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ALLUVIAL FAN FLOODING METHODOLOGY
AN ANALYSIS

PREPARED FOR

FEDERAL EMERGENCY MANAGEMENT AGENCY
CONTRACT EMW-84-C-1488

OCTOBER 1985

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TABLE OF CONTENTS

Acknowledgements i

Table of Contents ii

List of Tables iv

List of Figures v

List of Symbols viii

1.0 Introduction 1

2.0 Literature Review 3

2.1 Discussion of "Flood Plain Management Tools for Alluvial Fans" 7

3.0 Fan Formation and Process 8

3.1 Theoretical Aspects 8
3.2 Case Studies 10

3.2.1 Selection Criteria of Alluvial Fans 10
3.2.2 Observations of Alluvial Fans 13
3.2.3 Results of Case Studies 51

4.0 Fan Flood Analysis Methodology 62

4.1 Current Methods for Fan Flood Analysis 62

4.1.1 FEMA Method 62
4.1.2 Edwards and Thielmann's Modification 63
4.1.3 Discussion of the Current Methods 65

4.2 Major Factors Affecting Fan Floods 66
4.3 Classification of Fan Floods 68
4.4 Practical Considerations for the Analysis of Alluvial Fan Flooding 69
4.5 Proposed Modifications of Current FEMA Method 71

5.0 Study Findings and Recommendations 74

5.1 Study Findings 74
5.2 Recommendations 75

6.0 References 76

Appendix A Selected Observations of Channel Branching

Appendix B Comparison of Different Alluvial Fan Flood Analyis Methods

Appendix C Proposed Modification of FEMA "Guidelines and Specifications for Study Contractors: Appendix 6. Alluvial Fan Studies"

LIST OF TABLES

Table		Page
1.	Sources of Aerial Photographs for Alluvial Fans	12
2.	Summary of Alluvial Fan and Flood Channel Characteristics	54
3.	Summary of Single Channel Widths Calculated Using FEMA and Edwards & Thielmann's Methods	58

LIST OF FIGURES

Figure		Page
1.	Definition Sketch of Alluvial Fan Characteristics	14
2.	Topographic Map and Aerial Photograph of the Alluvial Fan below Northumberland Canyon near Austin, Nevada	16
3.	Topographic Map and Aerial Photograph of the Alluvial Fan below Masson Valley Tributary near Mason, Nevada	18
4.	Topographic Map and Aerial Photograph of the Alluvial Fans below Humbolt River Tributary Rye Patch and Oreana, and Rocky Canyon, Nevada	21
5.	Topographic Map and Aerial Photograph of the Alluvial Fan below Las Vegas Wash Tributary near Henderson, Nevada	25
6.	Topographic Map and Aerial Photograph of the Alluvial Fan below Piute Wash Tributary at Searchlight, Nevada	27
7.	Topographic Map and Aerial Photograph of the Alluvial Fan below San Antonio Wash Tributary near Tonopah, Nevada	29
8.	Topographic Map and Aerial Photograph of the Alluvial Fan below Eldorado Valley Tributary near Nelson, Nevada	31
9.	Topographic Map and Aerial Photograph of the Alluvial Fan below Lytle Creek near Fontana, California	33

10.	Topographic Map and Aerial Photograph of the Alluvial Fan below Day and Deer Canyons near Etiwanda, California	36
11.	Topographic Map and Aerial Photograph of the Alluvial Fan below Cucamonga Creek near Upland, California	39
12.	Topographic Map and Aerial Photograph of the Alluvial Fan below San Antonio Creek near Claremont, California	42
13.	Topographic Map and Aerial Photograph of the Alluvial Fan below Tahquitz Creek near Palm Springs, California	44
14.	Topographic Map and Aerial Photograph of the Alluvial Fan below Palm Canyon near Palm Springs, California	46
15.	Topographic Map and Aerial Photograph of the Alluvial Fan below Devil Canyon near San Bernardino, California	48
16.	Topographic Map and Aerial Photograph of the Alluvial Fan below Whitewater River near Whitewater, California	50
17.	Normalized Locations of Single Channels on Alluvial Fans	52
18.	Relationship Between Observed Length of a Single Channel and the Ratio of Canyon Slope to Fan Slope	56
19.	Relationship Between Fan Slope and the Ratio of Width Calculated Using the FEMA Method to Observed Width for a Single Channel	57

20. Relationship Between the Ratio of the Total Width for a Split Channel to the Width for a Single Channel and the Fan Slope 60

21. Comparison of Observed Widths Against Calculated Widths for Single Channels Using FEMA, and Edwards & Thielmann's Methods 64

LIST OF SYMBOLS

Symbol	
A	Avulsion Coefficient
A	Watershed drainage area
C	Transformation constant
D	Flow depth
G	Log Skewness
K	Log-Pearson Type 3 standard deviation
n	Manning's roughness coefficient
P	Probability of discharge for each depth and velocity
Q	Flow rate
S	Log standard deviation
S	Channel slope
S_{cny}	Canyon slope
S_{fan}	Alluvial fan slope
S_z	Standard deviation of Z
V	Flow velocity
W	Fan arc width
W	Channel width
W_c	Calculated channel width
W_o	Observed channel width
X	Log mean
Z	Transformed Log-Pearson variable
$\bar{Z}$	Mean of Z

1.0 INTRODUCTION

Alluvial fans are estimated to cover approximately one third of the land area in the southwestern United States. Although mostly associated with arid and semiarid regions, alluvial fans also exist in humid regions and occur throughout the country. Because of their relatively gentle slopes and well draining characteristics, alluvial fans are subject to urbanization at an increasing pace as the supply of flat bottom land is exhausted. Development on fans is subject to damage from floods because of the unpredictable and violent nature of flood waters.

To minimize losses as a consequence of flooding and to protect those living in flood prone areas, the Federal Government passed the National Flood Insurance Act of 1968 which is administered through the Federal Emergency Management Agency (FEMA). Its purpose is to provide insurance against flood losses and to provide guidelines for regulating flood plain development. Implementation of the act has required that FEMA address the flooding issues particular to alluvial fans.

To determine the flood risk and flood prone areas of fans, FEMA adopted a methodology based on work by Dawdy (1979). The existing methodology is based on two key assumptions which have not been verified in the past. The first of these is that the location of any stream channel on a fan is random; that it has an equal probability of occurring anywhere across the fan. The second is that the flow forms its own channel and remains in one channel throughout the flow event, except that the location of the channel can change through avulsion. FEMA commissioned DMA Consulting Engineers to conduct a study to verify the

appropriateness of the assumptions and, should the need be shown, to modify the method. This study has focused on the development of a historical data base of floods on alluvial fans. Fans for which flow measurements are available were identified and aerial photographs covering the flood events were sought. In developing the data base the goal was to bracket a flood event with before and after photographs so as to define the physical nature of the flood event on the alluvial fan proper. Personnel from Federal and local agencies in Arizona, California, Nevada, and New Mexico were contacted to obtain information of alluvial fan floods. A review of the literature was made, including a detailed analysis of a 1981 hydraulic investigation which was performed by the firm of Anderson - Nichols & Company.

2.0 LITERATURE REVIEW

A search of available literature was undertaken including a computer search through 12 data bases and the follow up of material referenced in the literature reviewed. Over 50 publications dealing with the subject of alluvial fans were reviewed. The overwhelming number of publications dealt with geologic and geomorphologic descriptions of fans. This included descriptions of fan material, fan make-up, fan deposits, fan age, and fan formation. Although it is universally agreed that water flow plays the key role in the fan formation process, very few of the publications addressed the hydrologic and hydraulic processes on fans.

The majority of investigations describe fans in the regions of the southwest. Bull (1960a, 1960b, 1961, 1963, 1964, 1966, 1968, 1973) studied fans on the east slopes of the Diablo Range in Western Fresno County, California. Denny (1965) gives a comprehensive description of fans in the Death Valley region. His study focused on three areas from the Panamint Range and the Funeral Mountains. He developed relationships between mean sediment size and fan slope, drainage area and width of wash, drainage area and fan slope, width of channel and slope of channel, and mean sediment size variation with distance from fan apex. Finally an expression was developed for the size of fans in terms of fan area as a function of drainage area.

Eckis (1928) gives a description of fans on the northern part of the San

Bernardino Basin in Southern California. Blissenbach (1954) discussed formation processes and alluvial fan deposits with emphasis on three fans in the Santa Catalina Mountains of Arizona.

An overview of alluvial fan characteristics is presented by Ansey (1965). This study discusses characteristics of both arid and humid region fans, classification of alluvial fans, and the incidence of alluvial fans, with particular emphasis on the Basin and Range Province. Such characteristics as fan gradient, width and radius are quantified on a gross basis.

Hooke (1967) describes two distinct types of alluvial fan deposits: water flow deposits and debris flow deposits. Water flow deposits are those laid down by running water while debris flow deposits are those flows having properties different than water with much greater specific densities and viscosities, resulting in non-newtonian flow. The sediment load of water flows may vary as a result of the processes of erosion and deposition. A debris flow on the other hand will not exhibit such a characteristic. It will flow as an entity, with the debris load coming to rest at a terminal point at which its momentum can no longer carry it further along the fan. Consequently debris flow deposits are characteristically sheetlike with lobate tongues that are well defined and terminate abruptly. Debris flows consist of muddy mixtures of gravel, sand and clay which can carry boulders in excess of 8 feet in diameter. Sharp and Nobles (1953), and Pierson (1981) have reported that these mud mixtures have water content between 20 and 40 percent by weight. Pierson (1981) has measured mud flows moving at velocities in excess of 15 feet per second on fans with slopes of 5 to 7 degrees.

Beaty (1974) argues that the primary agent in the formation of alluvial fans is the debris flow as opposed to what he terms the "so-called normal stream processes." In describing the formation of alluvial fans at the base of the White Mountains, along the California-Nevada border, Beaty contends that no more than 10 - 15 percent of the fan materials have been deposited by sediment- laden waters. In arguing the probability of occurrence of debris flows Beaty points out that during the 35 year period prior to 1970 there had been at least seven significant debris flows from canyons along the Western flanks of the White Mountain Range. He further cites, based on newspaper files and discussions with long time area residents, that two to three times as many debris flows occurred during the historical period dating back to the 1860's. The significant causative agent leading to debris flows according to Beaty are storms with precipitation intensities in excess of 50 - 70 mm/hr. Beaty believes that debris flows are highly unlikely without intensities equal to or exceeding those.

It is important to note that Beaty's work, although extensive, has been in the desert ranges of the Great Basin which have little or no vegetative cover. Such watersheds have ideal conditions for generating mud flows. However, it is arguable that for canyons with vegetation in the upland areas the frequency of debris flows would not show such a strong one to one relationship with precipitation intensity. If fan formation is dependent on catastrophic events then one is looking at events which may occur with relative infrequency to create the fans observed today. Beaty (1970) gives a rather simplistic but illustrative example of this. The Milner Creek fan on the western slopes of the

White Mountains is estimated to be 700,000 years old. The volume of the fan is 2.25 billion cubic yards. Assuming the fan was built at a constant rate, the average rate of deposition required would be 3,200 cubic yards per year. This translates to between 3 and 6 inches of deposit per 1000 years if the material were equally distributed over the growing fan. However, analysis of debris flow deposits indicates quite a different scenario. On July 26, 1952 a major debris flow occurred depositing 1,125,000 cubic yards of material on the fan. With debris flows of such a magnitude, only one event every 350 years, on the average, would be required to create the present fan.

