels each conveying a portion of the floodwater. Floodflow will be in defined distributary channels and adjacent flood plains. Separated floodwater may rejoin floodwater in another distributary channel while floodflow in yet another distributary channel may debouch on a base-level plain or discharge into a base-level stream.

Much of the floodwater of major floods will be in wide-flat flood plains adjacent to the relatively small defined channels. At channel forks or diffluences the apportionmant of floodflow is imprecise using conservation of energy and other methods mostly because (1) the slope of DFAs commonly is steep and the flow velocities may be critical or near critical in places where the roughness is low, (2) the mobile beds of the commonly small-defined channels scour and fill, and (3) obstructions to floodflow and variations of channel geometry in the vicinity of diffluences affect the amount of wide-shallow floodflow entering the two or more channels below diffluences. During major floods there may be critical flow in some reaches of the defined channels and subcritical flow in other rougher reaches. On land adjacent to the defined channels the flow is shallower and commonly encounters more roughness such as desert bushes and cacti. The velocities of most of the flood plain flow are subcritical (figure 9). While floodflow follows defined paths along the defined channels between stable ridges there can be a complex and changing mosaic of critical, supercritical, and subcritical velocities in the defined channels and on the adjacent flood plains.

Such a system defies precise definition and, therefore, water surface profile methods that balance energy gradients may be unwarranted in areas with several distributary channels because of the computational complexity and limited potential precision for these conditions.

Throughout central and southwestern Arizona, DFAs are sites of groundwater recharge as large amounts of runoff infiltrates into the beds of the distributary channels. The flood peaks of flash floods are also reduced through attenuation as the floodflow divides into many distributary channels (Thomas, Hjalmarson and Waltemeyer, 1994, p. 14). The movement of floodflow for such a system of channels is difficult to model precisely. The author recognizes

that attenuation effects and losses to infiltration for a system of several distributary channels should be considered in a comprehensive hydrologic analysis of site 6A because the associated reduction of peak discharge of the 100-year flood may be significant.

For site 6A, the attenuation effect may increase and the infiltration effect may decrease with recurrence interval of the particular flood in interest. Proportionately more floodflow of large floods that originate in the basin upstream may be temporarily stored on the wide flood plains adjacent to the distributary channels. Also, proportionately less floodwater of large floods that spreads over adjacent flood plains may be lost to infiltration.

Cross sections

Cross sections should be representative of the reach between them and should span the width of DFA that includes the channels which might convey the 100-year flood. If there is any doubt about which channels may convey floodwater, the width of a cross section should span the entire width of the DFA between the boundaries defined previously (plate 1). Cross sections are placed at intervals along the DFA which will subdivide the distributary channels into a series of subreaches of relatively uniform geometry and roughness. Cross sections normally are located at contour lines of detailed topographic maps because the flow is approximately perpendicular to contours of many DFAs. They should be located above and below all forks and joins of the network of channels such that the fork or join is in the middle of the subreach. In general, cross sections should be determined in accordance with procedures in water-surface profiles user's manuals such as HEC-2 (U.S. Army Corps of Engineers, 1990) and WSPRO (Shearman, 1990) and the Guidelines and Specifications for Study Contractors (FEMA, 1993).

The subdivision of cross sections for a DFA should be done primarily on the basis of channel geometry. Each of the channels that potentially may convey floodflow should be subdivided to facilitate the analysis of the amount and distribution of floodflow in the network of channels. The computer program should be capable of tabulating hydraulic characteristics for the subsections at many elevations for each cross section. Across some DFAs the roughness of defined channels is markedly less than the roughness of adjacent land and the subdivision should define the roughness differences. The smoother defined channels may have critical-flow conditions and the adjacent rougher land with shallower floodflow may have subcritical-flow conditions. Thus, the computer program should be capable of printing out values of Q at both critical and normal depths for the subareas at many elevations. Where the relatively small defined channels meander there may be additional roughness from flood-plain flow crossing the main channel (a small amount of this "short circuiting" condition is shown in figure 9). The subdivision of cross sections and the estimation of roughness coefficients for streams in Arizona is discussed by Thomsen and Hjalmarson (1991).

Summary of steps for flood boundaries

The flood boundaries and water levels can be determined as follows:

1.--Define the 100-year peak discharge. The primary diffluence and boundaries of the distributary-flow area and drainage basin were defined for the stability assessment.
2.--Define the major water courses throughout the DFA on detailed topographic maps.
3.--Estimate limits of flooding. The width of flow selected should include the probable flow paths and should lie within the bounds of the DFA defined for the assessment of stability.
4.--Select a cross section near the middle of each reach that represents the hydraulic conditions of the reach.
5.--Define areas and sub-areas of cross sections. High ridge lines separating the channels can be defined on detailed topographic maps.
6.--Select Mannings' *n* for the areas and sub-areas.
7.--Compute and tabulate conveyance and discharge for the area and/or sub-areas at increments of water surface elevation. Computed stage-discharge relations for the subareas can be very useful.
Along some defined channels the banks progressively become lower until there is little, if any, confinement of flow. The flow spreads downstream and laterally until it becomes confined in the nearby system of channels. The distribution of flow in the channel links below these areas can be estimated using the distribution of conveyance or cross sectional area along the contours on the DFA in the hydraulically expanding reach.
8.--Route the peak discharge down the channels using the tables of discharge or the rating curves for each distributary channel (sub-area).
The distribution of peak flow in this simple example is based on the assumption that the joining of separated flood peaks is at the peak discharge. The peak discharge is apportioned through the network of channel links by assuming that the flood peaks coincide at all the divides and joins. The reduction of peak discharge from channel storage and transmission losses to infiltration into the channel beds is assumed to be offset by tributary inflow for this simple example. For flow at normal depths, the apportionment of flow is based on channel conveyance and slope.
9.--Define the flood boundaries on the detailed topographic map.

This procedure can be modified to account for infiltration and attenuation effects. Also, for large DFAs with small drainage basins the component of peak discharge from within the DFA may be large and should be included in the hydrology. It may suffice to assume the runoff for the DFA offsets the loss of incoming floodflow to infiltration.

See Appendix F for selected hydraulic methods and a sketch of flood boundaries. (Addendum of 8/22/94)

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APPENDIX A: ALLUVIAL FANS AND DISTRIBUTARY-FLOW AREAS

Alluvial fans are landforms characterized by an apex where floodflow becomes unconfined and a land delta below the apex where stream channels have a radiating pattern. Distributary flow is flow that divides into two or more distributary channels. A **distributary channel** flows away from the main (other) channel, is separate from the main channel, and commonly does not return to the main channel. **Distributary flow** is diffuse flow where there is at least one distinct diffluence at the outflowing branch of a stream. There generally are channel forks, joins, and outlets for a system of distributary channels and the number of outlets is more than the number of forks. These flow systems, which have little to do with topographic relief, are called distributary flow areas (DFAs). **Sheet flow** also is diffuse, generally occurs where there is little topographic relief, commonly is unconfined and spreads freely, and is not considered to be distributary flow. Floodflow that leaves distributary flow areas onto base-level plains such as playas commonly is sheet flow. Areas with distributary flow (DFAs) have at least one channel fork or diffluence where at least two channel links are formed. Thus, **DFAs** are not landforms but rather areas of land where the drainage pattern is distributary as opposed to areas with the more common tributary drainage pattern. Because floodflow on alluvial fans commonly is distributary, alluvial fans are considered to be DFAs. Floodflow on some pediments is distributary and these erosional areas are also considered to be DFAs. Both aggrading landforms (alluvial fans) and degrading landforms (fan terraces and pediments) have systems of distributary channels.

Old alluvial fans (fan terraces) that were deposited during the Pleistocene Epoch (Melton, 1965, p. 10) are undergoing erosion today and commonly have well-incised tributary-drainage systems. Some areas of the old alluvial fans have been eroded and subsequently filled by alluvial fans which are actively aggrading today. Other old alluvial fans which form the upper portion of piedmonts have been eroded by channels which convey floodwater from upstream basins. Some of these channels traversing the old fans are entrenched distributary channels with forks and joins. These areas with distributary flow (DFA's) have a network of channels incised in stable Pleistocene surfaces where there is little aggradation and degradation in engineering time (100 years or perhaps a few hundred years). Other alluvial fans in central and southwestern Arizona are actively aggrading today and are component landforms that overlie or are between old-fan surfaces. In places, old-fan remnants crop out in the midst of an actively aggrading area. There is a variety of both active aggrading and degrading distributary-flow areas inseparably related to old alluvial fans on piedmont plains in central and southwestern Arizona .

In much of central and southwestern Arizona piedmonts have been eroded over long periods with the eroded material deposited over lowlands or transported to remote areas by base-level streams. Pediments composed of bedrock or old alluvial fans in the upper piedmonts comprise much of the mountain-valley region of central and southwestern Arizona. The alluvial fans of the general degradational environment of Arizona are less dynamic than the alluvial fans of tectonically youthful regions such as southern California and Nevada. The California and Nevada fans are extensive and aggrading as the recently uplifted drainage basins are eroded. There is a complex relation between old fans of different ages and active alluvial fans in predominately erosional environments and also in predominately depositional environments .

Areas with a network of channels with forks that distribute flow (DFA's), which include alluvial fans and any other landform where there are channels with forks and separate channel outlets, have a wide variety of geomorphic characteristics and associated flood hazards. The channels of a DFA become separated at the primary diffluence by a variety of interfluves that range from high stable ridges to low indistinct unstable ridges as found on many alluvial fans. The types of DFA's are related to the number of potential paths that floodflow may follow on the DFA. The simplest type of DFA is one in which floodflow separates into two well-defined stable channels with an interfluve higher than the potential 100-year flood. The most complex type of DFA has erratic flow paths that appear to occur randomly over most of the land surface.

Many geologists have described alluvial fans in terms of geomorphic processes and the literature contains numerous discussions on the physical similarities and dissimilarities of alluvial fans. The literature also contains several insightful discussions of, and arguments against, hypothetical formation processes of alluvial fans. Some of the most pertinent articles related to alluvial fans that the author has observed in Arizona include Harvey (1989), Denny (1967), Bull (1977), Lustig (1969), Hooke (1967), and Mabbutt (1977). Alluvial fans are described as depositional landforms but some channel networks with forks are stable and eroding. Geologists describe erosional, tectonic, fluvial and debris flow processes and the influence of vegetation, rock types, climate and other factors. Because these experts describe several types of alluvial fans and several processes without apparent agreement, the term DFA is used to describe these areas because all have a radiating or distributary network of channels. Also, some split channels observed in Arizona do not rejoin and are not associated with alluvial fan processes (Hjalmarson and Kemna, 1991). DFAs are not landforms but include landforms such as alluvial fans and are areas with a distributary network of channels.

In addition to the division of channels on DFA's, the channels also combine or join. On some DFA's there are many forks and joins and the location and geometry of the channels appears unstable. The network of channels on other DFAs also may appear chaotic, but the location of the entrenched channels is stable. The number of channel forks normally exceed the number of channel joins and two or more split channels have separate outlets to a base-level stream or base-level plain.

The channels of stable distributary-flow areas are not braided as dipicted by the CofE (1990, p. 2.2). According to the CofE alluvial fans are composed of braided channels that are a network of interlacing channels with unstable bars and islands. The CofE further describes braided channels in reference to figures depicting alluvial fans (CofE, 1990, figure 2.2.1 and 2.1.4). Active alluvial fans appear to have braided appearing channels while stable distributary-flow areas have seperate channels that distinctly are not braided. Stable distributary channels commonly have distinct flood plains along "islands" that are drained by tributary channels. Some also have erosional terraces. Also, some distributary channel systems do not return to a single main channel but instead remain seperated.

The potential flood hazards of DFA's are more difficult to define than the potential flood hazards of tributary stream systems. The drainage-basin area from which floodflow at a

particular distributary channel emanates commonly cannot be accurately defined because the distribution of the wide-shallow flow at diffluences can change and cannot be determined precisely even for the more stable channels. Some DFAs are aggrading over large portions of the area while other DFAs have small areas of gradual aggradation. Other DFAs are stable or slightly eroding and some have a stable network of channels entrenched in Pleistocene material. Some DFAs have a single diffluence with only two distributary channels while other DFAs have no defined channels. Hydraulic processes are at work on the more stable DFAs where the transported sediment does not overwhelm the flow and the water-sediment mixture behaves like a Newtonian fluid. Debris flow processes are at work often in symphony with hydraulic processes on other DFAs where well-mixed hyperconcentrated masses of water and debris flow like wet concrete unconfined by physical constraints down DFAs. DFAs with debris flows and the absence of defined-stable flow paths fit the classic description of alluvial fans as depositional areas. Equally apparent, however, are a number of DFAs in central and southwestern Arizona with stable flow paths and relatively stable or even slightly eroding surfaces. Some alluvial fans in Arizona are not aggrading and the streams are eroding or have eroded into underlying cemented material.

APPENDIX B. COMMENTS ON THE USE OF SOIL CHARACTERISTICS

Differences in soil color on the piedmont that could depict DFA's commonly are revealed on orthophotoquad maps and color aerial photographs. Light-colored alluvium may represent recent deposition, and the reddish color of adjacent soils may be from many years of soil development where iron and other compounds oxidize giving the soil a reddish color. A blackish-appearing surface can be from varnished rocks that take hundreds to thousands of years to form. Dark surfaces commonly form the boundaries of DFA's and indicate the limits of riverine flooding and significant deposition. The lighter surfaces commonly delineate the DFA's. Light-colored ribbons of sediment mark washes that debouch into fan-shaped tentacles at DFA's.

The U.S. Soil Conservation Service has produced general soils maps (1:500,000 and 1:600,000) for the entire State of Arizona. Soils are grouped in mapping units consisting of a few dominant soils and several minor soils that form a recognizable pattern over broad areas (Torrance, 1969, p. 1). Because of the relatively small scale, these maps are useful in locating large geomorphic features (such as the piedmont plain and base-level flood plains), but the maps are not useful in locating specific areas subject to distributary flow. Such broad mapping units commonly contain soil characteristics of both old fans and DFA's.

The soil color of the areas of active flooding on the DFA's of most of the 39 sample sites studies by Hjalmarson and Kemna (1991) was distinctly lighter and less reddish than the soil color of surrounding less active areas. For some sites, a difference of soil color between areas of apparent active and inactive flooding was not distinct. For these sites, all soils appeared to be light tan or light yellow, and boundaries, if any, were difficult to distinguish. Color differences are especially difficult to distinguish at the toe of DFA's where the light-colored soils of the DFA commonly irregularly blend with light-colored soils of base-level plains. Some sites where floodflow appeared to frequently spread over much of the DFA had distinctly lighter-colored soils on the DFA than on the surrounding areas. Differences in soil color for the purpose of distinguishing areas of active and inactive flooding are best observed on color aerial photographs and from aerial reconnaissance. Dark-brown surfaces in central and southwestern Arizona could be a coating of desert varnish.

Desert varnish on stones of large noncohesive alluvial surfaces can be a reliable indication of the absence of significant floodflow during the past few thousand years. The age of rock varnish for 51 samples taken in Hawaii and the southwestern U.S. commonly was more than 2,000 years (Dorn and others, 1989, p. 1365). A dark-brown desert varnish on the surface of stones exposed to the atmosphere can indicate that the stones have been undisturbed for perhaps 3,000 to 5,000 years (Dorn and Oberlander, 1982). A black-surface stain indicates the absence of significant flood depths for perhaps 10,000 years or more. According to Dorn and Oberlander (1982), an arid varnish of blackish manganese-rich type takes many thousands of years to completely coat the tops of stones.

Areas with stones covered with dark desert varnish might have been covered occasionally with floodwater that did not significantly disturb the stones. Slow, shallow floodwater that inundated these dark-colored areas may not have had the energy to disturb the rocky surface. A surface

covered with larger darkly stained stones and unstained smaller stones may indicate the occasional occurrence of floodwater of sufficient energy to move only the smaller stones. The gradation of desert varnish, for example, is apparent along the distributary channels of French Creek near Quartzite (Hjalmarson and Kemna, 1991,site 7) where the ridges of the interfluves are blackish, the channels are light tan or whitish, and the side slopes between the channels and ridges appear to gradually darken toward the ridges.

Incipient sediment-motion relations for large rocks (Wang and Wen Shen, 1985) can be used to roughly estimate flow depths needed to move varnished rocks. For example, where channel slope equals 0.03, specific weight of water equals 62.4 lbs/ft^3, specific weight of rock equals 165 lbs/ft^3, and modified Shields parameter for large rocks equals 0.25, tractive force and critical diameter for incipient-motion equations show that the flow depth, in feet, for incipient motion is about 13.8 times the rock diameter, in feet. The observed gradation of varnished rocks at a few sample sites may be explained by incipient-motion relations like the above. The absence of smaller varnished rocks near the channels indicated that small rocks have been moved. The absence of small varnished rocks along the side slopes of distributary-flow channels, however, could be the result of (1) abrasive action of sediment in runoff or (2) small-stone movement by strong winds that are frequent in central and southwestern Arizona .

APPENDIX C: COMMENTS ABOUT DISTRIBUTARY-FLOW AREAS IN THE ARID SOUTHWESTERN UNITED STATES.

Many DFA's in Arizona have different characteristics than the alluvial-fans in Nevada and California studied by DMA Consulting Engineers (1985). The California and Nevada fans had apexes in steep canyons at mountain fronts (DMA Consulting Engineers, 1985). In Arizona, however, most fan apices (primary diffluence as used in this study) are downslope from the mountain front, commonly in the lower half of the piedmont plain (Hjalmarson and Kemna, 1991) like the fans with entrenched channels described by Bull (1977) and discussed previously in this paper. DFA's in Arizona, which could be the result of climatic changes, are relatively less active (Melton, 1965, p. 10) than DFA's in Nevada and California, which could be the result of tectonic activity (DMA Consulting Engineers, 1985; Dawdy, 1979). According to Cooley (1977), alluvial fans in Arizona also could , in part, be "the result of structural warping--unwarping of the uplands and mountainous regions and downwarping of adjacent lowlands and valley areas."

Apparently because of the differences between DFA's in central and southwestern Arizona , Nevada, and southern California, the flood hazards of DFA's in Arizona are poorly understood by some hydrologists and engineers. The ratio of the drainage area and area of the DFA is smaller for DFA's in southern Arizona than in Nevada and southern California (Hjalmarson and Kemna, 1991). Less floodflow occurs at the PD for the same size DFA's in southern Arizona than in Nevada or southern California. Apparently because of the smaller discharge intensities for DFA's in Arizona (flood-peak discharge at the PD divided by the DFA), the paths of floodflow tend to be more stable.

Bull (1977, p.226-227) and Harvey (1989, p.142-143) indicate that alluvial fans progressively become less active or more stable as erosion on the fan surface tends to offset deposition. According to Lustig (1969), the predominantly pediment landforms at the base of mountain ranges in central and southwestern Arizona are more stable than the predominantly alluvial-fan landforms at the base of the larger mountain ranges in central Nevada and parts of eastern California (figure C1). Lustig reports that the mountain ranges of central and southwestern Arizona are shorter, narrower, lower, and smaller than the mountain ranges of central and western Nevada and parts of eastern California. He attributes these differences to the different ages of the ranges of central and southwestern Arizona that have an older "relief age" or longer "time span since topographic expression was achieved" (Lustig, 1969, .p62). Alluvial fans are considered by geomorphologists and at least one engineer (the author) to be in various states of relative activity and in various states of progressive change.