Drainage basin lithology is an important factor in the determination of the size of the fan and on the make-up of fan materials. Bull (1964) points out that fans derived from source areas underlain by mudstones and shales are larger than fans orginating from equal sized drainage areas underlain by sandstone. The larger fans are due to the greater erodibility of the mudstones and shales in comparison to sandstone. The greater erodibility leads to a larger source of fan make-up material.

Two investigations included laboratory model studies of fans. In the first there was no attempt to develop a model fan and the basis of similitude criteria (Hooke; 1967, 1968, 1979). A gross scaling was used whereby small fans were created under laboratory conditions for the purpose of observing the overall fan building phenomenon. No prototype fans were used for comparison. Flow rates were selected arbitrarily over a range of value from low to high relative to the size of the fan. The second laboratory investigation was by Anderson-Nichols and Company (1981) and will be discussed in detail herein.

2.1 Discussion of "Flood Plain Management Tools For Alluvial Fans

FEMA commissioned Anderson-Nichols and Company (ANCO) of Palo Alto, California to conduct a study of flood processes on alluvial fans and to develop management guidelines for regulations on alluvial fans. In 1981 ANCO completed a report documenting the results of their study. The ANCO report consists of two volumes. The first presents their results and recommendations. The second gives detailed documentation for their study, including mathematical formulation and description of model testing. The emphasis of the study was on the development of physical models representative of idealized and actual fan conditions. The physical models were used to model specific flood events on actual fans as well as to study the overall flooding phenomenon particular to alluvial fans. In addition, the models were used to test the effectiveness of using various structural and non-structural measures to reduce flood damages to buildings and other structures on alluvial fans.

As a result of the modeling effort three hydraulic zones are identified as occurring along the length of the fan. The first zone is immediately downstream of the fan apex and is categorized by a single channel. This one is followed by one where the flow is in a split channel. The last zone is towards the toe of the fan where the flow becomes braided, relatively shallow and wide. The results of this study confirm the existence of the three zones as identified by ANCO.

3.0 FAN FORMATION AND PROCESS

Alluvial fans develop below the mouth of a canyon by the outwash from the canyon draining an upstream watershed. Flooding on an alluvial fan is part of the natural process for the formation of the fan. Urbanization on an alluvial fan imposes potential obstruction to the flood flows, therefore structures are subjected to flood hazard. In this chapter, the formation and processes of alluvial fans are described first. The characteristics of alluvial fan floods are then investigated using aerial photographs of alluvial fans taken before and after specific flood events. Finally, the results of case studies are presented. These will be used as a data base for the evaluation of the current FEMA method for the analysis of fan floods.

3.1 Theoretical Aspects

Alluvial fans develop from the outwash of a canyon draining an erodible upstream watershed, which is subjected to high intensity and short duration rain storms. The sediments eroded from the watershed by the rain storms are transported downstream by the canyon flow and discharged onto the valley floor below the mouth of the canyon. Due to the spreading of water and the flat valley floor, the flow on the valley floor slows and becomes shallow. This results in low sediment transport capacity and causes the sediment to drop out, initially near the mouth of the canyon. As the deposits continue to accumulate, the slope of the alluvial deposits increases, and so does the sediment transport capacity of the flow. The sediments are therefore carried and deposited further downstream. When the alluvium reaches the canyon bed elevation, flood channels

are developed by the momentum of the canyon flow. At this time, the deposition of sediment is extended further downstream along the channels.

For unusual events, the sediment discharged onto the alluvial fan is so great in quantity that rapid deposition of sediment occurs at a point along a channel. Sediment deposition lessens the channel slope above the point of deposition, but also steepens the slope below that point. Lessening of channel slope further accelerates the deposition process already begun. The deposition process rapidly extends upstream along the channel reach to a point that channel overflow occurs and a new channel is developed to transport the flood water. This process of backfilling an existing channel and developing a new channel is called an avulsion. The new channel developed by avulsion is likely to have a different direction along the fan slope. Water and sediments are now carried by this new channel to a new deposition area on the fan. Repeated occurrence of avulsions on an alluvial fan over a long period of geologic time results in a uniform fan slope in the radial direction from the apex. The steepening of the channel slope below the deposition point also enables the downstream channel to carry more sediment further downstream. Massive deposition of sediment at the downstream area may also result in a low cross-fan debris dam, which leads to steepening the fan slope below the dam. The flood waters passing the openings of the debris dam would develop new individual alluvial fans below each opening. This process also advances the formation of the fan.

Although the avulsion process for fan floods is the major mechanism for creating a uniform fan slope in the radial direction over geologic time, avulsions may not occur often over a planning horizon. Thus, the relocation of a flood channel by avulsion is only associated with the rare flood events, such as the debris flow

resulting from a severe high-intensity short-duration rainstorm on a highly erodible watershed, or massive landslides, etc. Frequently, flood channels are found to be deeply incised onto the fan due to repeating uses by consecutive floods. The flood channels are stable until relocated by channel avulsion in a severe debris flow.

The formation process of an alluvial fan may be affected or modified by human activities, such as the installation of levees or of a lined channel to guide the flood water, the construction of dams to reduce the peak discharge on the alluvial fan, and the construction of a debris dam to intercept the sediment and debris. The above activities will either lower the rate of fan formation or direct the further development of the alluvial fan in designated directions.

3.2 Case Studies

The selection and study of alluvial fans using aerial photographs are described in the following subsections.

3.2.1 Selection Criteria for Alluvial Fans

The characteristics of alluvial fan floods were studied using USGS topographic maps and aerial photographs of the alluvial fans. The topographic maps were used to determine the fan slope, expansion angle, upstream watershed drainage area, canyon slope, and the geographic relationship to adjacent alluvial fans. The aerial photographs were used to determine the fan flood characteristics including channel patterns (such as single channel, split channels, and braided channels),

and channel direction, length, and width. Aerial photographs within three years before and after major floods were compared and the changes recorded to determine the changes in channel patterns by floods, particularly large floods which usually shape the channel patterns.

The alluvial fans studied were selected from California and Nevada. Fans were selected based on the following criteria:

- The fan must be well-defined so that the fan characteristics can be abstracted from the USGS topographic map and the aerial photographs.
- There must be a USGS gaging station for the measurements of flood discharge or there must be estimates of major flood discharges made by USGS.
- There must be aerial photographs covering the fan area within three years before and after the major flood considered. (For some alluvial fans, this criterion could not be met.)

The alluvial fans studied ranged from nearly undeveloped fans in Nevada to fans subjected to highly developed fans in California. For nearly virgin alluvial fans, the process which actually forms the alluvial fan can be seen. For the densely populated fans, the modification of fan floods as a result of man-made structures such as levees, dams, roads, buildings, etc. can be observed. The sources of aerial photographs of alluvial fans used in the present study are summarized in Table 1.

TABLE 1 SOURCES OF AERIAL PHOTOGRAPHS FOR ALLUVIAL FANS

ALLUVIAL FAN	EXPOSURE DATE	SOURCE OF PHOTOS
Northumberland Canyon near Austin, NV	6/19/81	USGS EROS Data Center
Mason Valley Trib. near Mason, NV	10/7/68, 10/25/72	USGS EROS Data Center
Humboldt River Trib. near Rye Patch, NV	6/23/73	USGS EROS Data Center
Rocky Canyon near Oreana, NV	6/23/73	USGS EROS Data Center
Humboldt River Trib. near Oreana, NV	6/23/73	USGS EROS Data Center
Las Vegas Wash Trib. near Henderson, NV	10/21/71, 12/20/72 6/25/75, 7/4/80	USGS EROS Data Center
Piute Wash Trib. at Searchlight, NV	10/7/68	USGS EROS Data Center
San Antonio Wash Trib. near Tonopah, NV	8/29/73	USGS EROS Data Center
Eldorado Valley Trib. near Nelson, NV	7/24/73, 5/12/72	USGS EROS Data Center
Lytle Creek near Fontana, CA	4/13/33, 9/8/35 3/10/38, 4/17/67 10/12/67, 1/30/69, 3/4/69	Whittier College, LA; San Bernardino County, CA
Day Canyon near Etiwanda, CA	9/8/35, 3/10/38 3/30/66, 1/30/69, 2/27/69	Whittier College, LA; San Bernardino County, CA

TABLE 1 (continued)

SOURCES OF AERIAL PHOTOGRAPHS FOR ALLUVIAL FANS

ALLUVIAL FAN	EXPOSURE DATE	SOURCE OF PHOTOS
Deer Canyon near Guasti, CA	9/8/35, 1/30/69 2/27/69	Whittier College, LA; San Bernardino County, CA
Cucamonga Creek near Upland, CA	3/10/38, 1/30/69 2/27/69	San Bernardino County, CA
San Antonio Creek near Claremont, CA	3/10/38	San Bernardino County, CA
Tahquitz Creek near Palm Springs, CA	4/20/59	San Bernardino County, CA
Palm Canyon near Palm Springs, CA	11/5/40	Whittier College, LA
Devil Canyon near	2/17/37 3/10/38	Whittier College, San Bernardino, CA
		LA; San Bernardino
Whitewater River near Whitewater, CA	6/8/36	Whittier College, LA.

3.2.2 Observations of Alluvial Fans

The observed results for individual alluvial fans based on the use of aerial photographs are presented in the case studies. The characteristics of alluvial fan are defined in Figure 1.

<u>Northumberland Canyon near Austin, Nevada</u>

The Northumberland Canyon, located on the eastern slope of the Toquima Range in Nevada, drains an upstream watershed of 15.1 square miles. The relatively mild

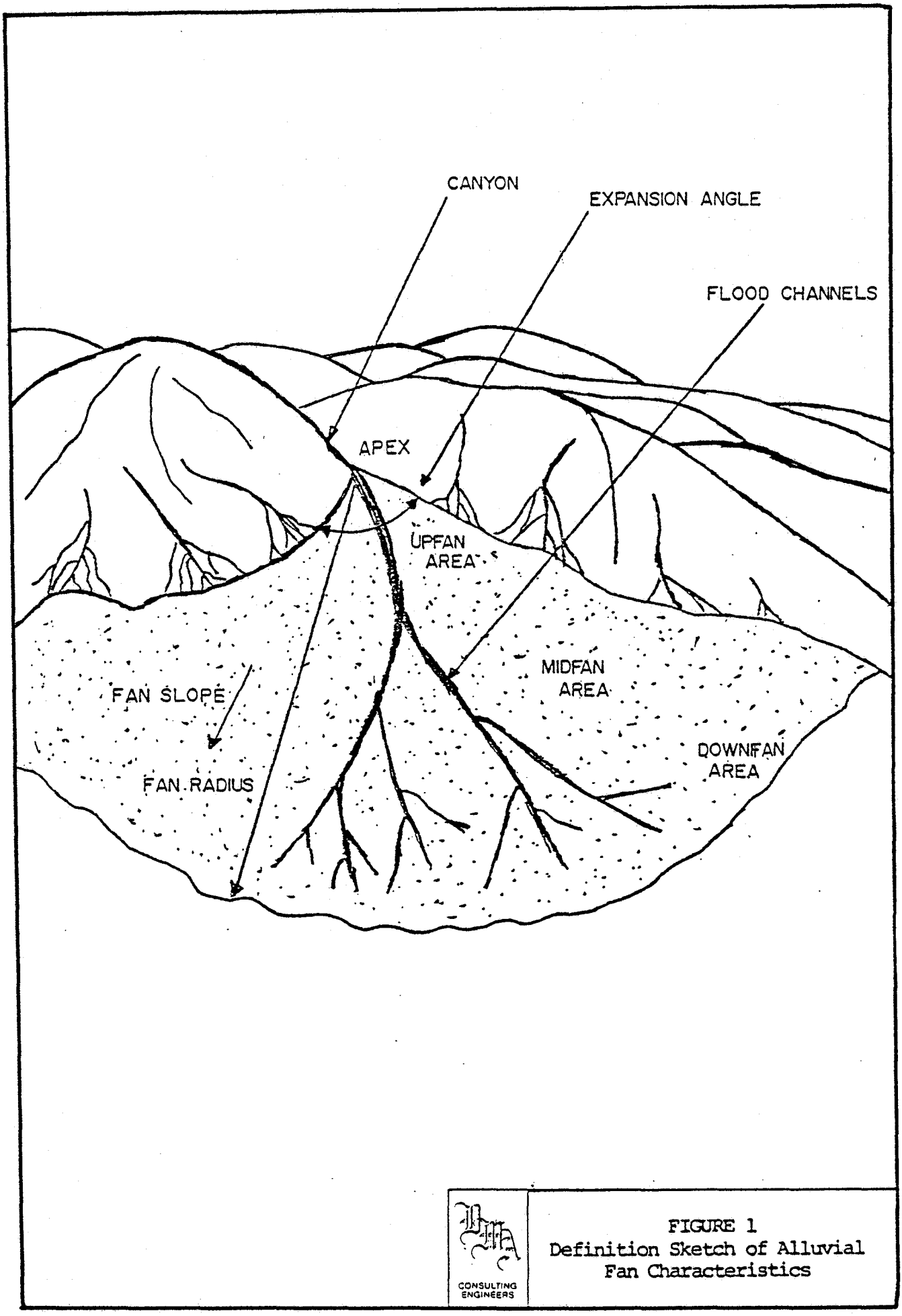

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FIGURE 1
Definition Sketch of Alluvial Fan Characteristics

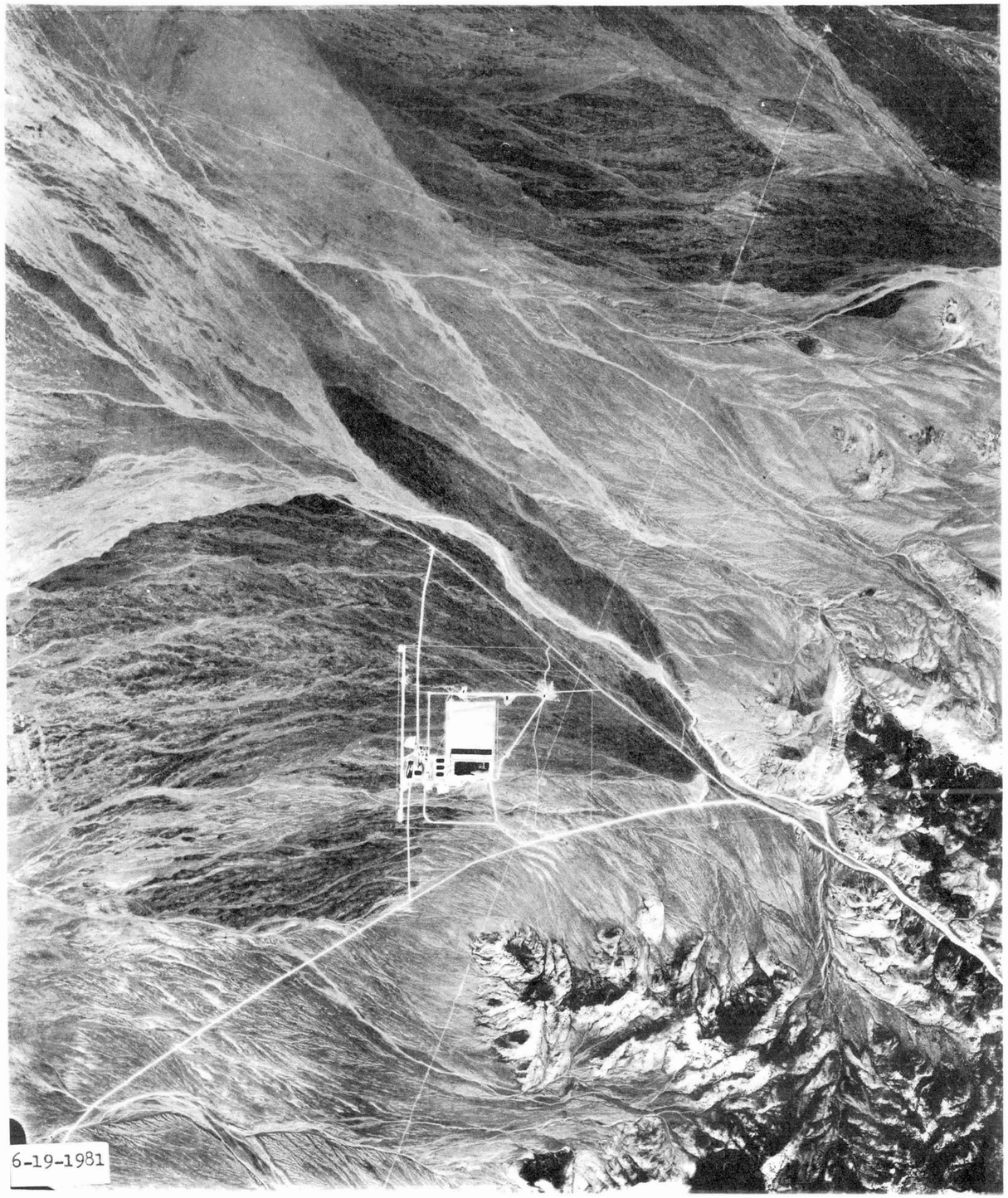
slope of 0.033 extends upstream into the canyon beyond the mountain front. The outwash from the canyon has developed a downstream alluvial fan with a slope of 0.033 at the upfan area and an expansion angle of 60 degrees. The upstream watershed is sparsely vegetated below 7600 feet. However, the region from elevation 7600 feet to 8800 feet is well vegetated. Flooding is usually caused by summer thunderstorms in the upstream watershed. A peak discharge of 7680 cfs was estimated for the fan flood on August 7, 1979. Channel patterns due to fan flooding were identified from an aerial photograph taken on June 19, 1981 (see Figure 2).

Analysis of the aerial photograph indicates the flood water was apparently confined in a single channel for a distance of approximately 3300 feet below the mouth of the canyon. Beyond this point to a point about 14,500 feet below the mouth of the canyon the flow continued in a single channel, but the channel width increased. The floodwater then broke out into a radial flow pattern with a 35 degree expansion angle. Further downstream, the flood became a braided-sheet flow with isolated elevated dry patches. The variation of the width for the single channel, obtained from aerial photographs is as follows:

DISTANCE IN FEET	0	2000	3300	4500	10400	12500
WIDTH IN FEET	100	127	137	403	462	383

where the channel distance is measured from the mouth of the canyon.

Two neighboring alluvial fans, subjected to the same thunderstorm on August 7, 1979, were also studied using the same aerial photograph. It was found that these two fan floods, starting with noticeable single channels at the fanhead,



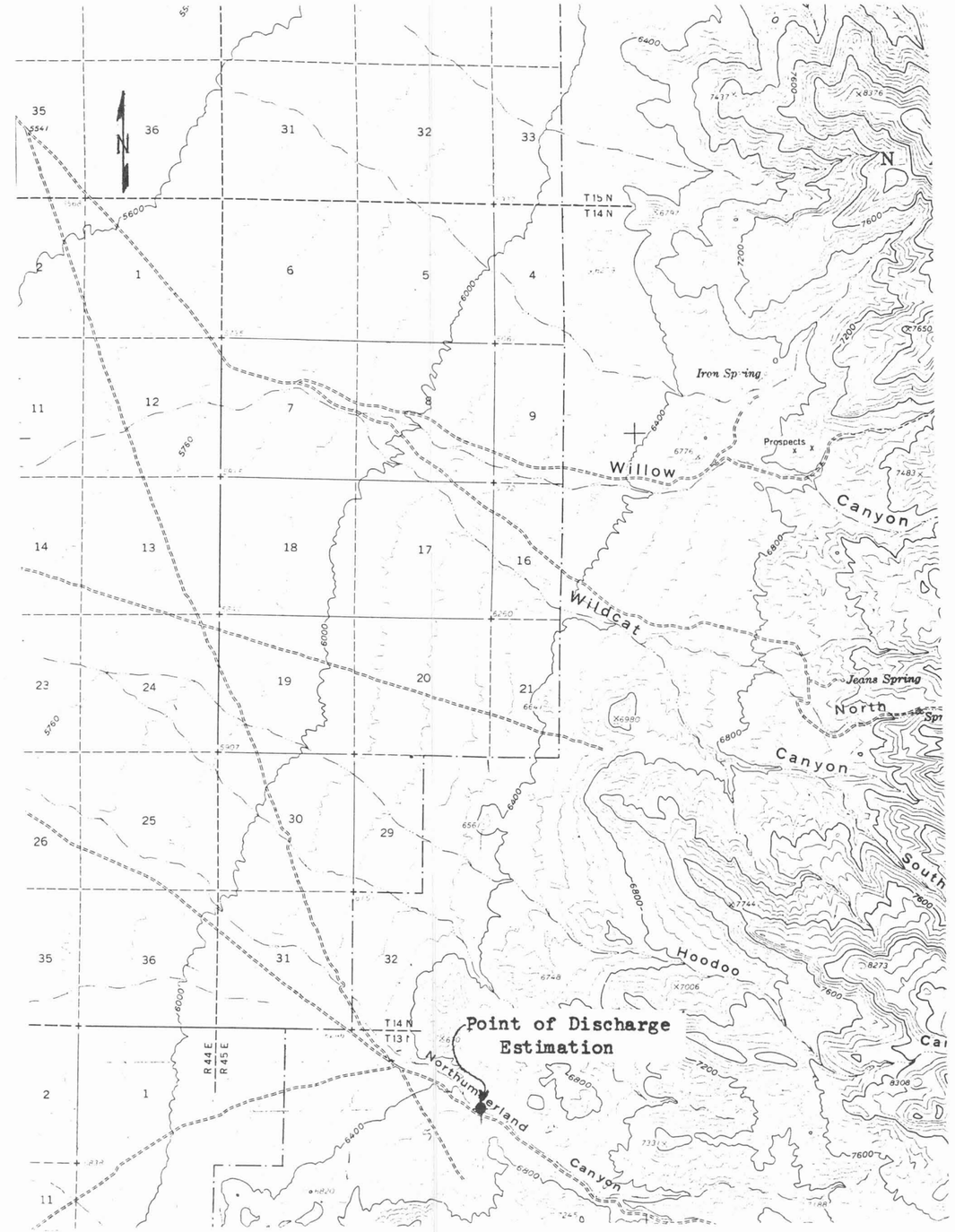


FIGURE 2
Topographic Map and Aerial Photograph of the Alluvial Fan below Northumberland Canyon near Austin Nevada

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spread into a radial sheet flow with an expansion angle of 25 degrees and 40 degrees, respectively. The apex for each individual radial sheet flow appeared to be quite random, but probably depended upon the deposition and erosion patterns resulting from the previous flood, the present discharge, etc. There is evidence of extensive mining at the mountain front and the mine tailings seem to have altered the flow pattern extensively on these neighboring fans.