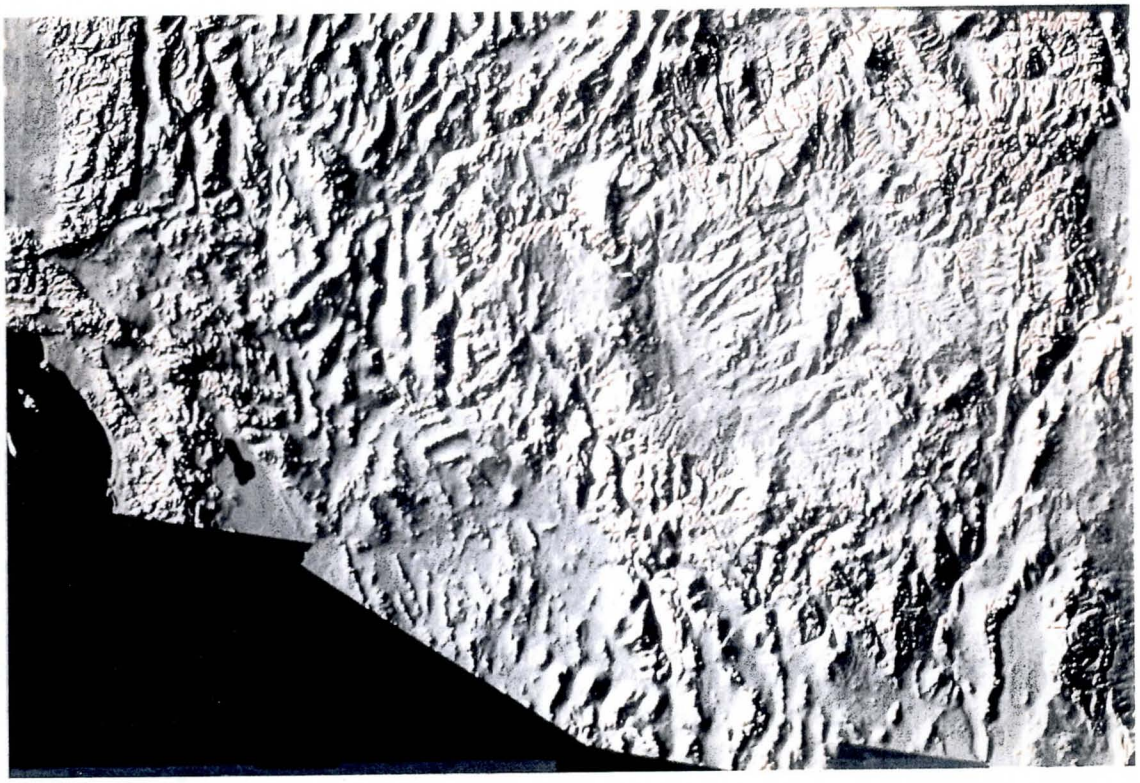


Figure C1 --Shaded- relief map of the southwestern United States showing the mountain-pediment-valley morphology of southern Arizona and the mountain-valley morphology of southeastern California and southern Nevada.

APPENDIX D: COMMENTS ON HYDRAULIC GEOMETRY

Dawdy (1979,p.1408) models the assumed overland flow on alluvial fans (condition he attributes to Lare and Eyster) by defining hydraulic geometry relations for the rectangular channel. The method by Dawdy is based on geomorphologic principles that were first presented for river channels by Leopold and Maddock (1953). Dawdy's method is based on the assumed overland flow condition with a rectangular channel and is based on the premise that the hydraulic geometry relations apply to the 100-year flood. While plots of channel width and depth for wide-flat alluvial channels commonly have a depth where dd/dw = -.005, the discharge corresponding to this depth commonly is much less than the 100-year flood. Thus, the assumption that the channel is rectangular and defined by dd/dw = -.005 is problematic. Dawdy (1979, p. 1412) also assumes "...that each flood event forms a single channel and flow remains in that channel throughout the event." Field evidence presented by DMA (1985) and in this paper does not support this last assumption.

The hydraulic geometry relations (presented previously in this paper) at a given cross section or at various cross sections along a stream for channel width, depth, and velocity are:

$$W = CwQ^b \qquad \text{(D1)}$$

$$D = CbQ^f \qquad \text{(D2)}$$

$$V = CvQ^m \qquad \text{(D3)}$$

The exponents of b = 0.4, f = 0.4, and m = 0.2 given by Dawdy (1979, table 1) are difficult to evaluate using indirect methods because (1) the discharge of the floodflow that formed the channels is unknown and (2) it appears that Dawdy's exponents are for a section and not a reach of channel for a discharge at a particular recurrence interval. The exponents at a particular location, however, can be computed and compared to the empirical and average values for the "at a station" relations by Leopold and Maddock (1953, p. 26) and Leopold and others (1964).

To test if the above hydraulic geometry equations apply to streams in Maricopa County cross sections of the stream channel were surveyed at the apexes (primary diffluences) of 13 alluvial fans where the floodflow is in a single channel (Hjalmarson, 1993, in press). The control for the reach at the PD's was the channel, and the cross sections commonly were in fairly uniform reaches. Using conveyance-slope methods, the exponents for the cross sections at each site were computed for the values of peak discharge of the 2-, 10-, and 100-year floods (Hjalmarson, 1993, in press). The mean values for the exponents of the sites were then computed for the 2-, 10-, and 100-year floods (table D1).

Table D1.--Empirical, average, assumed and computed hydraulic-geometry exponents for channel cross sections.

	Empirical values(1)		Average values(2)		Assumed values(3)	Computed values(4)		
Component	Cohesive bank material	Non-cohesive bank material	Ephemeral streams in south-western United States	Mid-western United States	Used for FEMA method	Average value for peak discharge at indicated recurrence interval		
						2-yr	10-yr	100-yr
Width	0.25	0.50	0.29	0.26	0.40	0.32	0.27	0.11
Depth	.43	.27	.36	.40	.40	.41	.44	.53
Velocity	.32	.23	.34	.34	.20	.27	.29	.36

(1) Leopold and others (1964, table 7-8).
(2) Leopold and others (1964, table 7-5).
(3) Dawdy (1979)
(4) Hjalmarson (1993, in press). Average exponents for 13 sites in Maricopa County, Arizona.

The method is limited because the channel geometry for the 2-, 10-, and 100-year floods is estimated by the surveyed cross sections when there was no flow. The differences between the geometry of the channels at the peak discharge of interest and at the time that the cross sections were surveyed is unknown. Small differences because of scour and fill during subsequent flow are considered likely.

The average of the exponents of the thirteen sites in Maricopa County for the 10-year flood (table D1) are similar to the exponents for the streams in the midwestern United States. The exponents of the 10-year flood for the sites in Maricopa County also are similar to the empirical exponents for cohesive bank material. The small differences are well within the potential error of the data because of the scatter of the width, depth, and velocity exponents for the sites. The computed average exponents for the 2-year flood also are similar to the exponents computed by Leopold and Maddock (1953).

The level of the 2-year flood was below the banks of the active channel as defined by several authors including Hedman and Osterkamp (1982). Because the active channel was difficult to define at the PD for several sites, it is uncertain if the level of the 10-year flood was below the top of the banks of the active channel. At most of the sites, however, much of the flow of the 10-year flood may be within the active channel.

The average exponents for the channel width, depth, and velocity for the 100-year flood are different than the exponents for the smaller floods (table D1). At all sites, the level of the 100-year flood was above what appeared to be the active channel but was below the top of the confining banks. At several of the sites, the level of the 100-year flood was above the small flood plains adjacent to the active channel. Hydraulic geometry equations for 100-year flood are different than the hydraulic geometry equations for the 2- and 10-year floods.

There appears to be no basis for assuming that hydraulic geometry relations with average exponents can be applied over a wide range of discharge. At many channels, the floodflow of the 100-year flood spreads over low terraces and other gently sloping land. For these channels, the width increases rapidly, and as reported by Leopold and Maddock (1953), the hydraulic relations are expected to be different.

The assumed overland flow condition used by Dawdy (1979) and defined by hydraulic geometry exponents (table D1) is not supported by data. The average hydraulic geometry exponents for alluvial fans in Maricopa County are different than those for a rectangular channel but are similar to the empirical exponents for a channel with cohesive bank material. The flow condition used by Dawdy and the assumption that channels are formed freely (non-cohesive bank material) are not supported in Maricopa County, Arizona.

The size and shape of the channels is related to the discharge and fluvial sediment characteristics. For two sites with similar sediment characteristics but different discharges, the shape of the channels will be similar but the size will be different.

The use of hydraulic geometry for alluvial channels implies a balance between the channel geometry, streamflow characteristics and fluvial sediment characteristics. It is well known that large floods change the channel geometry of ephemeral streams for many years. While these channels approach steady state in the absence of major floods, the imprint of rare events persists for many years. Judicious use of hydraulic geometry relations for ephemeral streams draining arid basins is suggested.

APPENDIX E.--MISCELLANEOUS CHANNEL CHARACTERISTICS

This appendix consists of three parts. First, a table of the capacity of the distributary channels at bank-full elevation. Second, plots of the cross sections that can be used for the hydraulic computations that were described briefly and third, a sample of the WSPRO (Shearman, 1990) output used for the conveyance-slope method. The cross sections are identified by the maximum elevation of the ridges at the ends of the particular cross section. Except at cross section 2084 the capacity of the channels far exceeds the discharge of 3,382 ft.^{3}/sec. for the 100-year flood at the PD. Cross section 2084 is in a reach where deposited sediment may be removed during large floods and the channel capacity may increase.

Table E1.--Approximate total capacity of the distributary channels at critical velocity.

Cross section (Max. elev., in ft)	Discharge, ft.^{3}/sec.
2122	5200
2108	6300
2090	7900
2084	3500
2078	7900
2074	8700
2064	6300
2054	9800
2040	5700
2030	7600
2020	14800
2000	8800
1980	19600
1970	25700
1962	14100
1954	15800
1946	20300
1938	13500
1924	11500
1914	8300
1900	11100