Mason Valley Tributary near Mason, Nevada

The alluvial fans in this region have been developed by the outwash from tributaries to Walker River in the Mason Valley and are located along the eastern slope of the Singatse Range. The village of Mason is situated on one of the fans and is about 1500 feet below the mouth of the canyon. The upland watersheds are all sparsely vegetated and drained by canyons of relatively mild slope. The alluvial fan on which Mason is located has a slope of 0.035 and an upstream canyon channel slope of 0.058. Although the upstream watershed has a drainage area of only 2.6 square miles, the USGS estimated a peak discharge of 4500 cfs for the flood of June 30, 1970. Two sets of aerial photographs, taken on October 7, 1968, and October 25, 1972, were used to identify the flow patterns of the 1970 flood. The aerial photograph of October 7, 1968, and the topographic map for this alluvial fan are shown in Figure 3. Examination of the aerial photographs showed no clear evidence of flood channels developed on the alluvial fan. There are, however, flood channels identifiable on the two other alluvial fans located south of the gauged alluvial fan. Those two alluvial fans have been developed by McConnell Canyon and Nevada Canyon, respectively (see Figure 3).

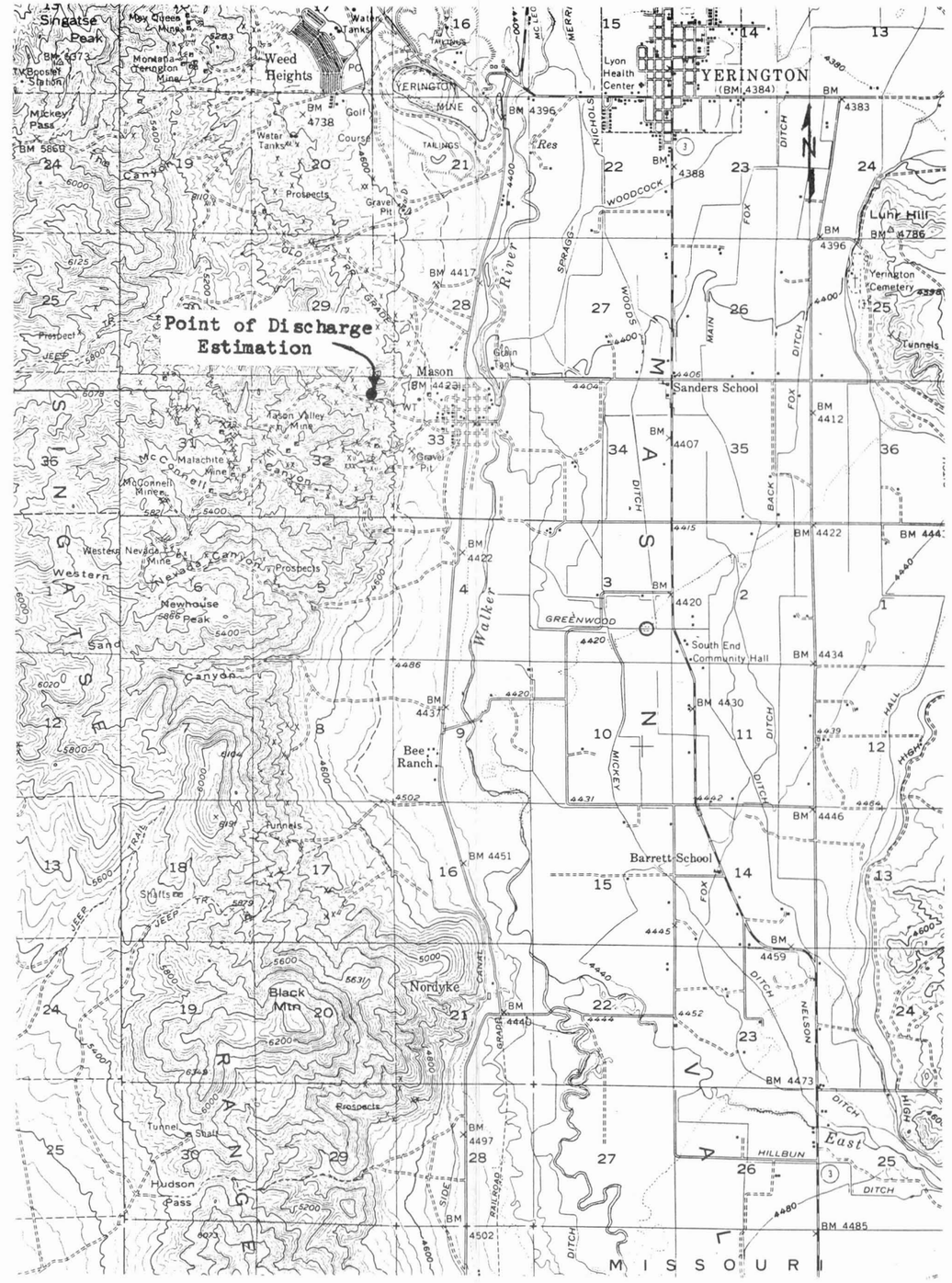

FIGURE 3
Topographic Map and Aerial Photograph of the Alluvial Fan below Mason Valley Tributary near Mason, Nevada

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McConnell Canyon The flood water branched into three channels immediately below the mouth of the canyon. The north channel spreads into a braided-sheet flow with an expansion angle of 20 degrees. The south channel, flowing along the southern boundary of the alluvial fan, bifurcated within a short distance below the mouth of the canyon. After passing the cross-fan West Side Canal, the southmost channel split into three branches but shortly rejoined into an apparently wide sheet flow. The middle channel maintained a single channel flow until it bifurcated shortly after passing the West Side Canal.

Nevada Canyon The flood water split into two branches immediately below the mouth of the canyon. The north branch further split into one large and three small channels. The large channel merged with one of the small channels at the cross-fan West Side Canal, then again separated into two channels of similar width below the West Side Canal. These two channels expanded radially into braided-sheet flows further downstream. One of the other small channels with relatively small flow apparently merged into the West Side Canal. The remaining channel bifurcated after passing the West Side Canal. The south branch consisted of a large and a small channel. The large channel expanded radially in a 30-degree angle while the small channel remained approximately the same width. Both of these channels slightly reduced their widths after passing the West Side Canal.

Comparison of those two sets of aerial photographs showed obvious shifting in major flood channels before and after the flood, even though the channel patterns were similar in appearance. This tends to show that the formation of those flood channels for those fans are random.

Humboldt River Tributary near Rye Patch, Nevada

This alluvial fan is located along the western slope of the Humboldt Range in Nevada. The upland watershed is barely vegetated and has a drainage area of 0.85 square miles. The canyon channel, with a slope of 0.11 near the mouth of the canyon, discharges flood water onto the alluvial fan with a slope of 0.071 and an expansion angle of 90 degrees. Flooding generally results from summer thunderstorm activity. The USGS has estimated a peak discharge of 8940 cfs for the flood of May 31, 1973, which is questionably high judging by the size of watershed. An aerial photograph taken on June 23, 1973 (see Figure 4) was used to determine the flood channel pattern.

The aerial photograph showed that a single channel had been developed near the center of the fan. The channel width of about 35 feet at the mouth of the canyon gradually increased to about 60 feet at a location 500 feet below the canyon mouth. The channel then shifted slightly toward the north and its width reduces to about 40 feet at a location 1,060 feet below the canyon mouth. Below that point, the channel expanded radially into a braided-sheet flow pattern with a 30-degree expansion angle and eventually discharged into the Humboldt River.

Rocky Canyon near Oreana, Nevada

The alluvial fan developed by Rocky Canyon is located along the western slope of the Humboldt Range near Oreana, Nevada. The canyon has a slope of 0.108 near the mouth and drains a sparsely vegetated watershed of 4.05 square miles. The alluvial fan expands in an angle of 110 degrees. The fan slope decreases gradual-

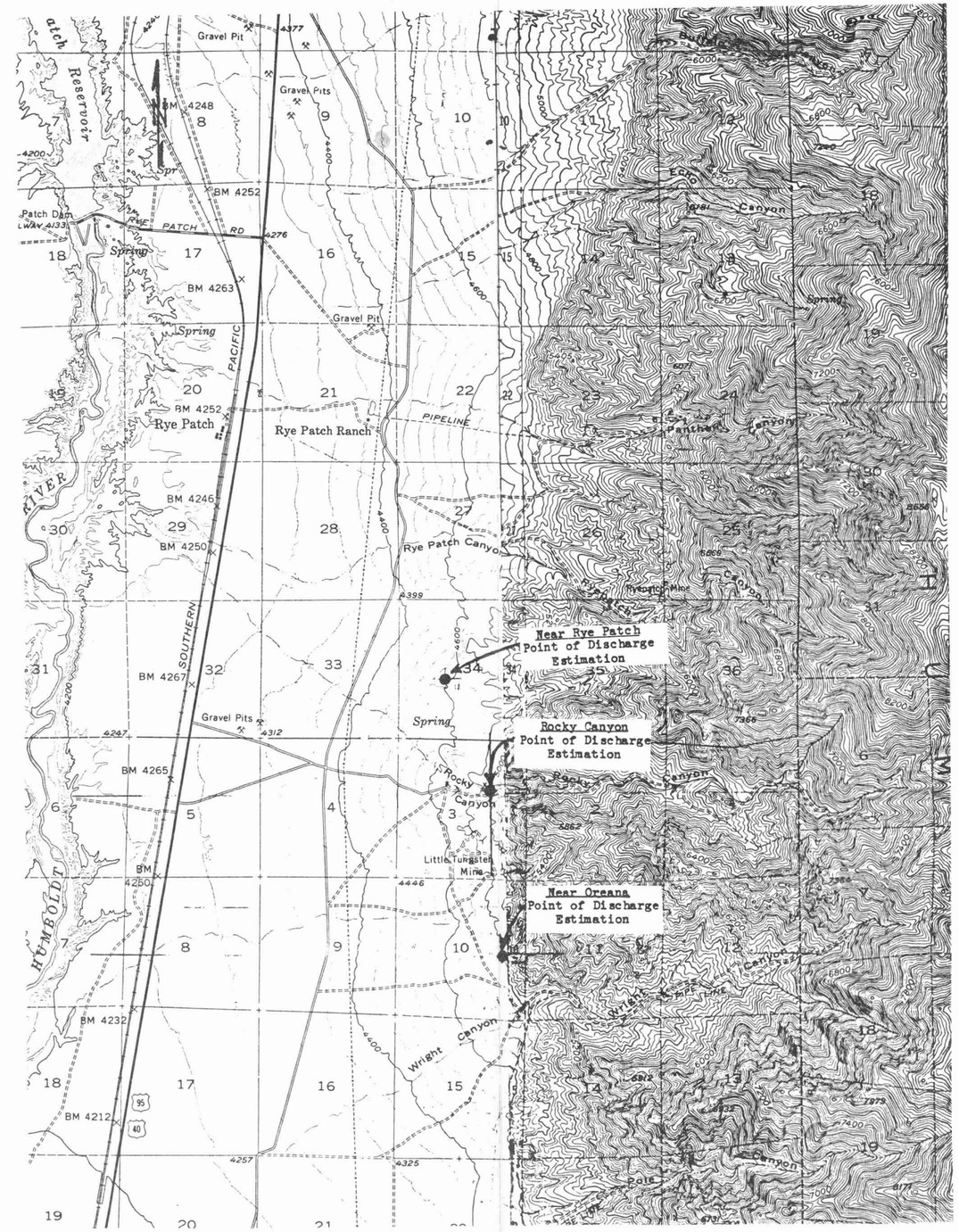

FIGURE 4
Topographic Map and Aerial Photograph of the Alluvial Fans below Humboldt River Trib. Nr Rye Patch and Oreana, and Rocky Canyon, NV

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ly from 0.058 near the canyon mouth to 0.013 near the east bank of the Humboldt River. Floods that discharge onto the alluvial fan are caused by summer thunderstorms. A peak discharge of 14,370 cfs has been estimated by the USGS for the flood on May 31, 1973. The fan flood pattern was identified for the flood of 1973 using an aerial photograph taken on June 23, 1973 (see Figure 4), less than one month after the flood. The flood flow split into two channels at about 1,500 feet above the canyon mouth with the north channel being wider than the south. The north channel, which probably carried the major portion of the floodwater, bifurcates at a point about 1,000 feet below the canyon mouth. The northmost channel further split into two branches at a point about 1,800 feet below the canyon mouth. One of the branches again bifurcates at a point about 2,200 feet below the mouth of the canyon. The south channel maintained a single channel pattern for about 5,000 feet below the canyon mouth and then became braided. Along the middle section of the fan, numerous braided channels apparently developed by previous floods could be seen. This indicated that shifting of flood channels has occurred in the recent past. The south channel maintained a width varying between 70 feet to 90 feet before the channel split at a point about 1000 feet below the canyon mouth.

Humboldt River Tributary near Oreana, Nevada

This alluvial fan, located along the western slope of the Humboldt Range, has been developed by an unnamed small tributary to the Humboldt River. The basin has a drainage area of 0.76 square miles, is sparsely vegetated, and is drained by a canyon with a channel slope of 0.124. The alluvial fan has an expansion angle of 90 degrees. The alluvial fan slope decreases from about 0.07 for the

upfan area to about 0.02 near the east bank of the Humboldt River. Similar to the other Humboldt River tributaries in this area, the fan floods are due to thunderstorm activity. The USGS has estimated a questionably high peak discharge of 6000 cfs for the flood of May 31, 1973. The fan flood pattern was identified using the aerial photograph of June 23, 1973 (see Figure 4). The flood channel bifurcated near the middle section of the fan immediately below the canyon mouth. The channel on the south apparently transported the major portion of the floodwater, and maintained a nearly constant width of 45 feet for some 1,500 feet and then became braided. The channel on the north traveled as a single channel for 1,300 feet, then bifurcated and rejoined after 4,200 more feet. Numerous highly braided old flood channels at the outfan area could be seen from the same aerial photograph. This indicates the likely tendency of channel relocation in future flood events on this fan.

Las Vegas Wash Tributary near Henderson, Nevada

The Las Vegas Wash is composed of many alluvial fans that have been developed by the canyons originating from the northern slope of the McCullough Range near Henderson, Nevada. These canyons flow mostly northward and eventually discharge into Duck Creek. The upstream watersheds of the canyons have little vegetation. The principal cause of floods is summer thunderstorms. The USGS maintains a gaging station, #09419697, on one of the alluvial fans, which measures stream discharge from an upstream watershed of 0.06 square miles. The alluvial fan slope extends into the canyon upstream of mountain front. The canyon draining this watershed has a slope of 0.058. The alluvium below the canyon is narrowly confined by the adjacent alluvial fans on both sides and has a slope of 0.050.

The major floods recorded by the USGS gaging station during the observation period had peak discharges of 655 cfs occurring on July 30, 1968, and 1290 cfs on July 1, 1980.

The flood channel pattern for Las Vegas Wash was studied using four sets of aerial photographs taken respectively on October 21, 1971, December 20, 1972, June 25, 1975, and July 4, 1980 (see Figure 5). Examination of the aerial photographs showed that the flood water flowed in a single channel 68 feet wide for 3,075 feet below the mouth of the canyon. The flood flow then merged with the flow from the adjacent fan and changed to a braided-sheet flow pattern further downstream. Comparison of aerial photographs taken on different dates further indicated that there was no apparent channel change during the period covered by the aerial photographs. One additional alluvial fan in the Las Vegas Wash area, designated as Fan A, with a canyon slope of 0.061 and fan slope of 0.056, was selected for the study using the same aerial photographs. The flood water in Fan A flowed in a single channel 183 feet wide for 3,250 feet below the canyon mouth, and then split and eventually changed into a braided-sheet flow. There were no apparent changes in channel pattern during the period 1971 - 1980.

Piute Wash Tributary at Searchlight, Nevada

The alluvial fan under consideration is only one of the many alluvial fans composing the Piute Wash near Searchlight, Nevada. This alluvial fan has been developed by the outwash from a canyon draining a watershed of 3.4 square miles. The alluvial deposit extends into the canyon upstream of the mountain front. The

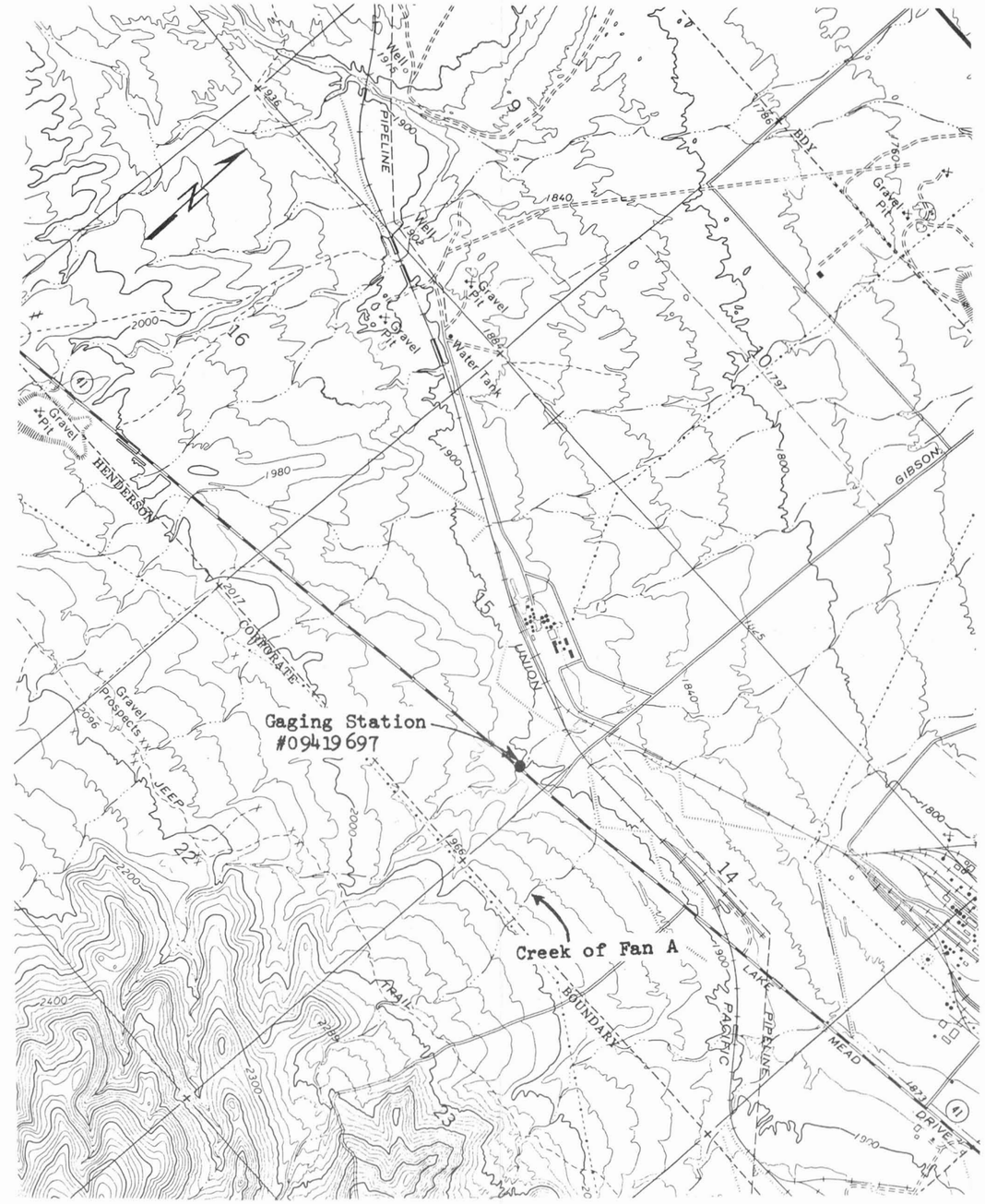

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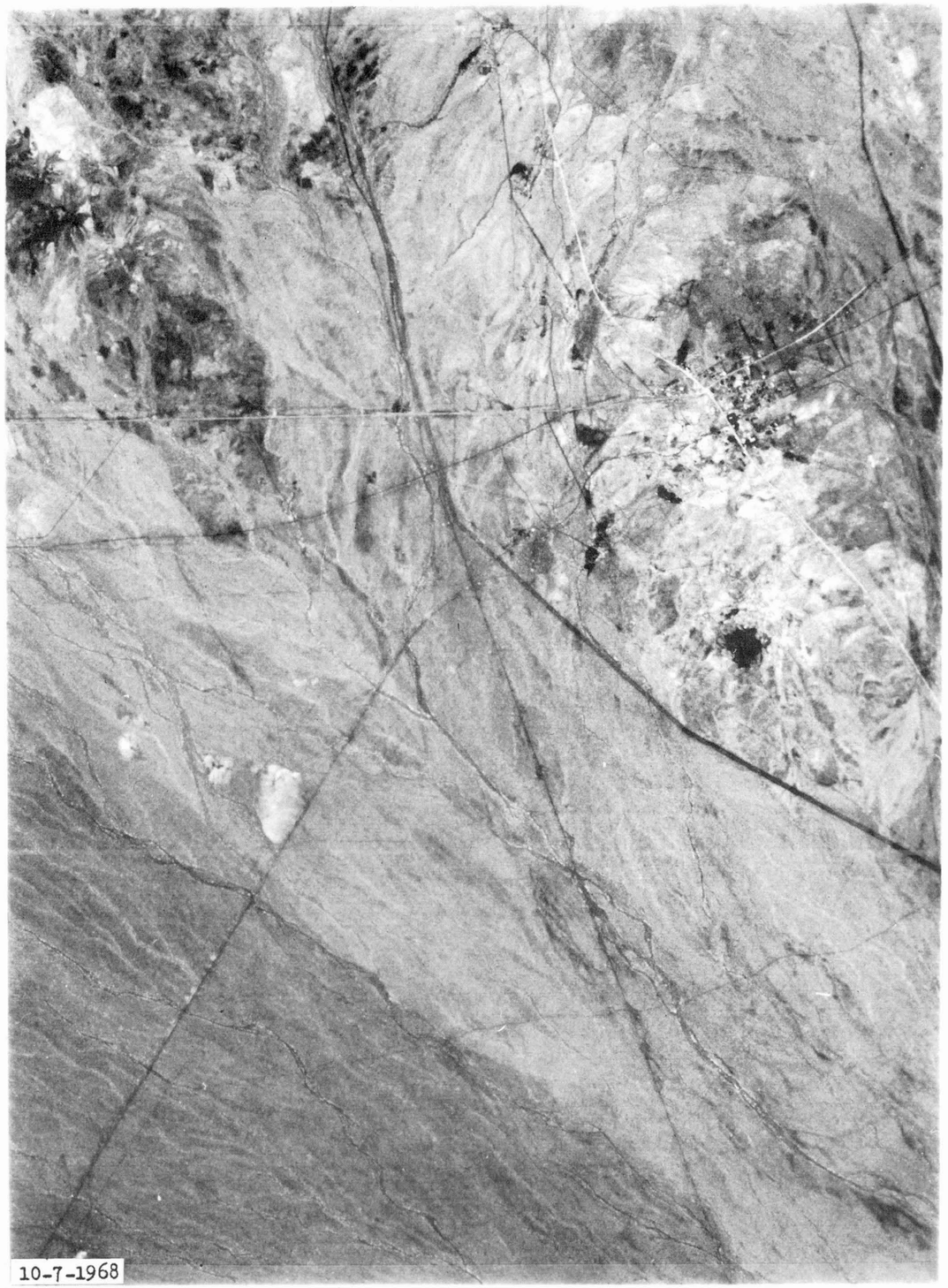
FIGURE 5
Topographic Map and Aerial Photograph of the Alluvial Fan below Las Vegas Wash Tributary near Henderson, Nevada