FEMA site 6A

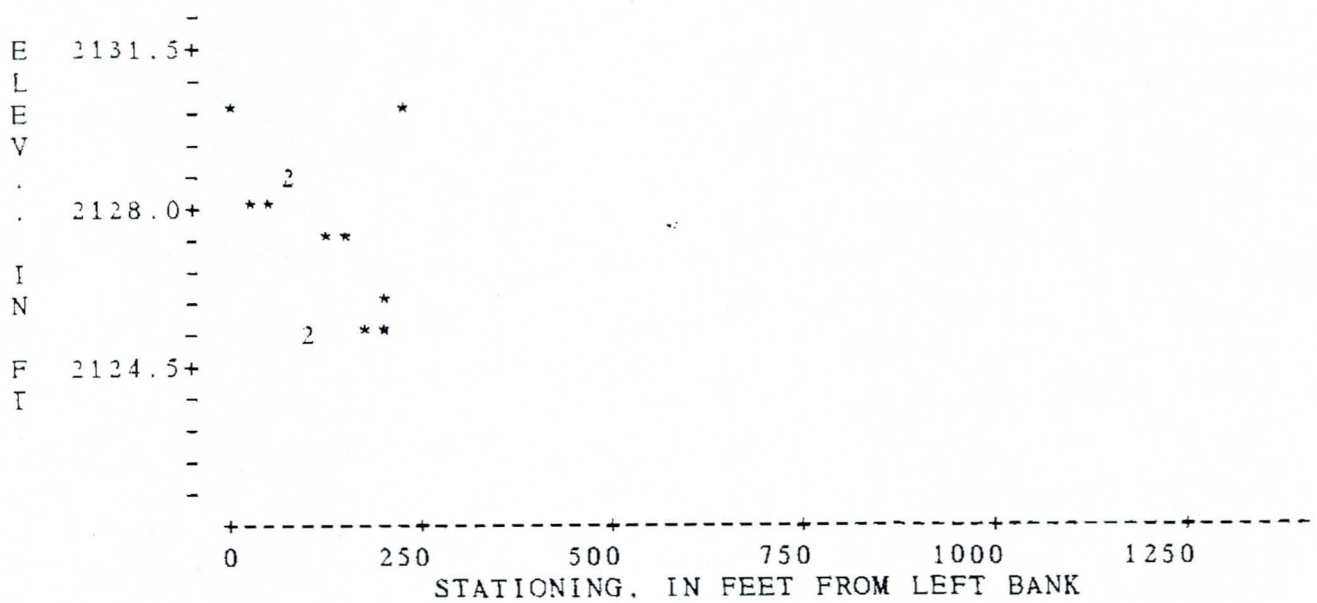


Figure .-- Cross section at 2130 ft. elevation

FEMA site 6A

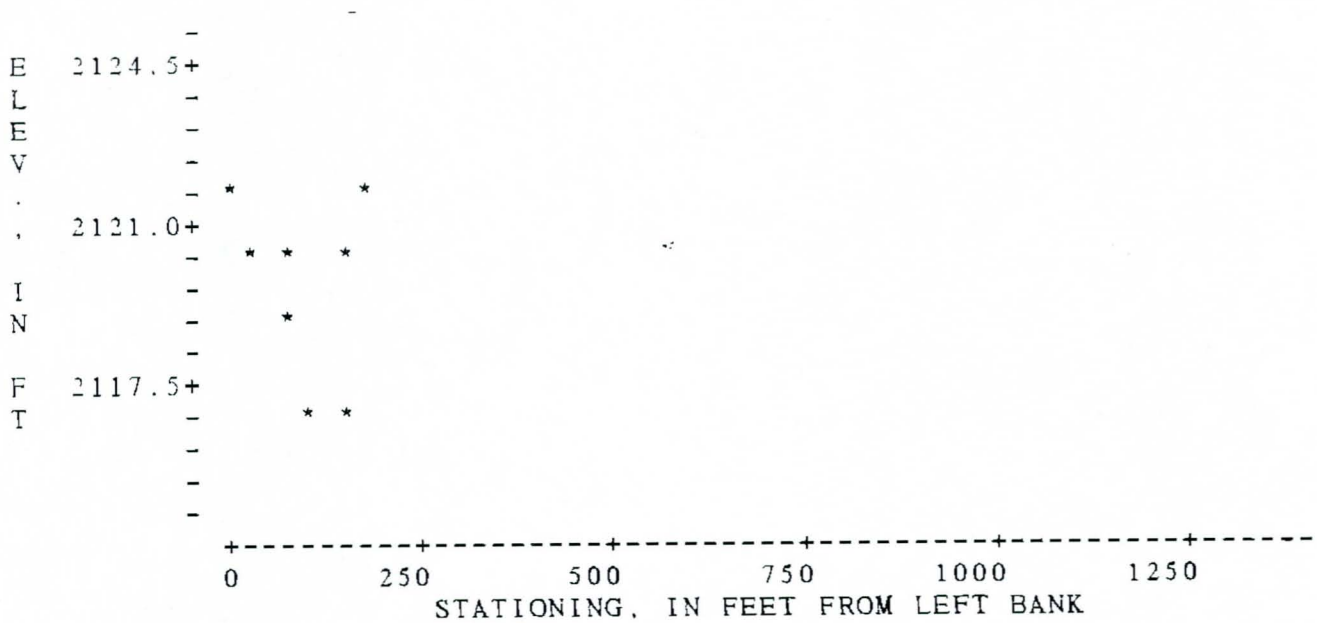


Figure .-- Cross section at 2122 ft. elevation

FEMA site 6A

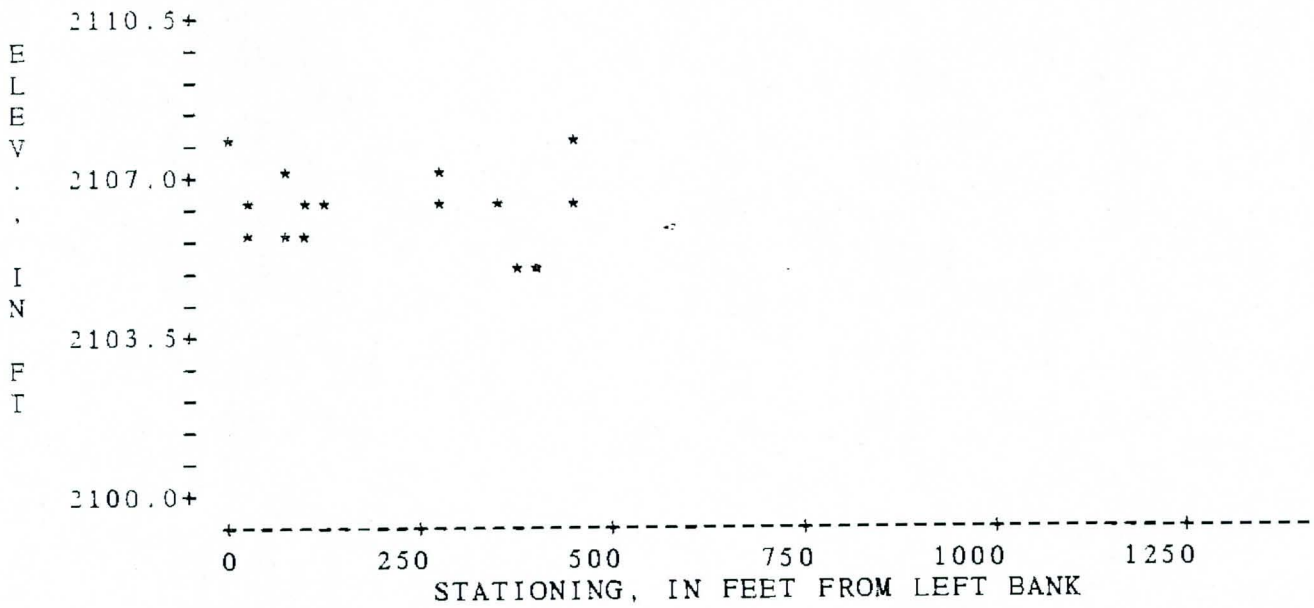


Figure .-- Cross section at 2108 ft. elevation

FEMA site 6A

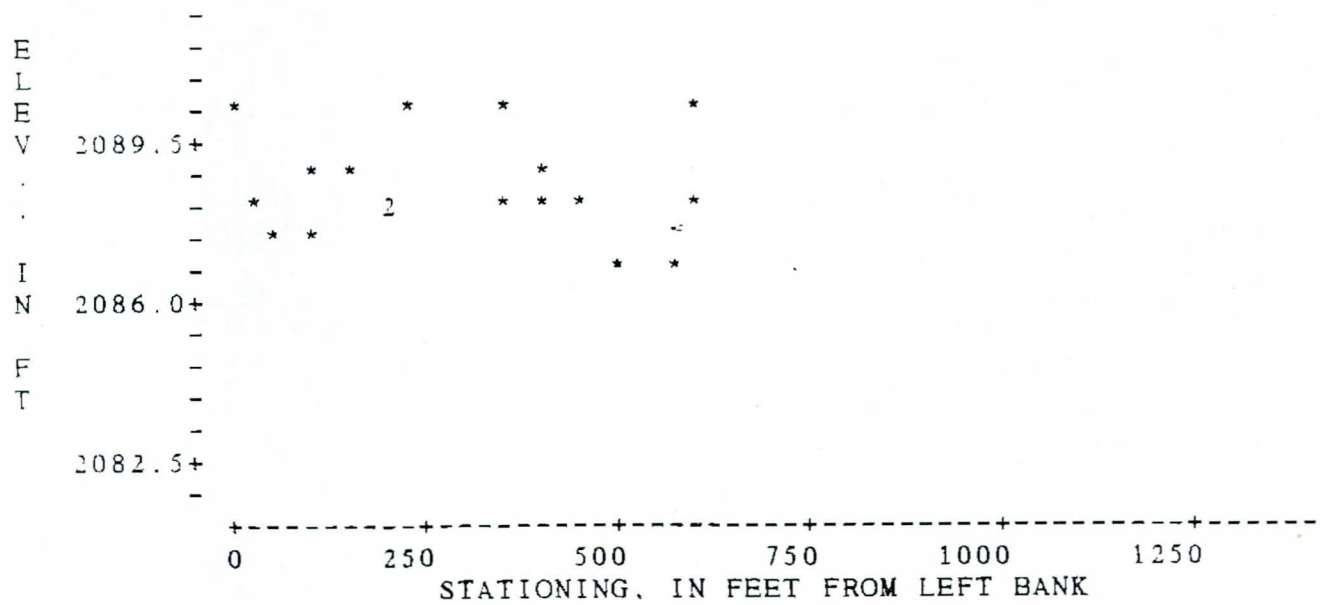


Figure .-- Cross section at 2090 ft. elevation

FEMA site 6A

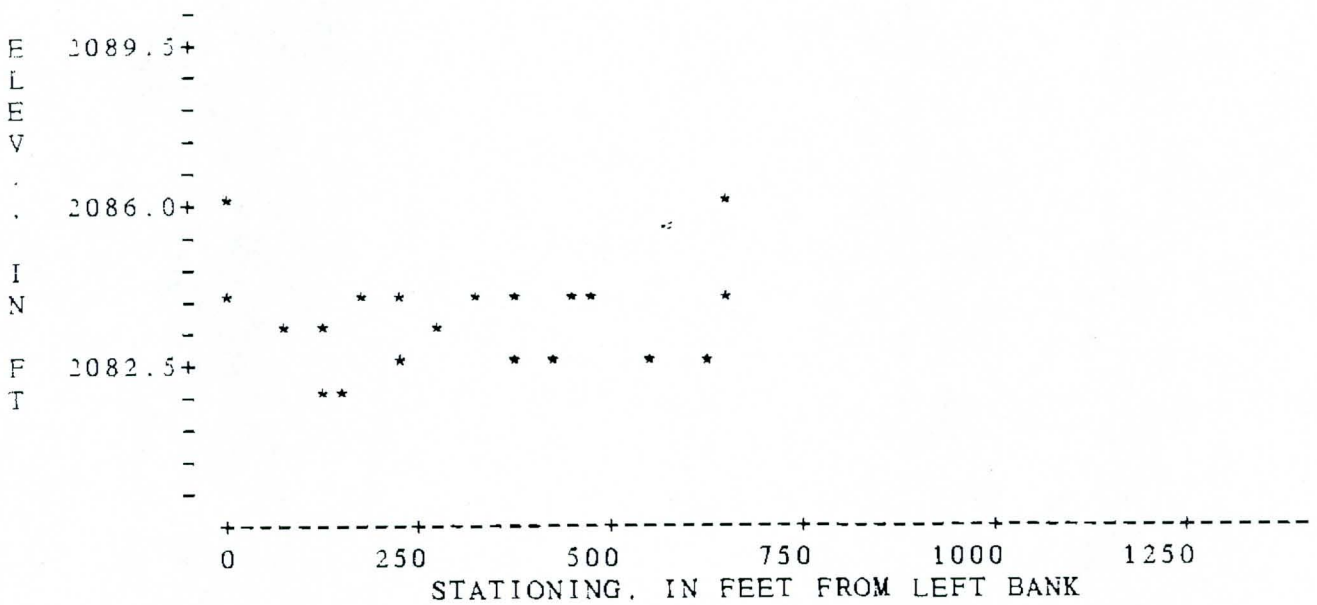


Figure .-- Cross section at 2084 ft. elevation

FEMA site 6A

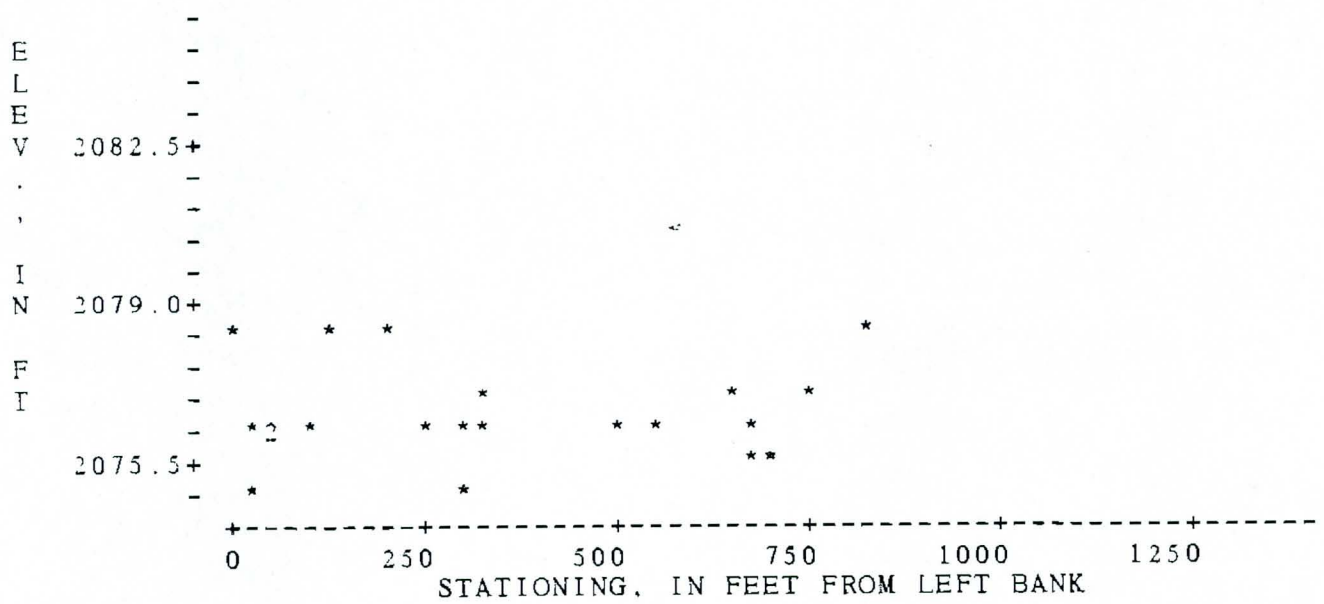


Figure .-- Cross section at 2078 ft. elevation

FEMA site 6A

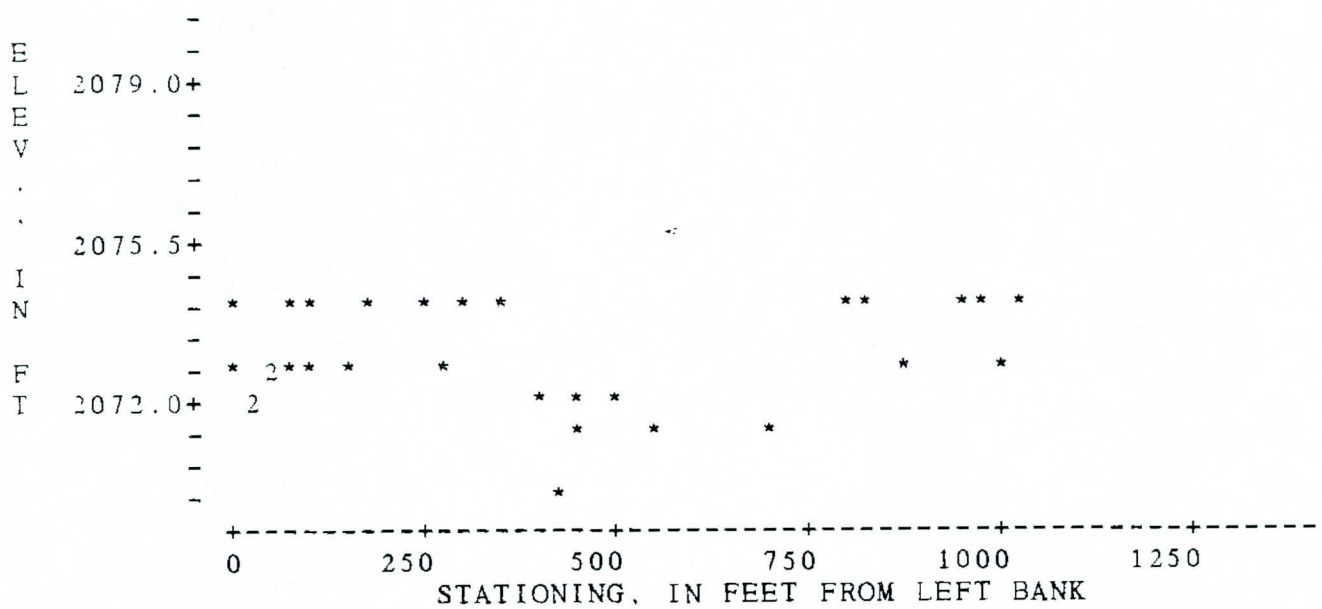


Figure .-- Cross section at 2074 ft. elevation

FEMA site 6A

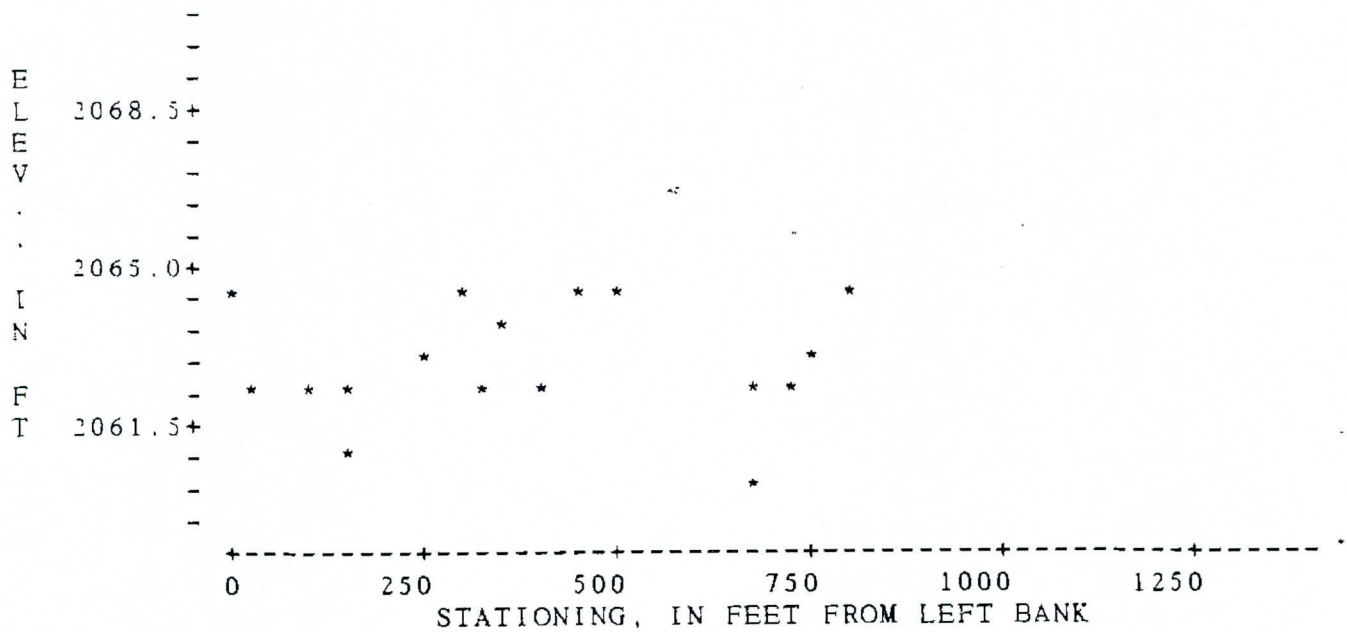


Figure .-- Cross section at 2064 ft. elevation

FEMA site 6A

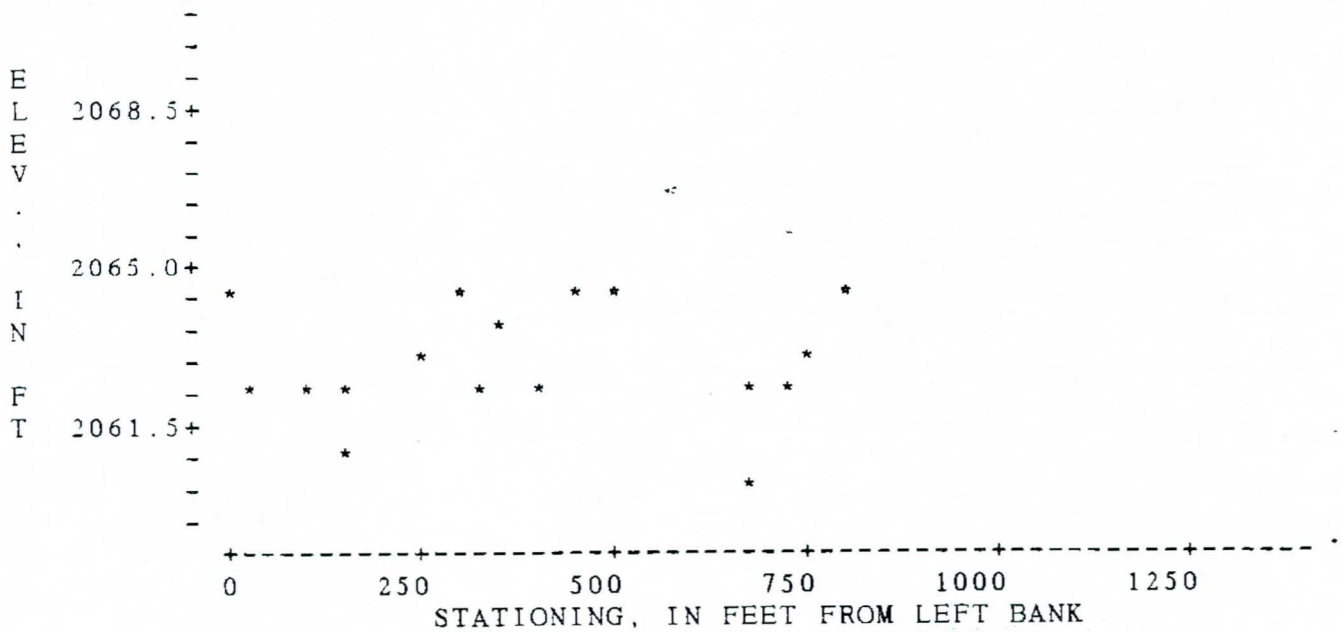


Figure .-- Cross section at 2064 ft. elevation

FEMA site 6A

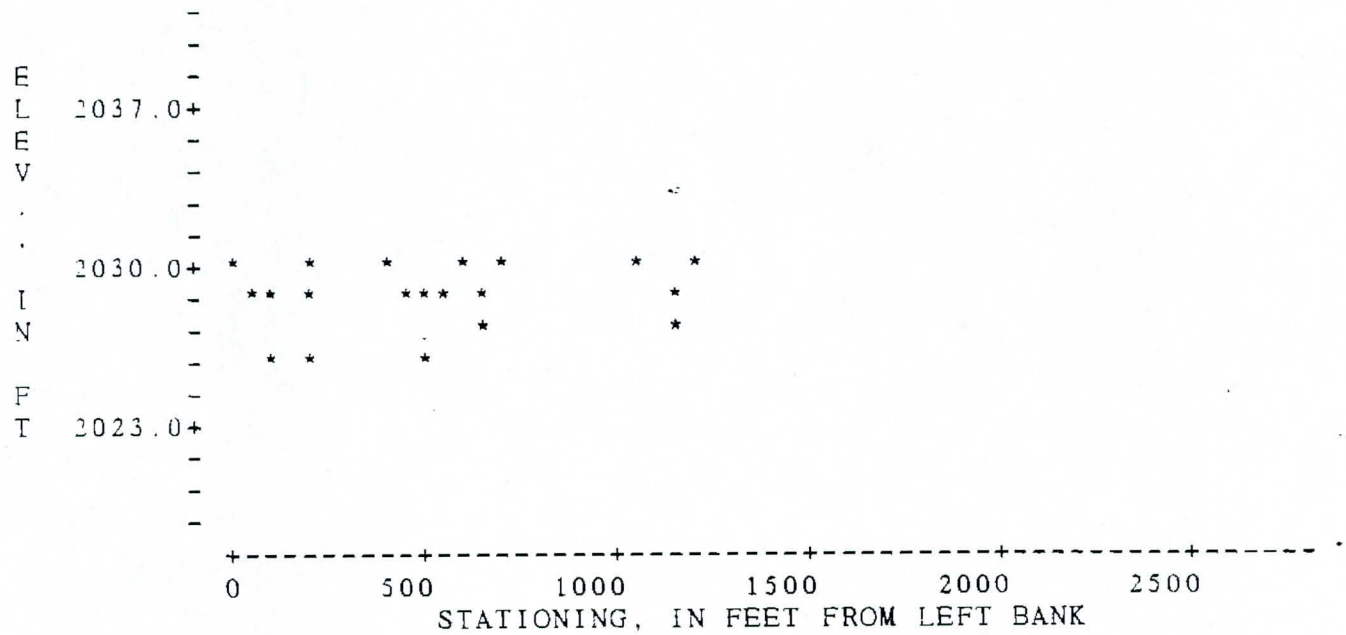


Figure .-- Cross section at 2030 ft. elevation

FEMA site 6A

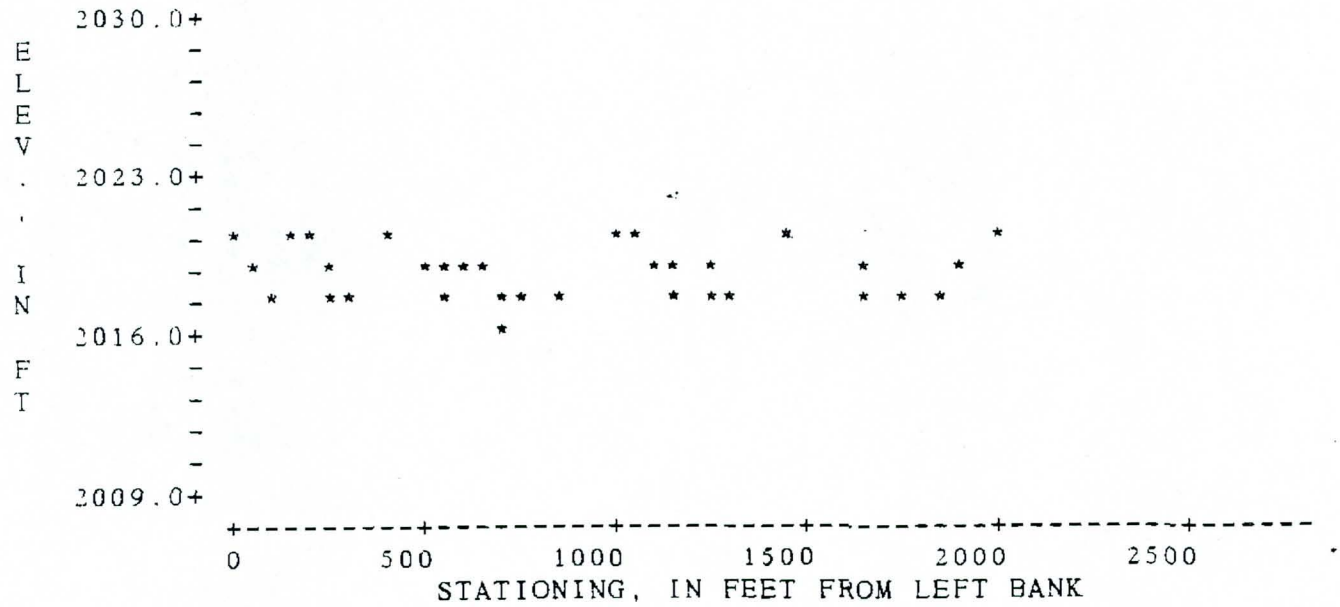


Figure .-- Cross section at 2020 ft. elevation

FEMA site 6A

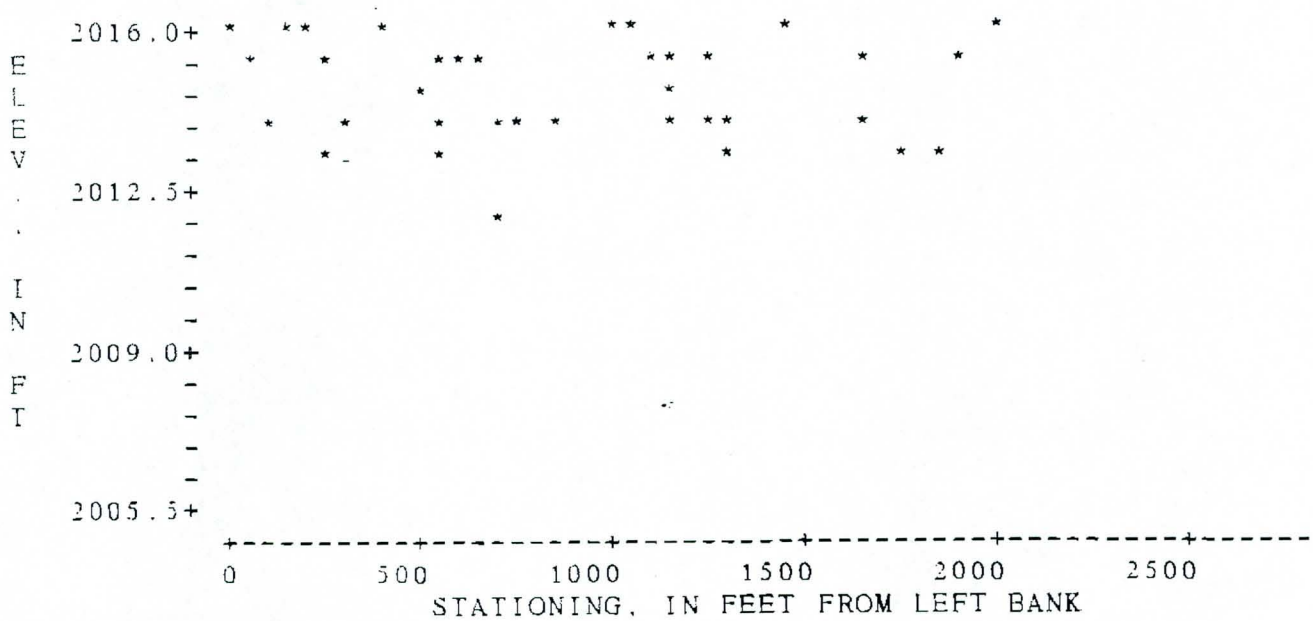
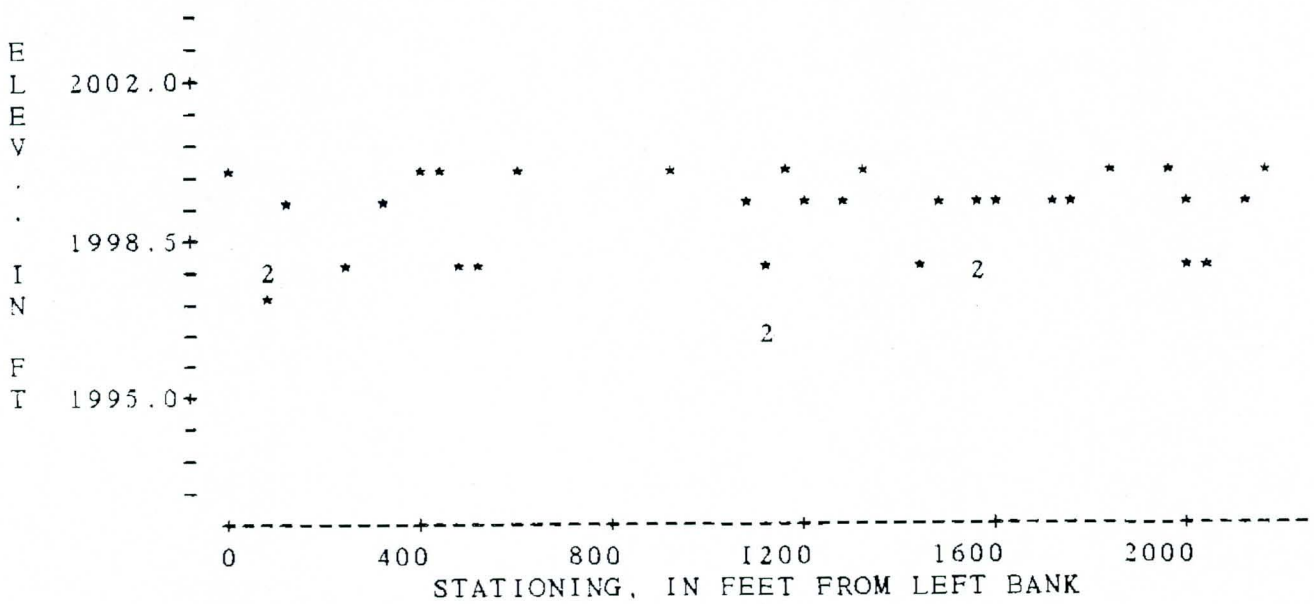


Figure .-- Cross section at 2016 ft. elevation

```
Y
MTB > STOP
*** Minitab Release 8.2 *** Minitab, Inc. ***
Storage available 16174

MTB > PLOT 'ELEV' VS 'STATION';
SUBC>   TITLE='Figure  .-- Cross section at 2000 ft. elevation';
SUBC>   TITLE=' '
* WARNING * Subcommand does not end in ; or . ( ; assumed ).
SUBC>   TITLE='FEMA site 6A';
SUBC>   XINCREMENT=250;
SUBC>   YINCREMENT=1;
SUBC>   YSTART =1993 2003;
SUBC>   XLABEL = 'STATIONING, IN FEET FROM LEFT BANK';
SUBC>   YLABEL = 'ELEV., IN FT'.
* Increment increased to cover range
* Increment increased to cover range


Y
                Figure  .-- Cross section at 2000 ft. elevation

                                FEMA site 6A
```




```
1 Points out of bounds          N* = 3
```