canyon therefore has a very mild slope of 0.016 near the canyon mouth. Similar to the other alluvial fans in the Piute Wash the studied alluvial fan has a mild slope of 0.016 and coalesces with the adjacent tributaries to form an apron characterized by straight, parallel contours. Summer thunderstorms, characteristic of this area, cause fan flood. USGS gaging station #09423300, located near the mouth of the canyon, recorded such floods with peak discharges of 207 cfs on August 4, 1970, 370 cfs on September 11, 1976, and 200 cfs on August 12, 1978.

The fan flood channel pattern was identified using an aerial photograph taken on October 7, 1968 (see Figure 6). The flood water flowed in a single channel down the fan to the confluence with the channel from an adjacent fan. This seemed to be the typical flood channel pattern in the wash, probably resulting from the lack of slope in the radial direction which generally characterizes other alluvial fans.

San Antonio Wash Tributary near Tonopah, Nevada

San Antonio Wash near Tonopah, Nevada, consists of many alluvial fans developed



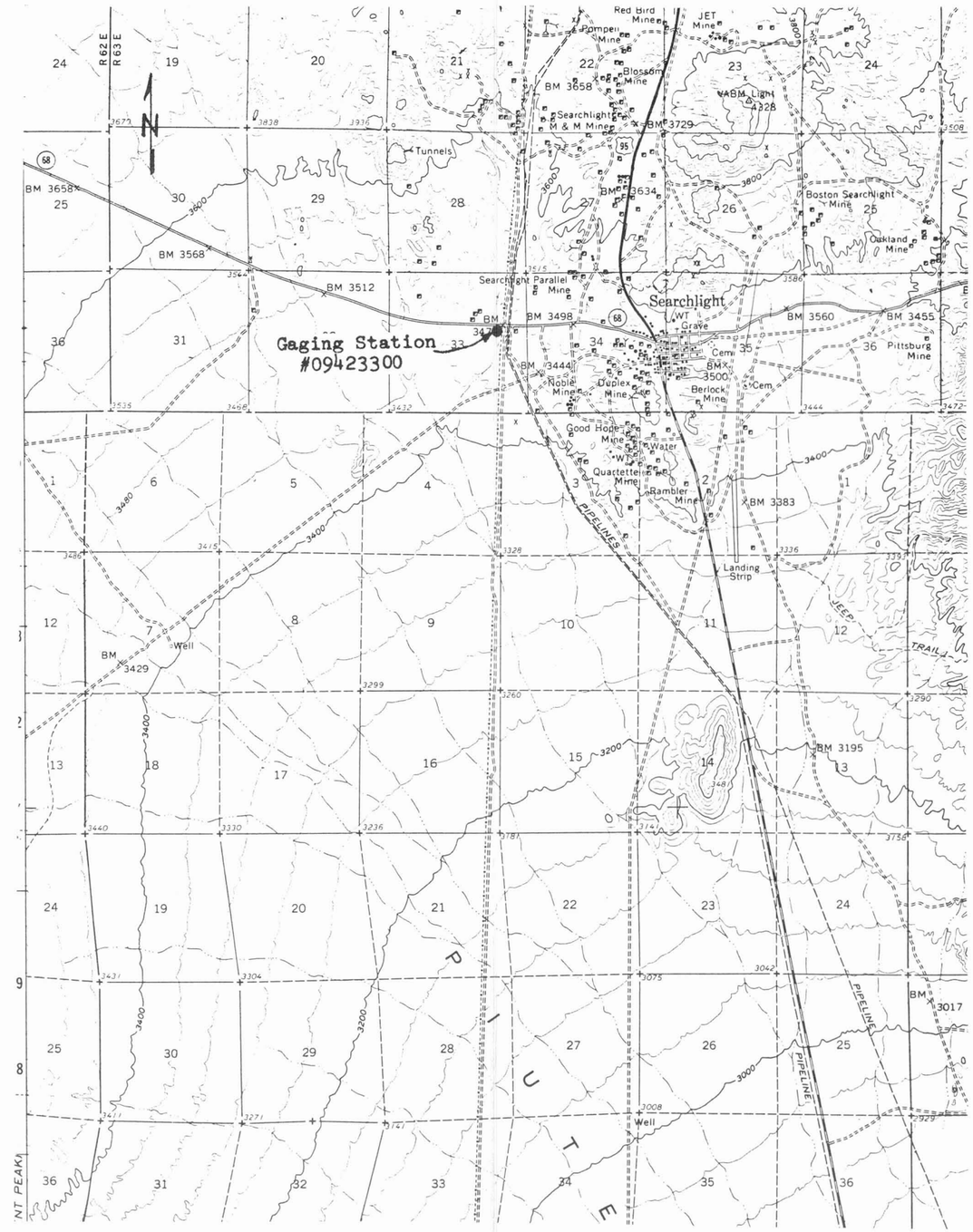


FIGURE 6
Topographic Map and Aerial Photograph of the Alluvial Fan below Piute Wash Tributary at Searchlight, Nevada

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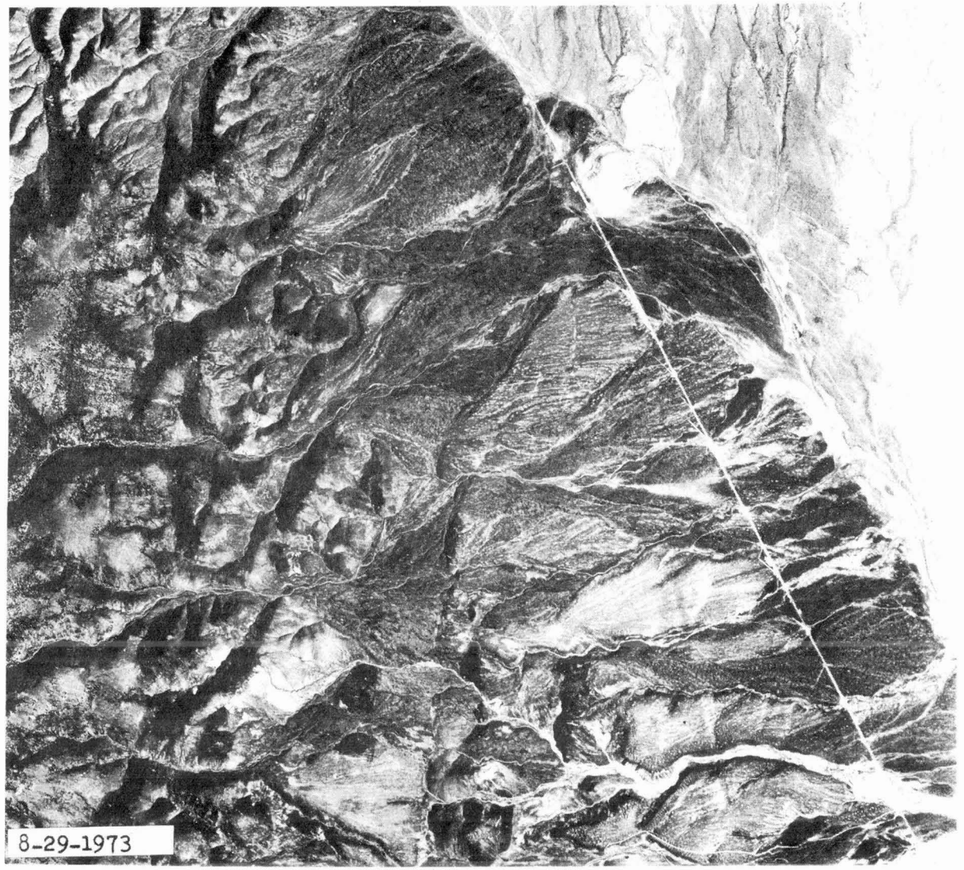
by tributaries originating from the eastern slopes of the San Antonio Mountains. The upland watersheds are sparsely vegetated and the fan floods result from summer thunderstorms. USGS gaging station #10249135 is situated near the toe of one of the alluvial fans in the area. The upstream watershed above the gaging station has a drainage area of 3.42 square miles and is drained by a canyon with a slope of 0.070. The alluvial fan below the gaging station has an expansion angle of 60 degrees and a slope of 0.053. The maximum recorded fan flood had a peak discharge of 660 cfs on August 13, 1972. An aerial photograph taken on August 29, 1973 (see Figure 7) was used to determine the channel patterns for the fan floods. The aerial photographs showed an elevated ridge with three openings spanning across the fan width about two miles below the apex. Several isolated hills are located downstream from the ridge on the southern section of the fan. The flood water flowed in a single channel near the northern boundary of the fan for a distance of 2,250 feet from the mouth of the canyon. Below this point it branched into numerous channels covering the northern half of the fan. Those channels, obstructed by the cross-fan ridge, concentrated and passed through the ridge at three openings to lead to three individual downstream alluvial fans. For the northern downstream alluvial fan the flow stayed in a single channel for 3,000 feet below the opening of the ridge. Beyond this point the channel bifurcated and rejoined within 1,750 feet and stayed as a single channel to the fan toe. For the middle downstream alluvial fan the flood water flowed in a single channel along the southern boundary of this fan. It collected flows from two small channels originating outside the fan before reaching the fan toe. For the southern downstream alluvial fan there was no evidence of flood channels. A well defined channel was, however, located slightly off and parallel to the southern border of the fan.