FEMA site 6A

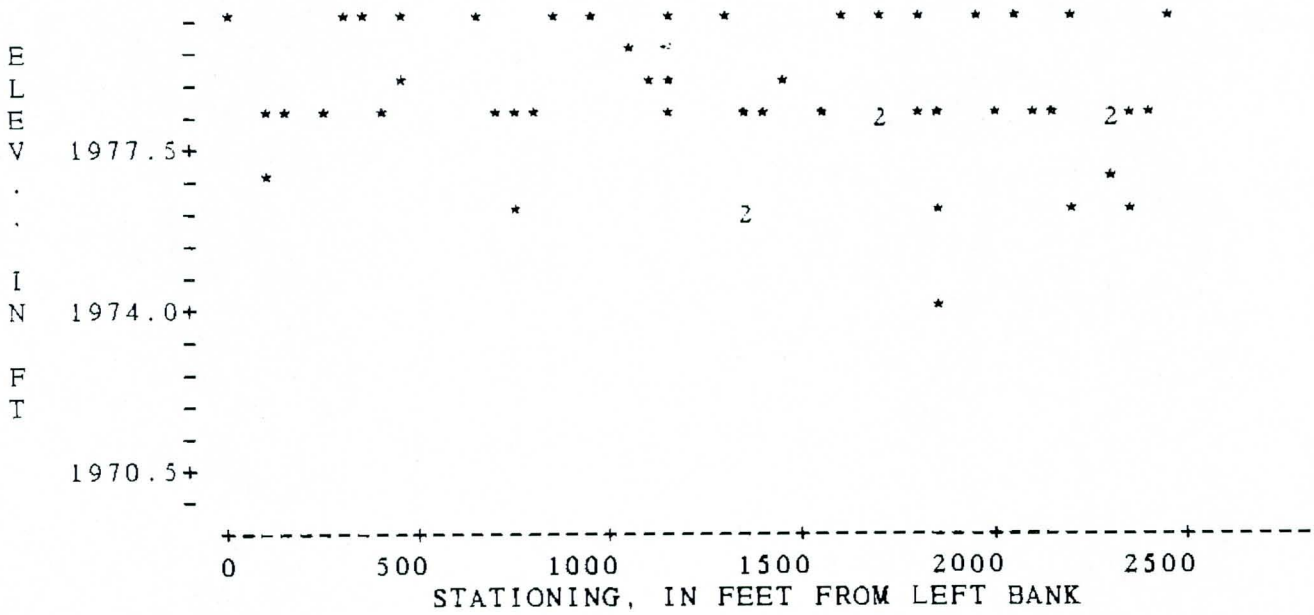


Figure .-- Cross section at 1980 ft. elevation

FEMA site 6A

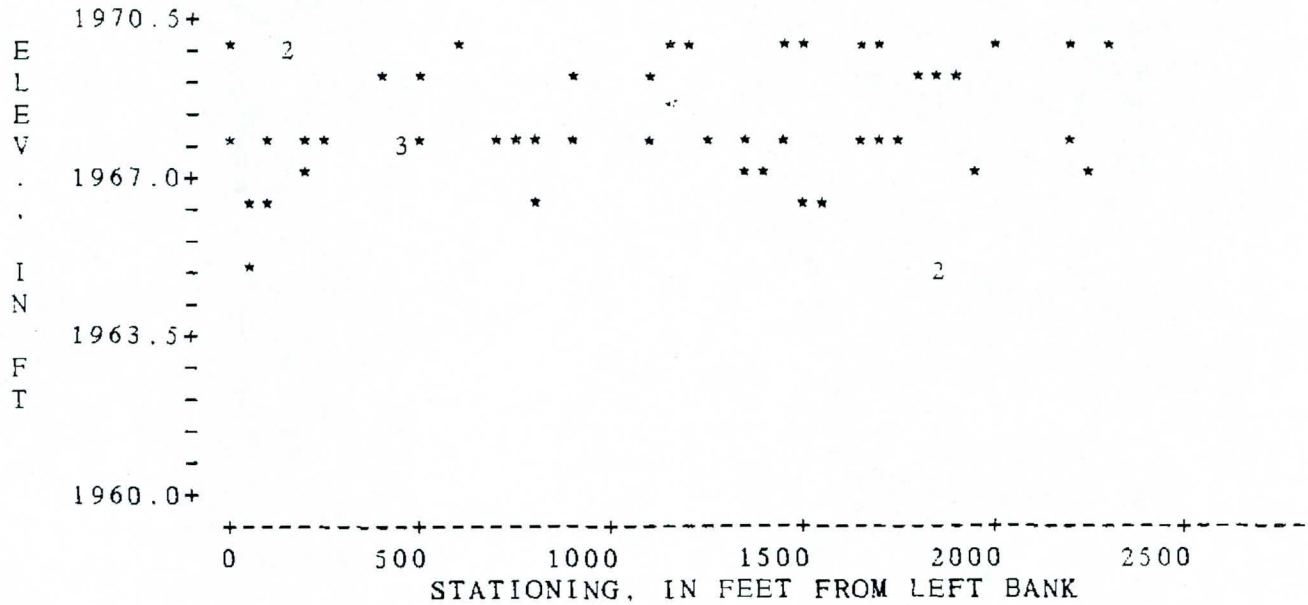


Figure .-- Cross section at 1970 ft. elevation

FEMA site 6A

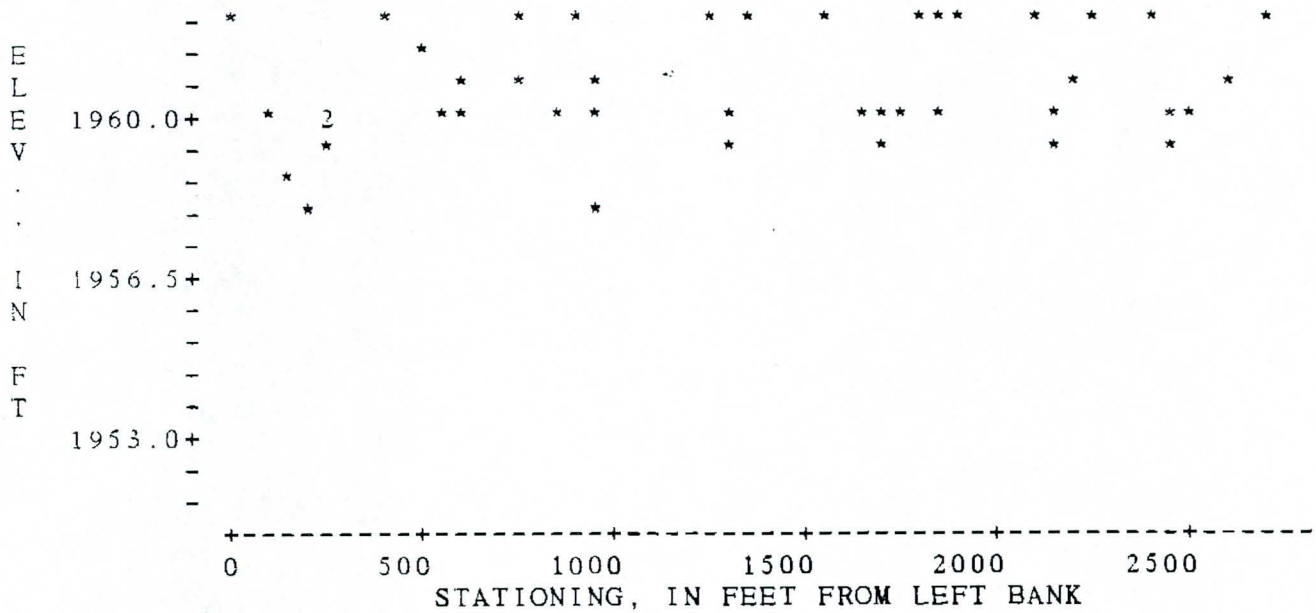


Figure .-- Cross section at 1962 ft. elevation

FEMA site 6A

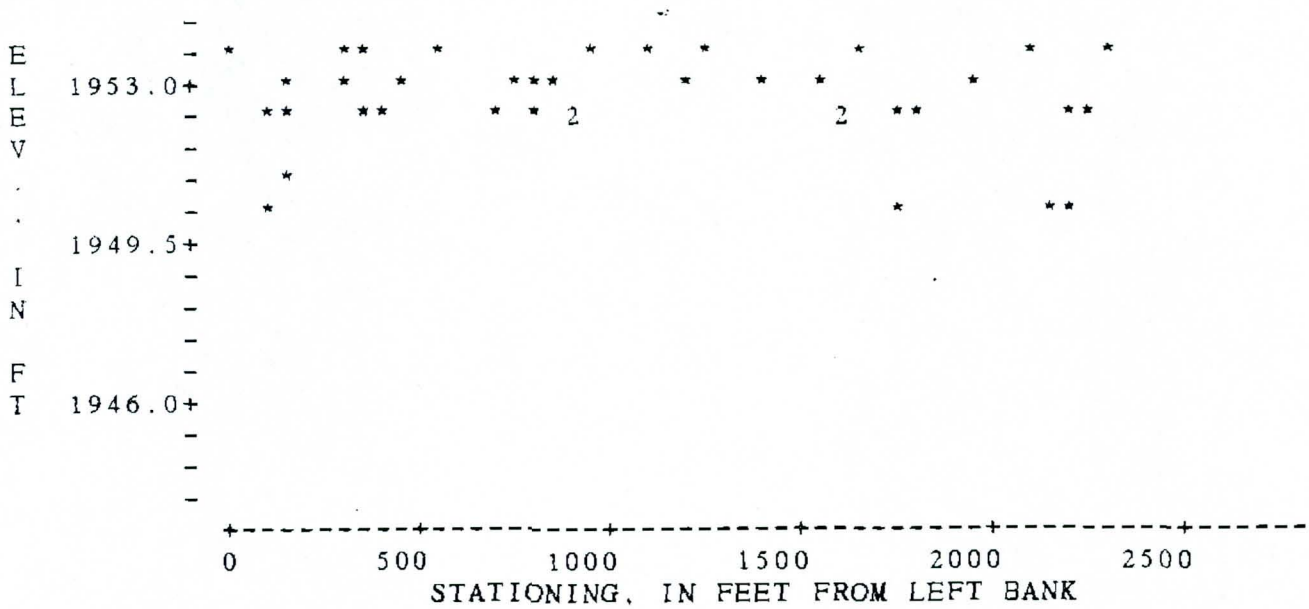


Figure .-- Cross section at 1954 ft. elevation

FEMA site 6A

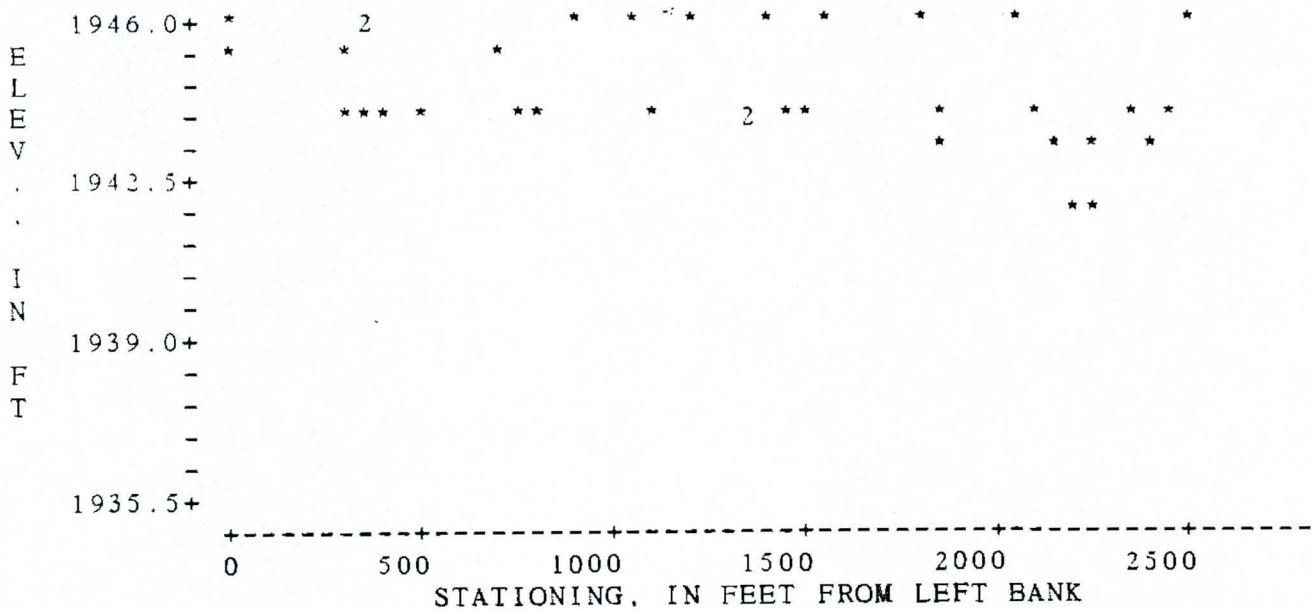


Figure .-- Cross section at 1946 ft. elevation

FEMA site 6A

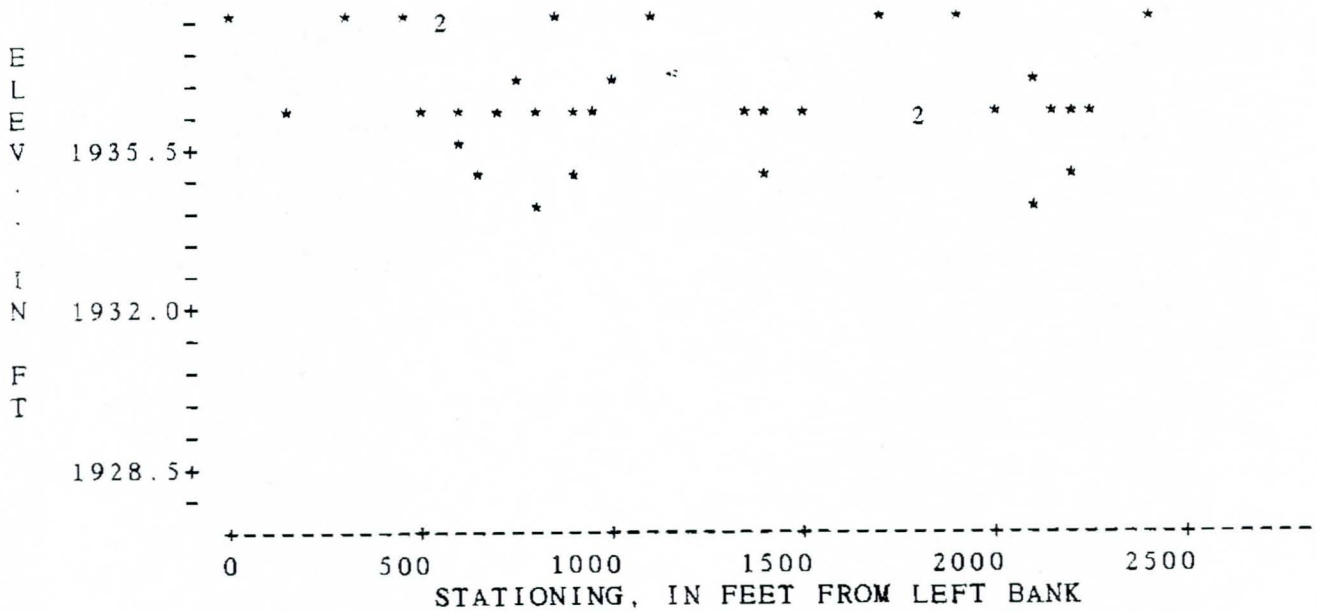


Figure .-- Cross section at 1938 ft. elevation

FEMA site 6A

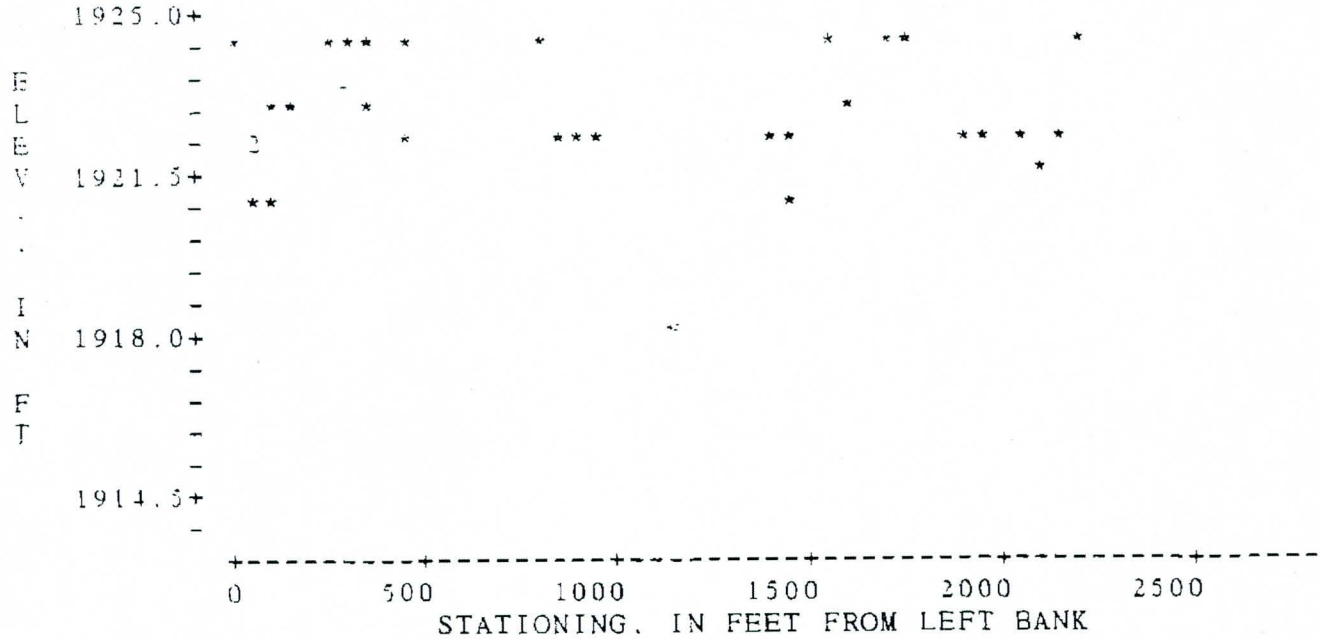


Figure .-- Cross section at 1924 ft. elevation

FEMA site 6A

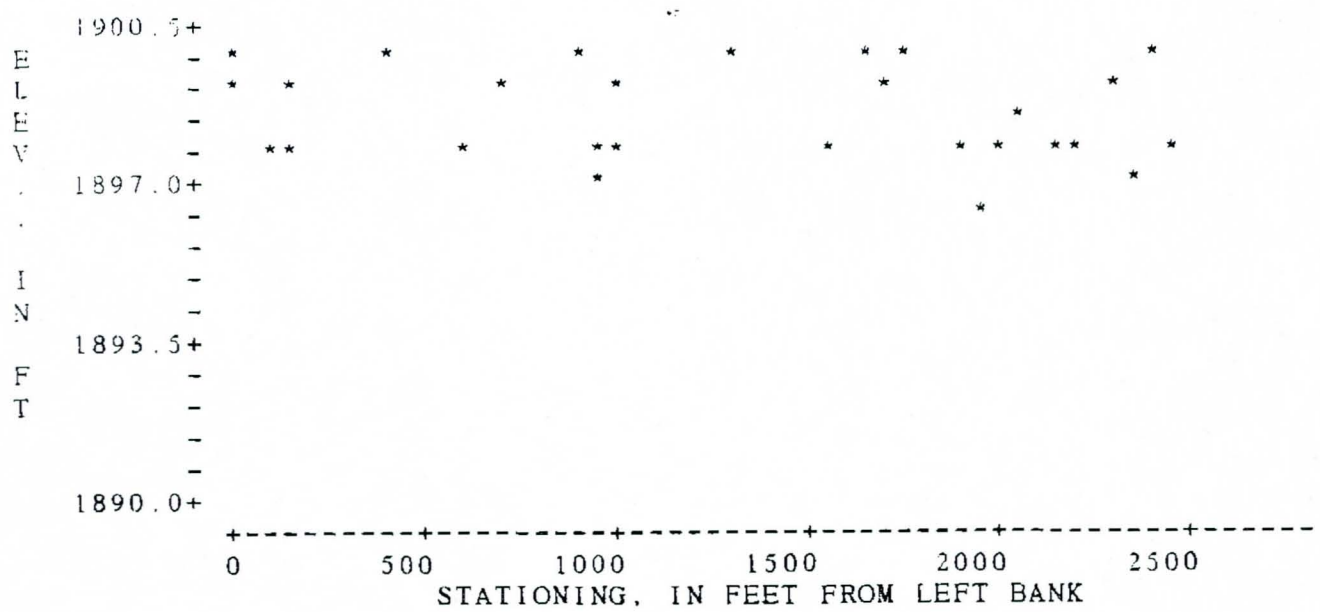


Figure .-- Cross section at 1900 ft. elevation

APPENDIX F(continued).
This is a sample of WSPRO output. See plot for section 1900 in this appendix. Also see plate 2, sheet 2 of this paper for the location of the cross sections. Comments have been inserted. Comments are at each channel (sub-area) corresponding to the discharge and water surface elevation. The hydrology was furnished by Joe Tram of the FCD.

```
1
 WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

             *** RUN DATE & TIME: 08-26-93  08:12

   T1         SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2

   T2         SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS

   T3         Q10=322  Q50 = 1831  Q100 = 3382   Q500 = 11709

   *

   Q            3382

 *** Q-DATA FOR SEC-ID, ISEQ =            1
   *

1
 WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
        SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
        Q10=322  Q50 = 1831  Q100 = 3382   Q500 = 11709
           *** RUN DATE & TIME: 08-26-93  08:12

 *** START PROCESSING CROSS SECTION - "X1900"
   XT   X1900 10000,0,0177

   GR         0,1900    20,1899    80,1898   160,1898   170,1899

   GR         400,1900   580,1898   720,1899   900,1900   940,1898

   GR         950,1897   980,1898  1000,1899  1300,1900  1530,1898

   GR         1670,1900  1700,1899  1770,1900  1900,1898  1950,1896

   GR         1990,1898  2070,1898.5 2130,1897.5 2170,1898  2300,1899

   GR         2370,1897  2380,1898  2400,1900

   *


 *** FINISH PROCESSING CROSS SECTION - "X1900"
 *** TEMPLATE CROSS SECTION "X1900" SAVED INTERNALLY.
1
 WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
        SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
        Q10=322  Q50 = 1831  Q100 = 3382   Q500 = 11709
```

```
*** START PROCESSING CROSS SECTION - "S1900"
  XS   S1900 10000

              COMMENT  The following are the roughness coefficients
                       and subdivision stations for the 8 channels or
                       sub-areas. The channel to the right is
                       ineffective and therfore was assigned a high
                       value of roughness coef.

  GT

  N          .040  .040    .040    .040    .040    .040 .040    5.040

  SA            400    900    1300   1670   1770   1990  2200

  *

  HP 1 S1900 1898...1,1899.9


*** FINISH PROCESSING CROSS SECTION - "S1900"
*** CROSS SECTION "S1900" WRITTEN TO DISK, RECORD NO. =  1

--- DATA SUMMARY FOR SECID "S1900" AT SRD =  10000.  ERR-CODE =      0

     SKEW      IHFNO     VSLOPE        EK        CK
       .0         0.      .0177       .50       .00

X-Y COORDINATE PAIRS  (NGP =  28):
       X       Y          X       Y          X       Y          X       Y
       .0 1900.00      20.0 1899.00      80.0 1898.00     160.0 1898.00
    170.0 1899.00     400.0 1900.00     580.0 1898.00     720.0 1899.00
    900.0 1900.00     940.0 1898.00     950.0 1897.00     980.0 1898.00
   1000.0 1899.00    1300.0 1900.00    1530.0 1898.00    1670.0 1900.00
   1700.0 1899.00    1770.0 1900.00    1900.0 1898.00    1950.0 1896.00
   1990.0 1898.00    2070.0 1898.50    2130.0 1897.50    2170.0 1898.00
   2300.0 1899.00    2370.0 1897.00    2380.0 1898.00    2400.0 1900.00

 X-Y MAX-MIN POINTS:
     XMIN       Y          X    YMIN      XMAX       Y          X    YMAX
       .0 1900.00    1950.0 1896.00    2400.0 1900.00         .0 1900.00

SUBAREA BREAKPOINTS (NSA =  8):
        400.    900.   1300.   1670.   1770.   1990.   2200.

ROUGHNESS COEFFICIENTS (NSA =  8):
         .040    .040    .040    .040    .040    .040    .040   5.040
1
WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2

        SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
        Q10=322  Q50 = 1831  Q100 = 3382   Q500 = 11709
           *** RUN DATE & TIME: 08-26-93  08:12
    CROSS-SECTION PROPERTIES:  ISEQ =  1;  SECID = S1900:  SRD =   10000.

           COMMENT          Output at 1898 ft. elev.  Q only in
                            channels(sub-areas) 3,6,7 and 8.  Channel
                            8 in ineffective because flow from this
                            DFA does not enter channel 8 on the right
                            side of the DFA
```

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
50 cfs from upstr. in 3rd channel. Elev = 1898.0(see plate 2)									
	3	20.	469.	40.	40.				80.
	6	90.	3350.	90.	90.				511.
	7	18.	259.	70.	70.				50.
	8	23.	4.	45.	45.				90.
1898.00		150.	4082.	245.	245.	1.64	940.	2380.	520.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	8.	65.	87.	87.				15.
	2	1.	6.	23.	23.				1.
	3	24.	604.	44.	44.				102.
	4	1.	5.	18.	18.				1.
	6	99.	3769.	96.	97.				572.
	7	26.	388.	105.	105.				74.
	8	27.	5.	49.	50.				115.
1898.10		187.	4843.	423.	424.	1.82	74.	2381.	524.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	17.	210.	94.	94.				42.
	2	5.	37.	46.	46.				8.
	3	29.	762.	48.	48.				127.
	4	4.	30.	37.	37.				7.
	6	109.	4233.	103.	103.				639.
	7	38.	606.	140.	140.				115.
	8	32.	7.	54.	54.				142.
1898.20		235.	5885.	522.	522.	1.91	68.	2382.	646.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
50 cfs fron upstream in channel 1. Elev = 1898.2(see plate 2)									
	1	27.	421.	101.	101.				80.
	2	10.	109.	69.	69.				23.
	3	34.	944.	52.	52.				155.
	4	8.	87.	55.	55.				18.
	6	120.	4743.	109.	110.				712.
	7	54.	949.	166.	166.				174.
	8	38.	8.	67.	68.				164.
1898.30		292.	7261.	620.	621.	1.91	62.	2383.	822.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	38.	693.	108.	108.				126.
	2	18.	234.	92.	92.				47.
	3	39.	1150.	56.	56.				186.
	4	15.	188.	74.	74.				38.
	6	131.	5302.	116.	116.				792.
	7	72.	1402.	188.	188.				251.
	8	46.	9.	85.	85.				192.
1898.40		359.	8978.	719.	719.	1.87	56.	2384.	1053.

1

WSPRO FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188 MODEL FOR WATER-SURFACE PROFILE COMPUTATIONS

SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
Q10=322 Q50 = 1831 Q100 = 3382 Q500 = 11709
*** RUN DATE & TIME: 08-26-93 08:12
CROSS-SECTION PROPERTIES: ISEQ = 1; SECID = S1900; SRD = 10000.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	49.	1024.	115.	115.				180.
	2	29.	425.	115.	115.				82.
	3	45.	1382.	60.	60.				221.
	4	23.	342.	92.	92.				66.
	6	143.	5910.	122.	123.				878.
	7	92.	1959.	210.	210.				343.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	61.	1415.	122.	122.				242.
	2	41.	691.	138.	138.				129.
	3	51.	1642.	64.	64.				260.
	4	33.	555.	111.	111.				103.
	6	156.	6571.	129.	129.				971.
	7	113.	2764.	210.	210.				467.
	8	66.	13.	120.	120.				281.
1898.60		521.	13651.	894.	894.	1.73	44.	2386.	1718.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	73.	1866.	129.	129.				312.
	2	56.	1042.	161.	161.				189.
	3	58.	1930.	68.	68.				302.
	4	45.	838.	129.	129.				152
1600 cfs in channels 6 and 7. Elev = 1898.7(see plate 2)									
	6	169.	7284.	135.	136.				1070.
	7	134.	3677.	210.	210.				604.
	8	79.	16.	137.	138.				342.
1898.70		614.	16652.	970.	971.	1.66	38.	2387.	2151.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	86.	2377.	136.	136.				391.
	2	74.	1487.	184.	184.				264.
	3	65.	2247.	72.	72.				349.
	4	59.	1196.	148.	148.				212.
	6	183.	8053.	142.	142.				1177.
	7	154.	4690.	210.	210.				752.
	8	94.	20.	155.	155.				415.
1898.80		715.	20070.	1047.	1047.	1.62	32.	2388.	2638.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	100.	2950.	143.	143.				477.
	2	93.	2036.	207.	207.				354.
	3	72.	2596.	76.	76.				399.
	4	75.	1638.	166.	166.				285.
	6	197.	8878.	148.	149.				1290.
	7	175.	5800.	210.	210.				910.
	8	110.	24.	172.	173.				501.
1898.90		824.	23922.	1123.	1124.	1.58	26.	2389.	3179.

1

WSPRO FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188 MODEL FOR WATER-SURFACE PROFILE COMPUTATIONS

SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
Q10=322 Q50 = 1831 Q100 = 3382 Q500 = 11709
*** RUN DATE & TIME: 08-26-93 08:12
CROSS-SECTION PROPERTIES: ISEQ = 1; SECID = S1900; SRD = 10000.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	115.	3586.	150.	150.				571.
	2	115.	2697.	230.	230.				461.
	3	80.	2976.	80.	80.				454.
	4	92.	2169.	185.	185.				371.
	6	212.	9762.	155.	155.				1412.
	7	196.	7001.	210.	210.				1079.
	8	128.	29.	190.	190.				599.
1899.00		940.	28221.	1200.	1200.	1.56	20.	2390.	3774.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	131.	4034.	175.	175.				645.
	2	139.	3449.	257.	257.				582.

	4	112.	2797.	203.	203.				471.
	5	0.	3.	10.	10.				1.
	6	228.	10707.	161.	162.				1540.
	7	217.	8292.	210.	210.				1256.
	8	147.	37.	191.	191.				735.
1899.10		1066.	32192.	1320.	1320.	1.57	18.	2391.	4331.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	150.	4610.	200.	200.				737.

600 cfs in 2nd channel. Elev = 1899.2(see plate 2)

	2	166.	4337.	284.	284.				722.
	3	102.	3036.	144.	144.				490.
	4	133.	3527.	222.	222.				585.
	5	2.	16.	20.	20.				4.
	6	245.	11713.	168.	168.				1676.
	7	238.	9669.	210.	210.				1442.
	8	167.	45.	192.	192.				881.
1899.20		1204.	36953.	1440.	1440.	1.58	16.	2392.	4962.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	171.	5314.	225.	225.				847.
	2	196.	5370.	311.	311.				883.
	3	118.	3383.	176.	176.				551.
	4	156.	4366.	240.	240.				715.
	5	4.	47.	30.	30.				10.
	6	262.	12782.	174.	175.				1820.
	7	259.	11129.	210.	210.				1637.
	8	186.	54.	193.	193.				1035.
1899.30		1354.	42446.	1560.	1560.	1.59	14.	2393.	5679.

1

WSPRO FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188 MODEL FOR WATER-SURFACE PROFILE COMPUTATIONS

SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
Q10=322 Q50 = 1831 Q100 = 3382 Q500 = 11709
*** RUN DATE & TIME: 08-26-93 08:12
CROSS-SECTION PROPERTIES: ISEQ = 1; SECID = S1900; SRD = 10000.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	195.	6151.	250.	250.				977.
	2	228.	6557.	338.	338.				1066.
	3	138.	3888.	208.	208.				635.
	4	181.	5321.	259.	259.				860.
	5	8.	102.	40.	40.				20.
	6	280.	13917.	181.	181.				1972.
	7	280.	12670.	210.	210.				1839.
	8	205.	63.	194.	194.				1198.
1899.40		1515.	48667.	1680.	1680.	1.59	12.	2394.	6488.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	221.	7124.	275.	275.				1126.
	2	264.	7906.	365.	365.				1271.
	3	160.	4544.	240.	240.				741.
	4	208.	6395.	277.	277.				1022.
	5	12.	184.	50.	50.				35.
	6	298.	15118.	187.	188.				2133.
	7	301.	14289.	210.	210.				2050.
	8	225.	73.	195.	195.				1368.
1899.50		1689.	55634.	1800.	1800.	1.58	10.	2395.	7392.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	250.	8241.	300.	300.				1294.
	2	301.	9427.	392.	392.				1500.
	3	185.	5353.	272.	272.				869.

1082 cfs in channel 4. Elev = 1899.6(see plate 2).

	5	18.	300.	60.	60.				56.
	6	317.	16388.	194.	194.				2301.
	7	322.	15986.	210.	210.				2267.
	8	244.	84.	196.	196.				1547.
1899.60		1875.	63375.	1920.	1920.	1.57	8.	2396.	8395.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	281.	9507.	325.	325.				1484.
	2	342.	11127.	419.	419.				1753.
	3	214.	6322.	304.	304.				1021.
	4	267.	8929.	314.	314.				1398.
	5	24.	452.	70.	70.				82.
	6	337.	17728.	200.	201.				2478.
	7	343.	17758.	210.	210.				2492.
	8	264.	95.	197.	197.				1733.
1899.70		2073.	71918.	2040.	2040.	1.56	6.	2397.	9502.

1

WSPRO FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188 MODEL FOR WATER-SURFACE PROFILE COMPUTATIONS

SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
Q10=322 Q50 = 1831 Q100 = 3382 Q500 = 11709
*** RUN DATE & TIME: 08-26-93 08:12
CROSS-SECTION PROPERTIES: ISEQ = 1; SECID = S1900: SRD = 10000.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	315.	10930.	350.	350.				1695.
	2	385.	13015.	446.	446.				2032.
	3	246.	7457.	336.	336.				1197.
	4	300.	10399.	333.	333.				1612.
	5	32.	646.	80.	80.				115.
	6	357.	19139.	207.	207.				2663.
	7	364.	19604.	210.	210.				2724.
	8	284.	106.	198.	198.				1926.
1899.80		2283.	81296.	2159.	2160.	1.55	4.	2398.	10714.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	351.	12516.	375.	375.				1928.
	2	431.	15100.	473.	473.				2336.
	3	281.	8767.	368.	368.				1397.
	4	334.	12012.	351.	351.				1846.
	5	40.	885.	90.	90.				154.
	6	378.	20623.	213.	214.				2857.
	7	385.	21522.	210.	210.				2963.
	8	303.	119.	199.	199.				2126.
1899.90		2505.	91543.	2279.	2280.	1.53	2.	2399.	12038.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	351.	12524.	375.	375.				1929.
	2	431.	15110.	473.	473.				2338.
	3	282.	8774.	368.	368.				1398.
	4	334.	12020.	352.	352.				1847.
	5	41.	886.	90.	90.				154.
	6	378.	20630.	214.	214.				2858.
	7	386.	21532.	210.	210.				2964.
	8	304.	119.	199.	199.				2127.
1899.90		2506.	91596.	2280.	2281.	1.53	2.	2399.	12044.

1

*

HP 1 S1900 1898.96,1.5,1900

1

SITE 6A OR SOUTH CHANNEL(LEFT) OF USGS SITE 2
SECTIONS MOSTLY FROM TOPO MAPS @ 1 IN.=200 FT., 2 FT. CONTOURS
Q10=322 Q50 = 1831 Q100 = 3382 Q500 = 11709
*** RUN DATE & TIME: 08-26-93 08:12
CROSS-SECTION PROPERTIES: ISEQ = 1; SECID = S1900; SRD = 10000.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	109.	3325.	147.	147.				533.
	2	106.	2420.	221.	221.				417.
	3	77.	2821.	78.	79.				432.
	4	85.	1946.	178.	178.				335.
	6	206.	9403.	152.	152.				1362.
	7	188.	6512.	210.	210.				1010.
	8	121.	27.	183.	183.				558.
1898.96		893.	26455.	1169.	1170.	1.57	22.	2390.	3531.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	390.	14282.	400.	400.				2185.
	2	480.	17400.	500.	500.				2669.
	3	320.	10270.	400.	400.				1624.
	4	370.	13782.	370.	370.				2100.
	5	50.	1173.	100.	100.				201.
	6	400.	22189.	220.	220.				3061.
	7	407.	23522.	210.	210.				3210.
	8	323.	132.	200.	200.				2334.
1900.00		2740.	102749.	2400.	2401.	1.52	0.	2400.	13482.

1

The capacity at bank full is about 13482-2334=11148 cfs or 3.3 times the discharge of the 100-year flood.

End of cross section 1900.

Note: The tables and figures of this appendix are numbered independent of the report and are not given in the list of illustrations or the list of tables.

APPENDIX F.--PRACTICAL HYDRAULIC METHODS FOR DEFINING FLOOD BOUNDARIES OF DISTRIBUTARY-FLOW AREAS WITH STABLE FLOW PATHS

Suggested practical methods to compute flow entering distributary channels at diffluences for both critical and subcritical flow velocities are defined. Conveyance-slope methods are used to compute water level at channel cross sections located at elevation contours that represent hydraulic conditions of channel reaches. A method to compute channel conveyance and define flood boundaries across stable distributary-flow areas is also defined and compared to a second method that is commonly used for riverine hydraulics. These channel conveyance-slope methods are based on Manning's equation and incorporate detailed channel subdivision to account for (1) the separated flow and (2) the well known interaction between the main channel(s) and floodplains associated mostly with differences in velocity head across the DFA.

The water-surface profile computation model (WSPRO) developed by Jim Shearman of the U. S. Geological Survey has been used satisfactorily to define the distribution of flood discharge in numerous channels across DFAs. The model is for one-dimensional, gradually-varied, steady flow in open channels where up to 20 subareas of discharge can be computed. Although not anticipated for many distributary-flow areas, the model can be used to analyze flow through culverts and bridges, embankment overflow, and multiple-opening stream crossings. WSPRO allows for differences in roughness coefficients with depth of flow and subarea. The reliable use of the conveyance-slope option of WSPRO is dependent on the proper location and subdivision of cross sections.

Distributary flow can be in channels and adjacent floodplains or become widely separated in defined channels and remain separated in defined channels. For the systematic definition of channel cross sections the author suggests that cross sections for channel conveyance computations be located along topographic contours especially where topography is mapped in detail. Cross sections located at contours are at the same reference level across the DFA and floodflow will, on the average, be perpendicular to the contours. Proper subdivision along the cross sections is also very important to define the distribution of discharge at diffluences and across DFAs. Where flow is not separated by high ridges or islands, it is well known that wide-shallow floodplains should be subdivided from the main channel to account for differences in velocity across the channel.

The velocity-distribution coefficients are described by Chow (1959, p. 27) for a channel section as follows: As a result of nonuniform distribution of velocities over a channel section, the velocity head of an open-channel flow is generally greater than the value computed according to the expression $V^2/2g$, where V is the mean velocity. When the energy principle is used in computation, the true velocity head may be expressed as $\alpha V^2/2g$, where α is known as the *energy coefficient*.

If the flow in the floodplain and main channel of a compound channel are computed separately the sum of the separate discharges will overestimate the true discharge. Likewise, if the flow is in multiple channels that are separated by high ridges, the subarea method that computes a single alpha for a single compound channel will underestimate the true discharge. Because flow across many DFAs is in both separate and compound channels, proper subdivision is necessary and several conveyance-slope computations across the DFA may be required.

Some practical methods of using the conveyance-slope technique are given in three examples. The computation of separated discharges at a diffluence where flow velocities are critical (example 1) and subcritical (example 2) is described. The proper location of cross sections across DFAs is described in the third example. Thomsen and Hjalmarson (1991) discuss the subdivision of several cross sections found in Maricopa County, Arizona and Davidian (1984) discusses subdivision and the proper division of flow into separated channels. Defined flood boundaries are shown in a forth example and the results are briefly compared with the approximate flood insurance zones of the FEMA Alluvial Fan Method.

Example 1.

Where the channel in which the flood boundaries are being computed divides into two or more channels that are separated such that the flow paths are considered different, each path (distributary channel) must be handled as a separate channel. For example, in figure 1, step 1 the total discharge (Q_T) is split into two separate components (Q_A and Q_B). The conveyance-slope technique uses normal depths and greatly simplifies the computation of Q_A and Q_B because the energy components between cross section are not balanced. The problem is to determine the separated discharges (Q_A and Q_B) and to define the probable boundary at the diffluence cross section (Figure 1, step 2) by properly selecting the location of the diffluence cross section (Figure 1, step 3) where Q_A and Q_B are computed.

Note
The 100-year flood is confined to the main channel and adjacent flood plain at the diffluence cross section.

Each channel below the diffluence can be calibrated by establishing a stage-discharge relation for the diffluence cross section. The author prefers to use WSPRO to generate a rating table for the diffluence section using normal depth computations. The diffluence section is selected just upstream where flow separation occurs and the water surface elevation is the same across the channel. The boundary between the channels is estimated and projected upstream to the diffluence. Flow to the left of the boundary enters channel A and flow to the right enters channel B (Figure 1). The cross section geometry at the diffluence is next defined (See figure 2 and table 1, part a).

The WSPRO input instruction for example 1 includes a conveyance-slope computation at the 100-year discharge of 523 cfs and a channel slope of 0.022 (SK line). The computed Froude No. generated by the program was 1.01 for this condition (see part b2 of table 1). Critical flow conditions (Froude No. = 1) are used with the computation instruction given on line HP (part b1, table 1) to produce tables of cross-section properties and (or) velocity and conveyance distribution. The HP instruction represents the 2nd or "precise" instruction with 0.01 ft. increments of stage following an initial instruction (not shown) using 0.1 ft. increments of stage.

The values of discharge for channels A and B are determined using the "WSPRO rating table" for the diffluence (part b1, table 1). At a water surface elevation (WSEL) of 15.31 ft. the total discharge is 525 cfs or almost equal to Q100 of 523 cfs. Computed values in the left and right subareas are 280 and 246 cfs, respectively. The value of Q_A = 278 cfs and Q_B = 245 cfs are determined using a simple ratio adjustment (part b1 of table 1).

The flood boundaries along channels A and B are next estimated based on critical velocity and/or conveyance-slope computations and estimates for each channel (figure 3). The conveyance-slope computations for channels A and B were computed separately using the conveyance and slope for each channel (part A of figure 3). The flood boundaries are estimated from the computed water levels at the cross sections and the topography (part B of figure 3).

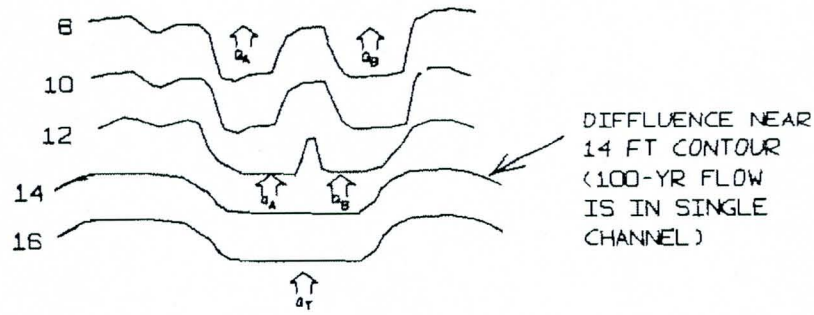
The division of flow into channels A and B is based on the technique by Davidian (1984, p. 32). The cross section for the diffluence is located upstream from the branches and the approximate division of flow is estimated (step 2 of figure 1). The upstream section is subdivided at the division of flow and the division of Q_T into components Q_A and Q_B is based on the portion of channel conveyance to the left and right of the division line. It should be noted that the upstream section is shown at the branch or upstream end of the island by Montalvo (1982, p.III-1). The author feels that some separation of flow commonly will occur upstream of Montalvo's section and the common water surface elevation is located upstream as shown by Davidian (1984). Thus, the "diffluence section" is located where the flow starts to split and the water surface elevation for the separated channels can become different.

Example 2

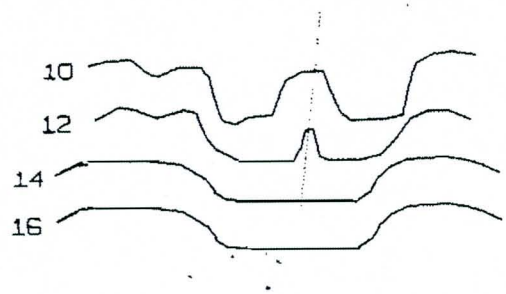
This example is for the same conditions of example 1 except the slope is subcritical. The slope of 0.022 is changed to 0.01 on the WSPRO input instruction for this example (see part a, table 2). The computed Froude No. generated by the program was 0.71 at a dicharge of 523 cfs (see part b, table 2). Channel conveyance conditions (Froude No. < 1) are at a water surface elevation of 15.55 ft. The computation sequence for subcritical flow velocities is nearly identical to the sequence for critical flow velocities except as follows:

GIVEN: DETAILED TOPOGRAPHIC MAP (A PORTION AT A DIFFLUENCE IS SHOWN BELOW).

STEP 1.--IDENTIFY DIFFLUENCE AND CHANNELS ON DETAILED TOPOGRAPHIC MAP



STEP 2.--DEFINE THE PSUEDO-BOUNDARY BETWEEN THE TWO CHANNELS AND PROJECT THE BOUNDARY UPSTREAM TO THE DIFFLUENCE.



STEP 3.--DEFINE THE CROSS SECTION AT THE DIFFLUENCE. SEE FIGURE 2 FOR DETAIL.

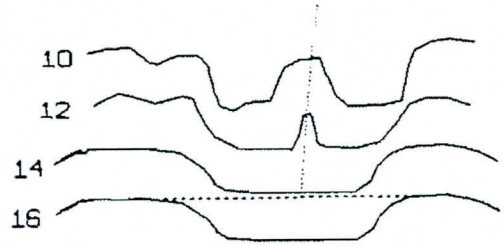
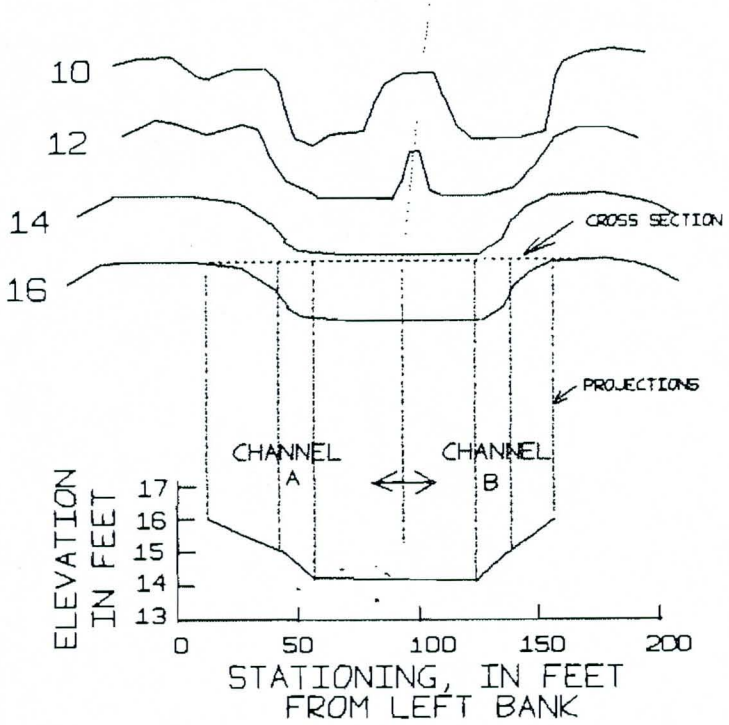


FIGURE 1.--DIVISION OF FLOW AT A DIFFLUENCE.

PORTION OF TOPOGRAPHIC MAP FROM FIGURE 1.



CROSS SECTION AT DIFFLUENCE SHOWING PSEUDO DIVISION OF FLOW TO CHANNELS A AND B.

FIGURE 2.--CROSS SECTION AT DIFFLUENCE FROM TOPOGRAPHIC MAP.

Table 1.--WSPRO input and output for example 1.

a.--WSPRO Input file for Example 1

```
T1        EXAMPLE 1 OF DIVISION OF FLOW AT A DIFFLUENCE
T2        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
T3        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
*
Q         523
SK        0.022
*
IS   I14   1
GR         9,16 42,15 55,14.2 123,14.2
GR         140,15 157,16
*
N            0.038  0.036
SA               93
*
HP 1 I14   15.3,0.01,15.35
PI   I14
*
EX
ER
```

b.--WSPRO Output for Example 1.

```
1
 WSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

           *** RUN DATE & TIME: 06-20-94  19:16

   T1        EXAMPLE 1 OF DIVISION OF FLOW AT A DIFFLUENCE
   T2        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
   T3        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
   *
   Q         523
 *** Q-DATA FOR SEC-ID, ISEQ =            1
   SK        0.022
   *
1
 WSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        EXAMPLE 1 OF DIVISION OF FLOW AT A DIFFLUENCE
        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
           *** RUN DATE & TIME: 06-20-94  19:16
```

Table 1.-- (continued).

```
*** START PROCESSING CROSS SECTION - 'I14  '
  IS   I14   1
  GR         9,16 42,15 55,14.2 123,14.2
  GR         140,15 157,16
  *
  N            0.038  0.036
  SA               93
  *
  HP 1 I14   15.3,0.01,15.35

*** FINISH PROCESSING CROSS SECTION - 'I14  '
*** CROSS SECTION 'I14  ' WRITTEN TO DISK, RECORD NO. =  1

--- DATA SUMMARY FOR SECID 'I14  ' AT SRD =      1.  ERR-CODE =      0

     SKEW     IHFNO    VSLOPE        EI        CI
      .0        0. *********       .50       .00

X-Y COORDINATE PAIRS  (NCP =   6):
      X      Y          X      Y          X      Y          X      Y
     9.0   16.00      42.0   15.00      55.0   14.20     123.0   14.20
   140.0   15.00     157.0   16.00

 X-Y MAX-MIN POINTS:
    XMIN      Y          X    YMIN      XMAX      Y          X    YMAX
     9.0   16.00      55.0   14.20     157.0   16.00       9.0   16.00

SUBAREA BREAKPOINTS (NSA =  2):
        93.

ROUGHNESS COEFFICIENTS (NSA =  2):
        .038    .036
1
WSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        EXAMPLE 1 OF DIVISION OF FLOW AT A DIFFLUENCE -
        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
          *** RUN DATE & TIME: 06-20-94  19:16
    CROSS-SECTION PROPERTIES:  ISEQ =  1;  SECID = I14  ;  SRD =      1.

b1.--Normal depth computations at Froude No. = 1.
```

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR	
	1	52.	1857.	61.	61.				276.	
	2	46.	1730.	52.	52.				243.	
15.30		98.	3588.	113.	113.	1.00	32.	145.	517.	

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR	
	1	53.	1887.	61.	61.				280.	use 278 channel A **
	2	46.	1760.	52.	52.				246.	use 245 channel B **
15.31		99.	3646.	114.	114.	1.00	32.	145.	525.	total 523 = Q100 **

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	54.	1916.	62.	62.				284.
	2	47.	1789.	52.	52.				250.
15.32		100.	3705.	114.	114.	1.00	31.	145.	533.

Table 1.--(continued).

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	54.	1946.	62.	62.				288.
	2	47.	1819.	53.	53.				254.
15.33		101.	3765.	115.	115.	1.00	31.	146.	541.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	55.	1977.	62.	62.				292.
	2	48.	1849.	53.	53.				258.
15.34		103.	3825.	115.	115.	1.00	31.	146.	549.

WSEL	SA#	AREA	K	TOPW	WETP	ALPH	LEW	REW	QCR
	1	55.	2007.	63.	63.				296.
	2	48.	1879.	53.	53.				262.
15.35		104.	3886.	116.	116.	1.00	30.	146.	557.

b2.--Conveyance-slope computation for Q = 523 cfs and slope = 0.022.

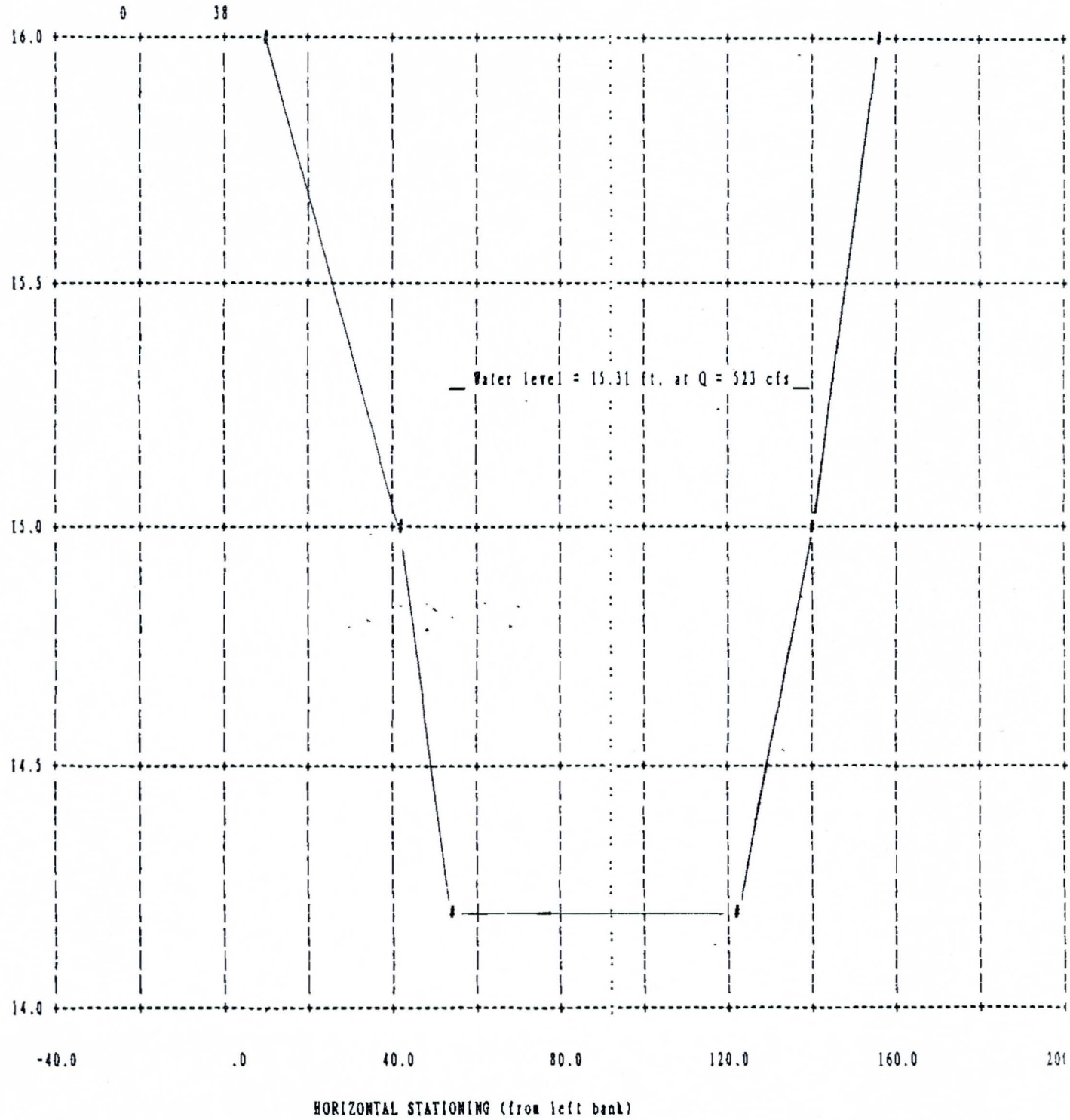
```
 +++ BEGINNING PROFILE CALCULATIONS --   1
1
 WSPRO          FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188            MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS


  ===015 WSI IN WRONG FLOW REGIME AT SECID 'X14  ':  USED WSI = CRWS.
                                WSI,CRWS =    15.29      15.30

  XSID:CODE   SRDL    LEW     AREA   VHD .  HF     EGL -  CRWS.     Q    WSEL
       SRD    FLEN    REW        K  ALPH   HO     ERR     FR#    VEL

 X14  :XS   ******    32.      98.   .44 *****   15.74   15.30   523.   15.30
        1. ******   145.    3587.  1.00 ***** *******    1.01    5.33
   ER

1  NORMAL  END  OF  WSPRO  EXECUTION.
```

Table 1.--(Continued).