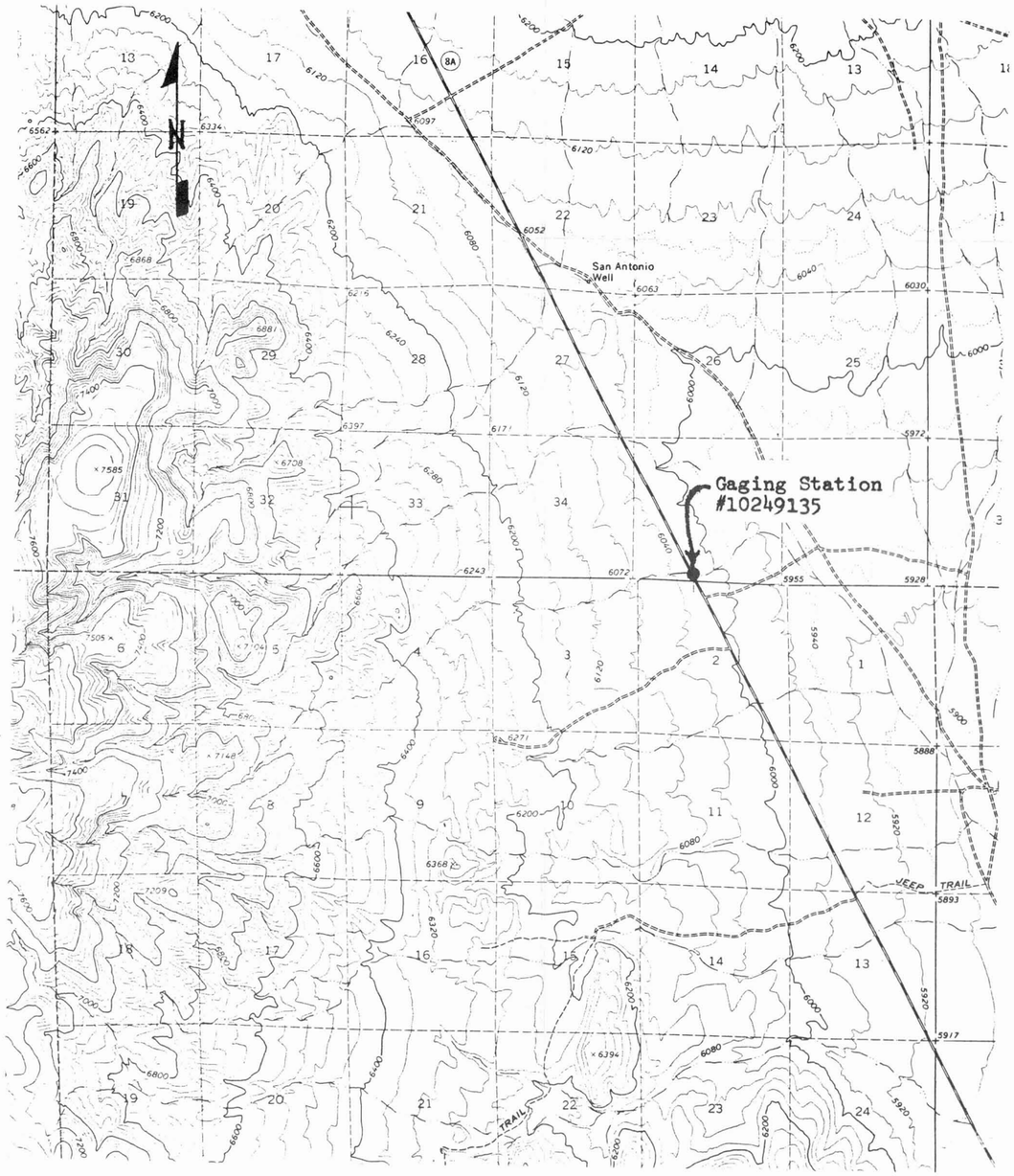


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FIGURE 7
Topographic Map and Aerial Photograph of the Alluvial Fan below San Antonio Wash Tributary near Tonopah, Nevada

Eldorado Valley Tributary near Nelson, Nevada

These alluvial fans are developed by tributaries originating from the Eldorado Mountains near Nelson, Nevada. The upstream watersheds for these tributaries have little vegetation and floods result from thunderstorm activity. The alluvial fans coalesce to form an alluvial apron a short distance below the canyon. USGS gaging station #10248510 is located at one of the canyons, which drains an upstream watershed of 1.4 square miles. The alluvial deposit extends into the canyon above the mountain front to result in a canyon slope of 0.036 near the canyon mouth. The alluvial fan below this canyon has a similar slope of 0.036. The gaging station has recorded floods with peak discharges of 530 cfs on August 4, 1970, and 232 cfs on June 8, 1972. Two sets of aerial photographs, taken on May 12, 1972, and July 24, 1973 (see Figure 8 for the latter), respectively, were used to identify the flood channel pattern on the fan. The aerial photographs showed that the flood water flowed in a wide, shallow, and not well-defined channel for about 2000 feet below the canyon mouth. Downstream of that point it changed into a braided-sheet flow pattern and eventually coalesced with the flows from the adjacent fans in a complete sheet flow pattern. The above observed flood channel pattern seemed to be typical for the fans in this area.

A comparison of the two sets of aerial photographs indicated that there was no obvious change in channel pattern and locations although a flow of 232 cfs occurred in the period between the times that these two sets of aerial photographs were taken.

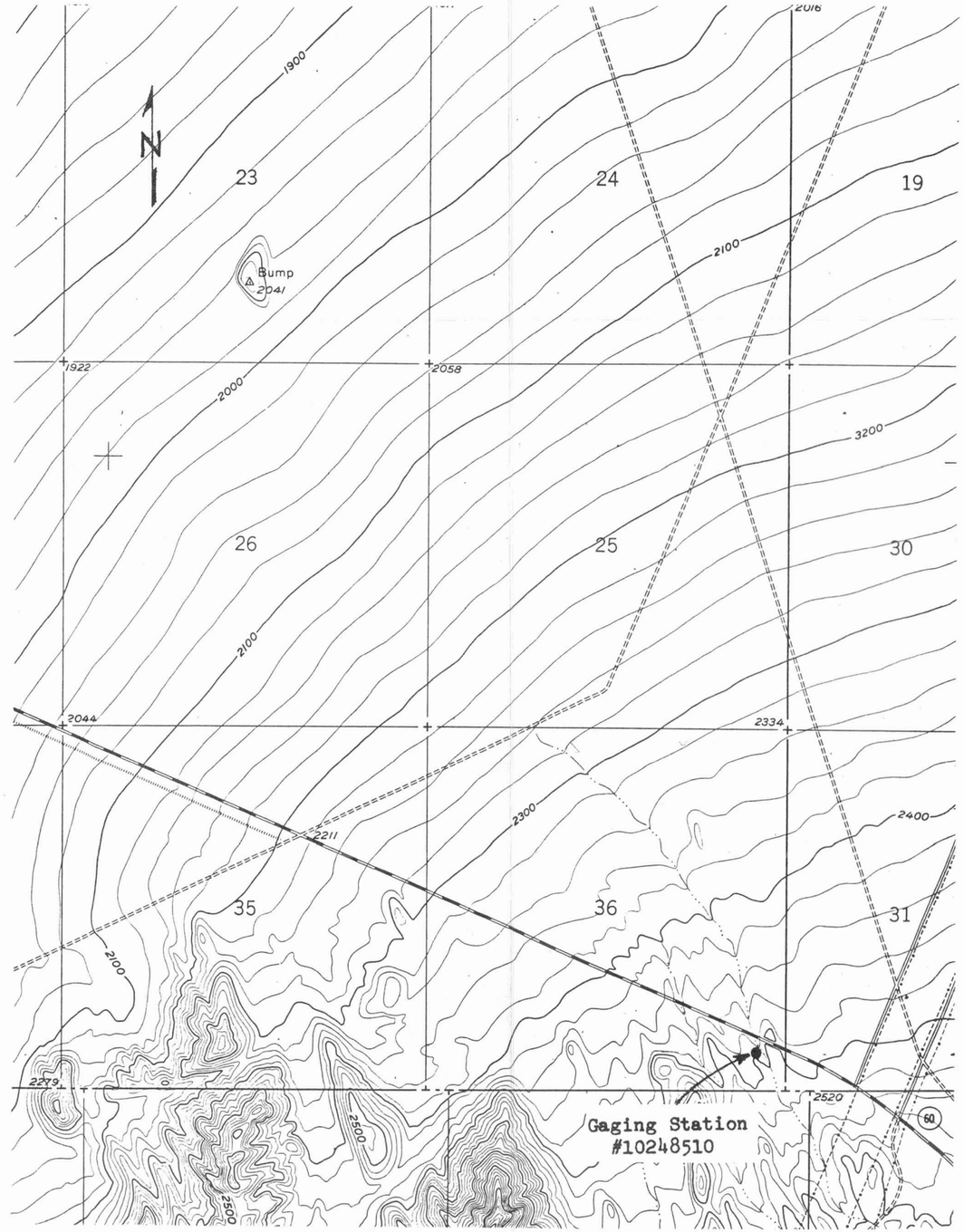

FIGURE 8
Topographic Map and Aerial Photograph of the Alluvial Fan below Eldorado Valley Tributary near Nelson, Nevada

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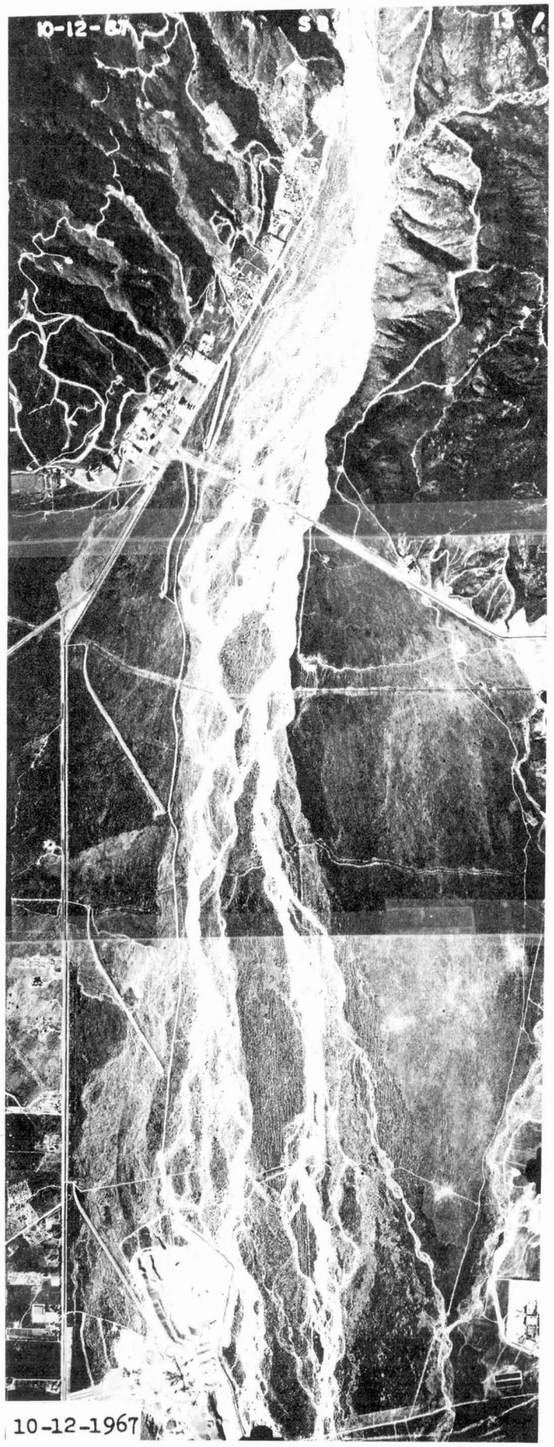
Lytle Creek near Fontana, California

The alluvial fan developed by the outwash from Lytle Creek is located at the northern end of Fontana, California. Lytle Creek, originating from the San Gabriel Mountains, has an upstream watershed of 46.3 square miles. The canyon slope is about 0.031 near the mouth of the canyon. The upstream watershed is vegetated with sparse forests. The climate is mesothermal humid, of Mediterranean type with hot dry summers, and abundant winter rainfall in the mountains. The major fan floods are usually caused by the winter storms with intensive short duration rainfall. The alluvial fan below Lytle Creek has an expansion angle of 95 degrees and a slope of 0.026 at the upfan area. Lytle Creek flows on the fan to meet Cajon Creek about three miles below the mouth of the canyon. The alluvial fan is densely developed and is protected by levees along many sections of the creek. USGS gaging station #11062000 is situated about one mile above the mouth of the canyon. The discharge recorded by the gaging station shows great variation over the observation period. For instance, the annual peak discharge ranged from 65 cfs on April 28, 1951, to 25,200 cfs on March 2, 1938, and 35,900 cfs on January 25, 1969.