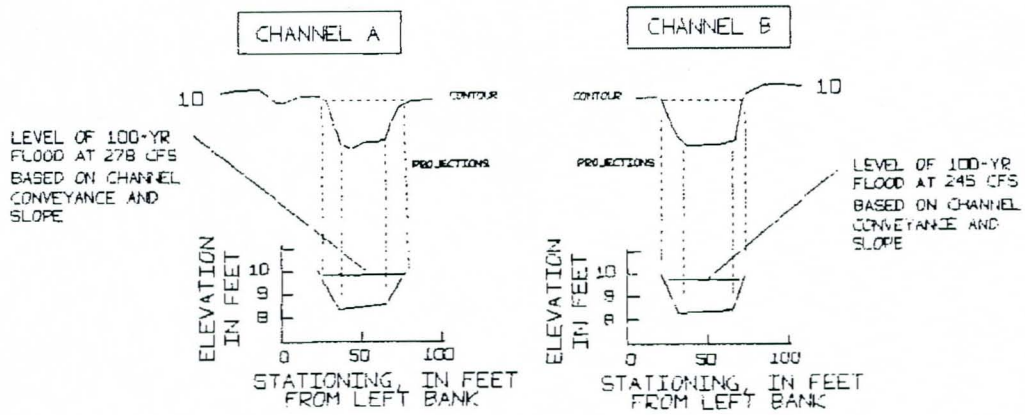
c.--WSPRO plot of cross section for Example I (See figure 2).

PI I14

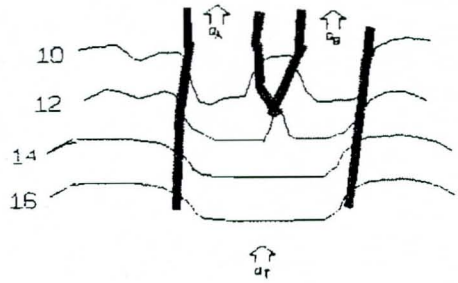
1 --- CROSS SECTION OUTLINE PLOT --- SEQ-NOB = 1 SEC-REF-DIST = 1.0 SECID = 'I14 '



A. CONVEYANCE-SLOPE ESTIMATE FOR CHANNELS A AND B USING SEPARATE CHANNELS



B. FLOOD BOUNDARIES



CHANNEL	DISCHARGE
TOTAL	523 cfs
A	278 cfs
B	245 cfs

See figures 1 and 2 for computation steps

FIGURE 3.--ESTIMATED FLOOD BOUNDARIES FOR EXAMPLE 1

Table 2.--WSPRO input and output for example 2.

Note: Conditions are the same as for example 1 except the slope is 0.01 instead of 0.022. Velocities are subcritical for example 2.

a.--WSPRO input file for example 2.

```
T1        EXAMPLE 2 OF DIVISION OF FLOW AT A DIFFLUENCE
T2        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
T3        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
*
Q         523
SK        0.01
*         THE SLOPE = 0.01 GIVES SUBCRITICAL FLOW VELOCITIES
*         FOR THIS EXAMPLE ( NO. 2 )
IS   I14   1
GR         9,16 42,15 55,14.2 123,14.2
GR         140,15 157,16
*
N            0.038  0.036
SA               93
*         THE FOLLOWING HP INSTRUCTION IS THE 2ND COMP.= PRECISE
HP 1 I14   15.54,0.01,15.56
PI   I14
*
EX
ER
```

b.--WSPRO ouput for example 2. Sequence edited for this discussion.

```
1
 WSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

          *** RUN DATE & TIME: 06-21-94  13:11

   T1        EXAMPLE 2 OF DIVISION OF FLOW AT A DIFFLUENCE
   T2        CROSS SECTION IS FROM TOPOGRAPBIC MAP.
   T3        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
   *
   Q         523
 *** Q-DATA FOR SEC-ID, ISEQ =            1
   SK        0.01
   *         THE SLOPE = 0.01 GIVES SUBCRITICAL FLOW VELOCITIES
   *         FOR THIS EXAMPLE ( NO. 2 )
1
 WSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
 P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        EXAMPLE 2 OF DIVISION OF FLOW AT A DIFFLUENCE
        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
          *** RUN DATE & TIME: 06-21-94  13:11

 *** START PROCESSING CROSS SECTION - 'I14  '
   IS   I14   1
   GR         9,16 42,15 55,14.2 123,14.2
   GR         140,15 157,16
   *
   N            0.038  0.036
   SA               93
   *         THE FOLLOWING HP INSTRUCTION IS THE 2ND COMP.= PRECISE
   HP 1 I14   15.54,0.01,15.56

 *** FINISH PROCESSING CROSS SECTION - 'I14  '
 *** CROSS SECTION 'I14  ' WRITTEN TO DISK, RECORD NO. =  1
```

Table 2.--(continued).

```
--- DATA SUMMARY FOR SECID 'X14  ' AT SRD =      1.  ERR-CODE =      0

     SKEW     IHFNO    VSLOPE        EK        CK
       .0        0. *********       .50       .00

X-Y COORDINATE PAIRS  (NGP =   6):
      X       Y        X       Y        X       Y        X       Y
     9.0   16.00     42.0   15.00     55.0   14.20    123.0   14.20
   140.0   15.00    157.0   16.00

 X-Y MAX-MIN POINTS:
    XMIN       Y        X    YMIN     XMAX       Y        X    YMAX
     9.0   16.00     55.0   14.20    157.0   16.00      9.0   16.00

SUBAREA BREAKPOINTS (NSA =  2):
        93.

ROUGHNESS COEFFICIENTS (NSA =  2):
       .038    .036
1
VSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        EXAMPLE 2 OF DIVISION OF FLOW AT A DIFFLUENCE
        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
           *** RUN DATE & TIME: 06-21-94  13:11

 XSID:CODE   SRDL    LEW     AREA   VHD    HF     EGL    CRWS      Q    WSEL
      SRD    FLEW    REW       K   ALPH    HO     ERR     FR#    VEL      -

X14  :XS   ******    24.     128.   .26 *****   15.81   15.30    523.   15.55
        1. ******   149.    5229.  1.01 ***** *******     .71   4.08          Subcritical flow **
  ER

1  NORMAL  END  OF  WSPRO  EXECUTION.

The HP instruction is used to compute the conveyance for channels A and B
at the diffluence cross section corresponding to WSEL = 15.55.

VSPRO        FEDERAL HIGHWAY ADMINISTRATION - U. S. GEOLOGICAL SURVEY
P060188          MODEL  FOR  WATER-SURFACE  PROFILE  COMPUTATIONS

        EXAMPLE 2 OF DIVISION OF FLOW AT A DIFFLUENCE
        CROSS SECTION IS FROM TOPOGRAPHIC MAP.
        100-YEAR Q = 523 CFS    BY HJALMARSON  JUNE 1994
           *** RUN DATE & TIME: 06-21-94  13:11
    CROSS-SECTION PROPERTIES:  ISEQ =  1;  SECID = X14  ;  SRD =      1.

     WSEL  SA#     AREA        K   TOPW   WETP  ALPH    LEW    REW     QCR
            1      68.    2641.    69.    69.                         383.
            2      59.    2498.    56.    56.                         340.
    15.54         127.    5139.   125.   125.  1.01    24.   149.    721.

     WSEL  SA#     AREA        K   TOPW   WETP  ALPH    LEW    REW     QCR
            1      69.    2677.    69.    69.                         388.
            2      59.    2533.    56.    56.                         345.
    15.55         128.    5210.   126.   126.  1.01    24.   149.    730.

     WSEL  SA#     AREA        K   TOPW   WETP  ALPH    LEW    REW     QCR
            1      69.    2714.    69.    70.                         393.
            2      60.    2568.    57.    57.                         349.
    15.56         129.    5282.   126.   126.  1.01    24.   150.    739.
```

End of table 2.

1.-- The conveyance-slope computation (result of the Q and SK instructions of WSPRO) is used for WSEL when flow velocities are subcritical.

2.--The HP instruction (also used for example 1) is used to determine the distribution of conveyance for channels A and B at a water surface elevation of 15.55 ft. Computations were made at 15.54, 15.55, and 15.56 ft. for this example to demonstrate the instruction and computation (part a, table 2).

The values of discharge for channels A and B are determined using the conveyance ratio for the diffluence based on cross-section properties at WSEL = 15.55 as shown in part b, table 2. The conveyance (K value) for channel A and channel B is 2677 and 2533, respectively and the 100-year discharge = 523 cfs. The discharge for channel A is:

$$Q_A = \frac{2677}{2677+2533}(523 \text{ cfs}) = 269 \text{ cfs.}$$

The discharge for channel B is:

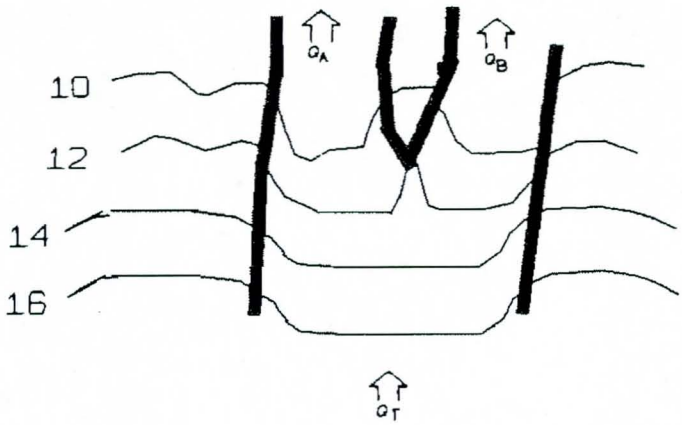
$$QB = 523 - 269 = 254 \text{ cfs or } \frac{2533}{2677 + 2533}(523 \text{ cfs}) = 254 \text{ cfs.}$$

The flood boundaries along channels A and B are next estimated based on critical velocity and/or conveyance-slope computations and estimates for each channel (figure 4). The conveyance-slope computations for channels A and B were computed separately using the conveyance and slope for each channel as shown previously in example 1. The flood boundaries are estimated from the computed water levels at the cross sections and the topography.

Example 3.

Distributary-flow areas with stable flow paths commonly have a fan shape where the width of the DFA widens below the primary diffluence. Many of these DFAs have active areas of distributary flow inset in old fan remnants where erosional processes are at work and the channels are tributary. Elevation contours commonly are slightly convex shaped when viewed downslope. Large areas of concave-shaped contours also are common. The surface of DFAs can be smooth and undissected or irregular and greatly dissected by both distributary and tributary stream channels.

Distributary flow can become widely separated in defined channels and present special problems for the systematic definition of flood boundaries. The author suggests that cross sections for channel conveyance computations be located along contours as shown in figure 5 (elevation-contour method). If detailed topographic maps are available, the channel cross section across the DFA can be defined as outlined in example 1 (figure 2) and shown in figure 5. Major advantages of the elevation-contour method are (1) the

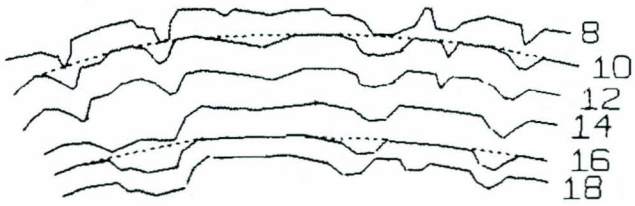


CHANNEL	DISCHARGE
TOTAL	523 cfs
A	269 cfs
B	254 cfs

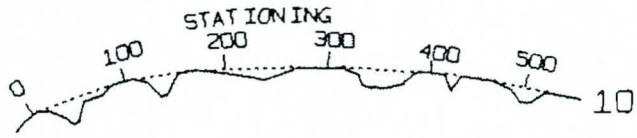
See figures 1 and 2 for computation steps.

FIGURE 4.--EXTIMATED FLOOD BOUNDARIES FOR EXAMPLE 2.

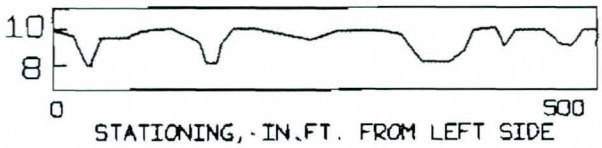
A. CONTOURS



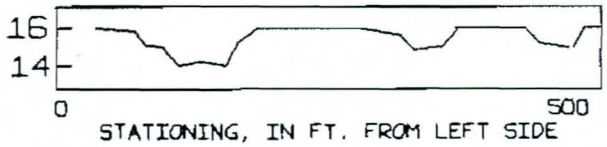
B. CONTOUR AT 10 FT. ELEVATION



C. CROSS SECTION AT 10 FT. ELEVATION



D. CROSS SECTION AT 16 FT. ELEVATION



NOTE: SCALE IS APPROXIMATE.

FIGURE 5.--DEFINITION OF CROSS SECTIONS ALONG A DFA.

same reference level for cross-section geometry is used across the DFA and (2) the floodflow will, on the average, be approximately perpendicular to the cross sections because floodflow on the DFA generally is perpendicular to the elevation contours. It has been long recognized that cross sections should be perpendicular to the anticipated flow lines which are approximately perpendicular to contour lines (CofE , 1990, p. 15). A minor disadvantage is that floodflow in a few channels may be skewed to the cross section requiring local adjustment to channel conveyance while maintaining overall cross-section stationing.

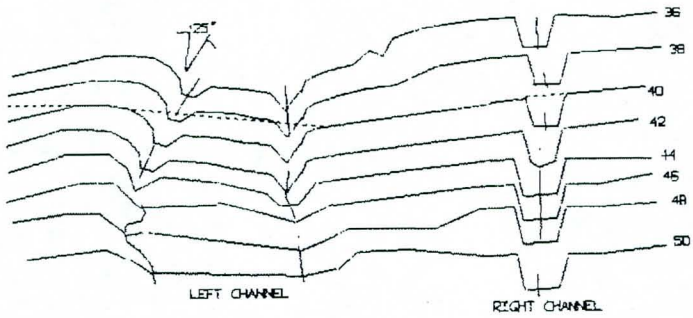
The same reference level for cross-section geometry was used across the 39 DFAs studied by Hjalmarson and Kemna (1992). Hjalmarson and Kemna found that the degree of flood hazard and the large ridges separating floodflow were readily defined using the topography along contours. Also, the capacity of channels at bankful elevation shown in Appendix E of this report was defined along elevation contours.

An advantage of the elevation-contour method is shown in figure 6 where a cross section is determined across the DFA at the 40 ft. contour. The cross section is first determined using the elevation-contour method (parts A and C, figure 6). The resulting first small channel on the left side of the DFA is skewed to the right requiring a correction for skew using the XS record of WSPRO (Shearman, 1990, p. 80). To eliminate the skew, a second cross section is defined using the "perpendicular-flow method" (parts B and C, figure 6). There is no skew at the channels but the resulting elevation of the right side of the cross section is higher. The cross section has a general slope to the left indicating, for example, that runoff exceeding channel capacity on the right will cascade to the channels on the left. There appears to be three channels because of the distortion of elevation and total conveyance between the small channels on the left. Such a sloping cross section, which is difficult to avoid on DFAs in Arizona, shows a false relief across the DFA and a lesser combined channel capacity.

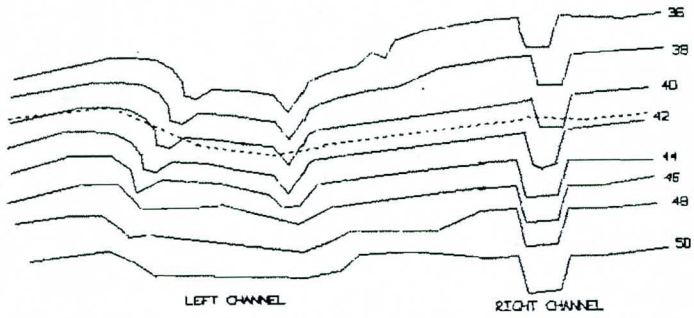
The capacity of the left channel is evaluated for the perpendicular-flow and elevation-contour methods using the left channel which includes the two small channels (figure 6 and figure 7A). The channel conveyance for the elevation -contour method is shown by relation 1-2-3 (figure 7B). The channel conveyance for the perpendicular-flow method is shown by relation A-C-B-D-E. The marked difference of computed conveyance for this example is mostly the result of the false relief and cascading effect of the perpendicular-flow method. For the perpendicular-flow method the channel conveyance of the left channel(s) at bankful stage is considerably less than the true conveyance of the elevation-contour section method mostly because the overflow area 1-2 is excluded.

Where the elevation-contour method results in a section that is not perpendicular to the anticipated flow, an adjustment should be used to obtain the effective cross section properties such as channel conveyance and width of flow. An adjustment to conveyance of the left channel may be considered necessary because some of the flow in the left side of the channel is skewed about 25 degree to the cross section. At bankful stage about 1/3 of

A. ELEVATION-CONTOUR METHOD



B. PERPENDICULAR-FLOW METHOD



C. CROSS SECTIONS FOR THE ELEVATION-CONTOUR AND PERPENDICULAR-FLOW METHODS

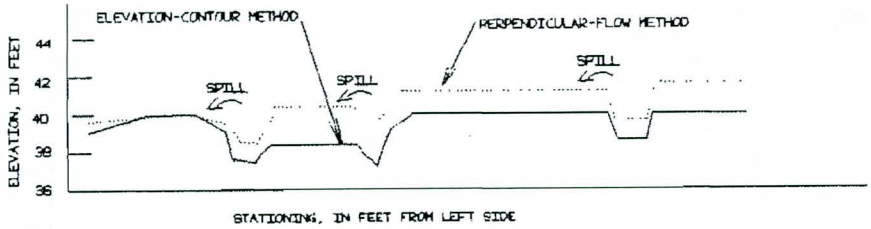
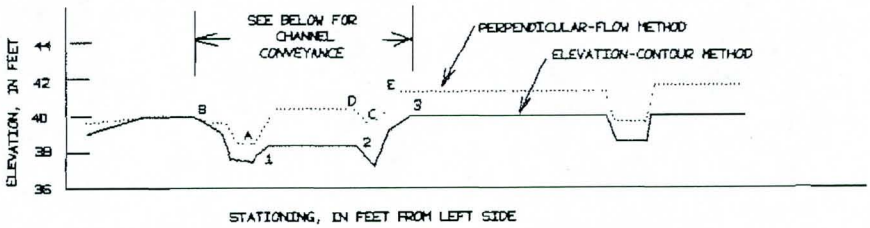


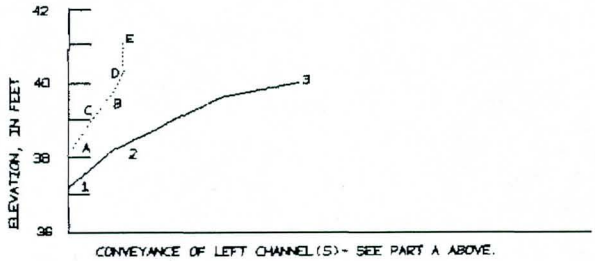
FIGURE 6.--COMPARISON OF METHODS OF DEFINING CROSS SECTIONS FOR DISTRIBUTARY-FLOW AREAS.

A. CROSS SECTIONS FOR THE ELEVATION-CONTOUR AND PERPENDICULAR-FLOW METHODS
(SEE FIGURE 6 FOR PLAN VIEW)



A. THALWEG OF SMALL CHANNEL ON LEFT.
B. TOP OF BANK WHERE THERE IS SPILL TO THE LEFT.
C. THALWEG OF SMALL CHANNEL ON RIGHT.
D. TOP OF BANK WHERE THERE IS SPILL TO THE LEFT.
E. TOP OF BANK.

B. CHANNEL CONVEYANCE FOR THE ELEVATION-CONTOUR AND PERPENDICULAR-FLOW METHODS



1. THALWEG OF MAIN CHANNEL.
2. TOP OF BANK SEPARATING THE SMALL CHANNELS.
3. TOP OF BANKS.

FIGURE 7.--COMPARISON OF CHANNEL CONVEYANCE FOR METHODS OF DEFINING CROSS SECTIONS.

the computed discharge is skewed at an average of 20 degrees while 2/3 of the computed discharge is not skewed. The corresponding approximate adjustment is:

$$Q_{pa} = (Q_p (\cos. 20^o) + 2\, Q_p)/_3 = 0.98\, K_p$$

where K_p = channel conveyance at peak discharge for skewed section.

Thus, the conveyance could be reduced by 2 percent, if judged to be significant. Such a small adjustment is considered unnecessary where the channel geometry is from 2 ft. topography and the conveyance-slope method is used to compute the flood levels.

The above adjustment is best made with the XS record of WSPRO. The skew is the acute angle the section must be rotated to orient the section normal to the anticipated direction of flow. For the above example the average angle is $20^o/3$ or about 7°. The model applies the cosine of skew to the horizontal dimension of the section to compute cross section properties (Shearman, 1990, p. 81).

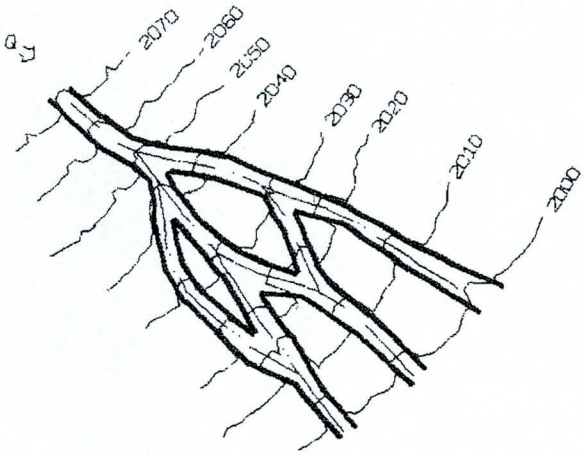
The elevation-contour method has been successfully applied to many distributary-flow areas in Arizona (Hjalmarson and Kemna, 1992). Although not experienced, the method may not be satisfactory for all conditions such as where there is a general change in elevation at a defined channel. Such abrupt changes in elevation are not common on distributary-flow areas but the author has found that all distributary-flow areas are different. Thus, judgement should be used when applying the elevation-contour or any other method to define the cross sections.

Example 4.

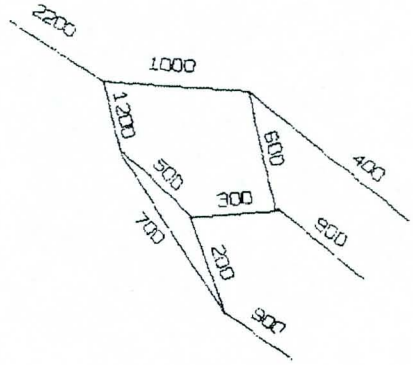
Mapped flood boundaries are shown for a DFA with stable paths of flow in figure 8A. The distribution of peak flow in this simple example is shown in figure 8B. The peak discharge is apportioned through the network of channels by assuming the flood peaks coincide at the forks and joins. The apportionment of flow was based on channel conveyance at the diffluent sections as described in examples 1 and 2. Water surface elevations were estimated along the channels using conveyance-slope computations and the corresponding flood boundaries were mapped on the detailed topographic map.

The riverine type flood hazard depicted in figure 8A is considerably different than the flood hazard depicted using the FEMA Alluvial Fan Method (figure 8C). Although only implied and not specifically shown, the potential flood hazard along the defined channels (figure 8A) is more severe with higher velocities and greater depths than shown for these areas in figure 8C. Conversely, the ridges separating the defined channels (figure 8A) are depicted with the same hazard as the defined channels in figure 8C. This simple example of two potential kinds of flooding on DFAs shows the importance of the flow path stability assessment described in this report and the associated flood hazard.

A. DISTRIBUTARY CHANNELS WITH FLOOD BOUNDARIES



B. SCHEMATIC OF FLOW PATHS WITH PEAK DISCHARGE FOR CHANNEL LINKS



C. APPROXIMATE FLOOD INSURANCE ZONES

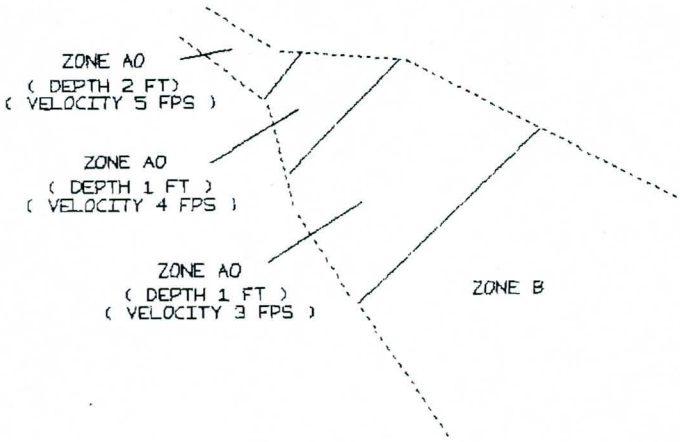


FIGURE 8. SKETCHES OF DISTRIBUTARY-FLOW AREA WITH STABLE FLOW PATHS SHOWING FLOOD BOUNDARIES, DISTRIBUTION OF PEAK DISCHARGE AND POTENTIAL FEMA FLOOD INSURANCE ZONES

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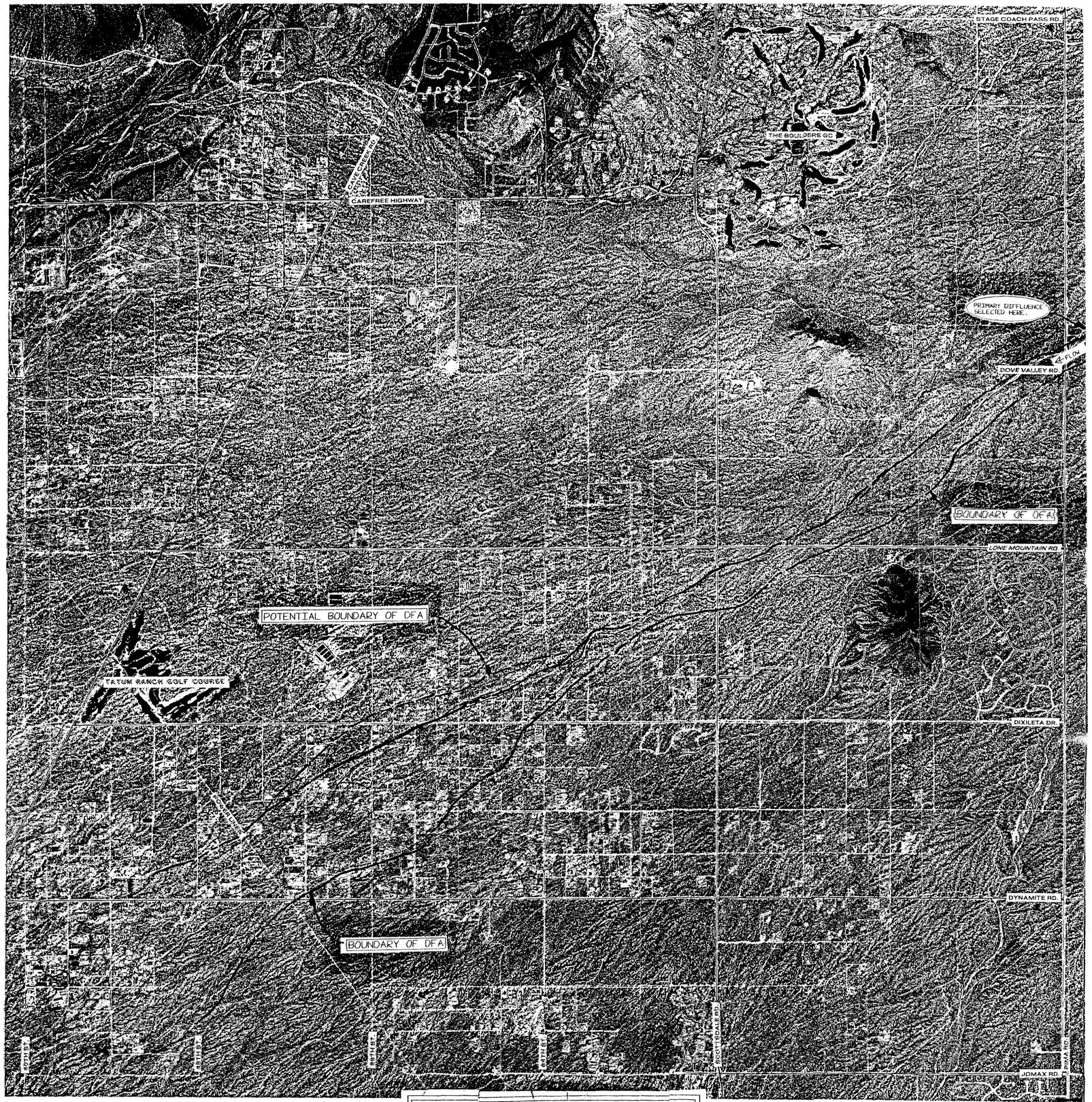

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PLATE 1.- PRIMARY DIFFLUENCE, BOUNDARIES AND FLOW PATHS OF SITE 6A.
HALMAR W. HALMAR
SHEET 3 OF

PHOTO DATE: DECEMBER 13, 1986
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PHOTO SCALE: 1" = 1760 FT

SEE SHEETS 1 & 2 FOR TOPOGRAPHY & FLOW PATHS

UNITED STATES
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CAVE CREEK QUADRANGLE
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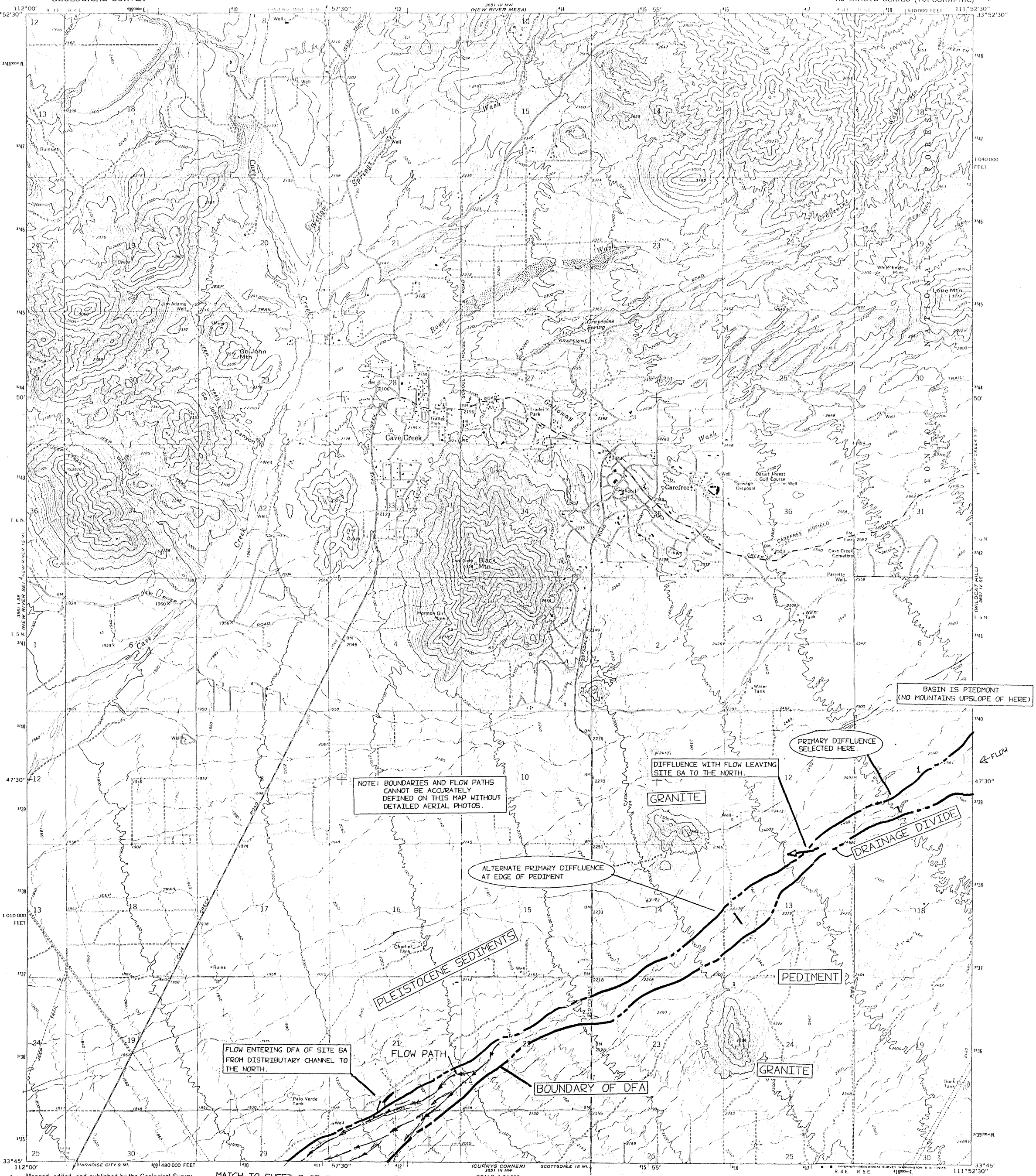

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Topography by photogrammetric methods from aerial photographs taken 1962. Field checked 1965

Polyconic projection. 1927 North American datum
10,000-foot grid based on Arizona coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue

UTM GRID AND 1965 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET (GN, MN, 0°31' 9 MILS, 14° 249 MILS)

SCALE 1:24 000

1 MILE — 7000 FEET — 1 KILOMETER

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

ROAD CLASSIFICATION
Medium-duty — Light-duty
Unimproved dirt

ARIZONA — QUADRANGLE LOCATION

PLATE 1.--PRIMARY DIFFLUENCE, BOUNDARIES AND FLOW PATHS OF SITE 6A.

HJALMAR W. HJALMARSON, PE

SEE SHEET 3 OF 3 FOR COPY

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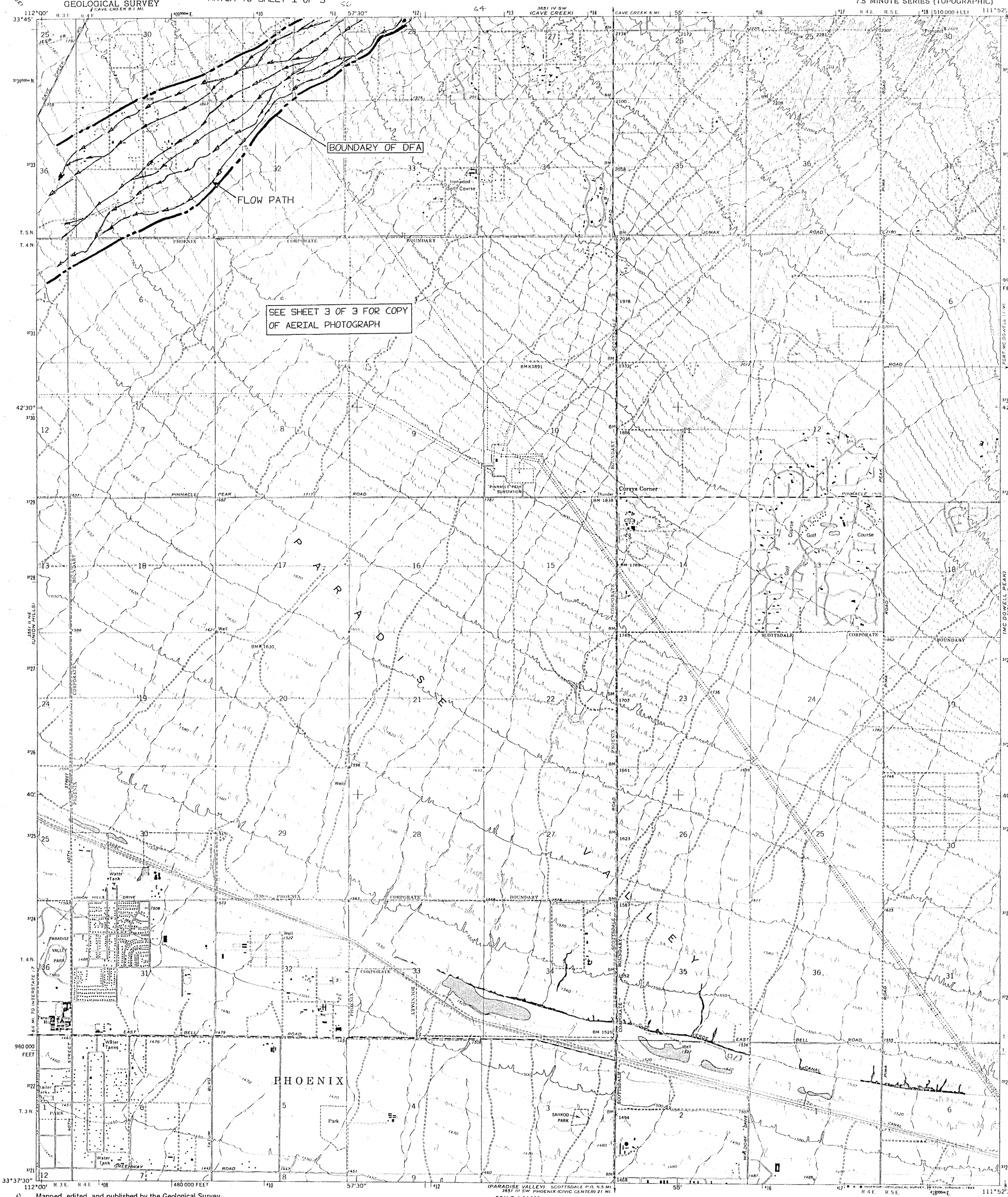
CAVE CREEK, ARIZ.
N3345—W11152.5/7.5

1965

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

MATCH TO SHEET 1 OF 3

CURRYS CORNER QUADRANGLE
ARIZONA--MARICOPA CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



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Topography by photogrammetric methods from aerial photographs taken 1962. Field checked 1964

Polyconic projection. 10,000-foot grid ticks based on Arizona coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue. 1927 North American Datum
To place on the predicted North American Datum 1983 move the projection lines 1 meter south and 65 meters east as shown by dashed corner ticks

There may be private inholdings within the boundaries of the National or State reservations shown on this map

Revisions shown in purple and woodland compiled from aerial photographs taken 1978 and other sources. This information not field checked. Map edited 1982

UTM GRID AND 1982 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

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ROAD CLASSIFICATION
Medium-duty — Light-duty
Unimproved dirt

ARIZONA

PLATE 1.--PRIMARY DIFFLUENCE, BOUNDARIES AND FLOW PATHS OF SITE 6A.
HUALHAR V. HUALHARSON, PE
SHEET 2 OF 3

CURRYS CORNER, ARIZ.
N3337.5—W11152.5/7.5

1964
PHOTOREVISED 1982
DMA 3651 IIINW-SERIES V898