The fan flood patterns and their potential changes due to major floods were identified using the aerial photographs of April 13, 1933, September 8, 1935, March 10, 1938, April 17, 1967, October 12, 1967 (see Figure 9), January 30, 1969, and March 4, 1969. Examination of the aerial photographs indicated that the canyon became wider below the Penstock Ridge, located about one mile above the mouth of the canyon, and that the flood waters flowed in almost a single



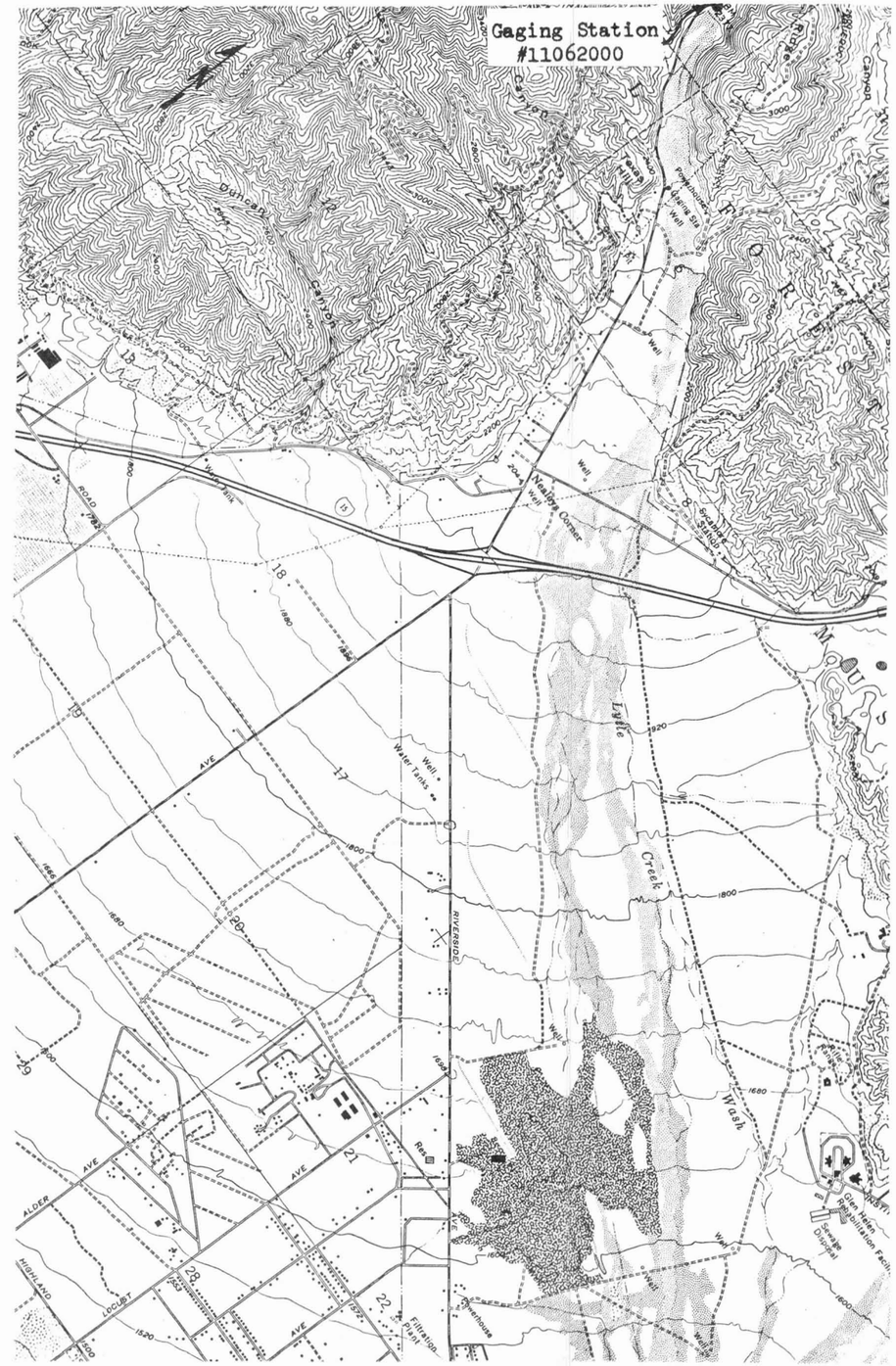


FIGURE 9
Topographic Map and Aerial Photograph of the Alluvial Fan below Lytle Creek near Fontana, California

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channel with some isolated dry patches. The flood however, became highly braided from about one mile below the mouth of the canyon to its confluence with Cajon Creek.

Comparison of aerial photographs of 1935 and March 10, 1938 indicated that the flood of March 2, 1938, with a peak discharge of 25,200 cfs, essentially followed the old channels developed by previous floods from the mouth of the canyon to its confluence with Cajon Creek. Comparison of aerial photographs of 1967 and 1969 also indicated similar flood channel patterns and channel locations before and after the 1969 flood with 35,900 cfs peak discharge. The above findings indicated that the major fan floods essentially follow the previous channels and, if they exceeded the channel capacity, widened and deepened the channels by erosion to accommodate the flood flow.

Day Creek near Etiwanda, California

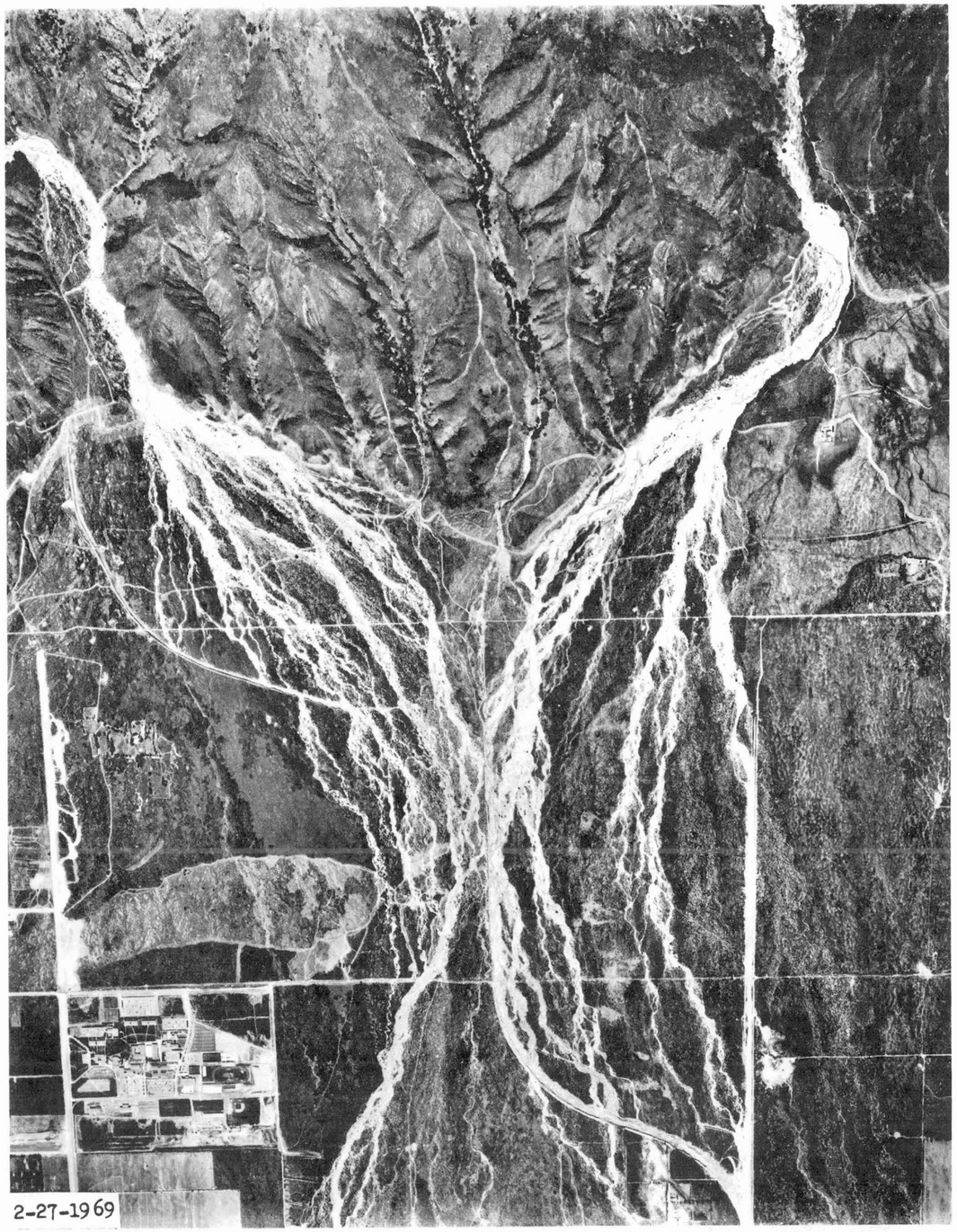
Day Creek originates in the southern part of the San Gabriel Mountains, has a canyon slope of 0.149 near the canyon mouth, and drains an upstream watershed of 11.9 square miles. The upstream watershed is covered with sparse forests. The alluvial fan has a slope of 0.103 near the fan head and gradually decreases in the radial direction. The expansion angle of the fan is about 80 degrees. The fan floods in Day Creek are usually caused by winter storms between November and April. The annual peak discharge in Day Creek varied from 16 cfs on April 1, 1964, to 4,200 cfs on March 2, 1938, and 9,500 cfs on January 25, 1969, as recorded by USGS gaging station #11067000, located at the mouth of Day Canyon. The alluvial fan has been only sparsely developed in the far fan area, and

vineyards and orchards are the most common land use of the fan. To protect those developments, levees have been built to confine the flood water to the western part of the fan, and they eventually direct the flow to a lined channel at the far fan area.

The channel pattern for major fan floods was identified using the aerial photographs of September 8, 1935, March 10, 1938, March 30, 1966, January 30, 1969, and February 27, 1969 (see Figure 10). The aerial photographs show that the flood water flowed in a single channel about 268 feet wide along the west boundary of the fan for 2,400 feet below the mouth of the canyon. Below this point, the width of the channel increased to about 870 feet at a point about 3,660 feet below the canyon mouth. Beyond, the flood channel repeatedly bifurcated to cover almost the entire eastern half of the fan (see Appendix A). The flood water within this region, however, was confined by two levees, which gradually tapered to form a single channel for Day Creek to pass through Etiwanda.

The aerial photographs of 1935 and 1938 were used to determine changes in flood channel patterns due to the fan flood occurring on March 2, 1938. Except for a new channel about 15 feet wide and 5700 feet long branched from the single channel reach, no apparent change in channel pattern was detected.

Comparisons of the aerial photographs of 1938 and 1966 showed that the flood channel pattern remained essentially unchanged except for those areas affected by the levees constructed after 1938.



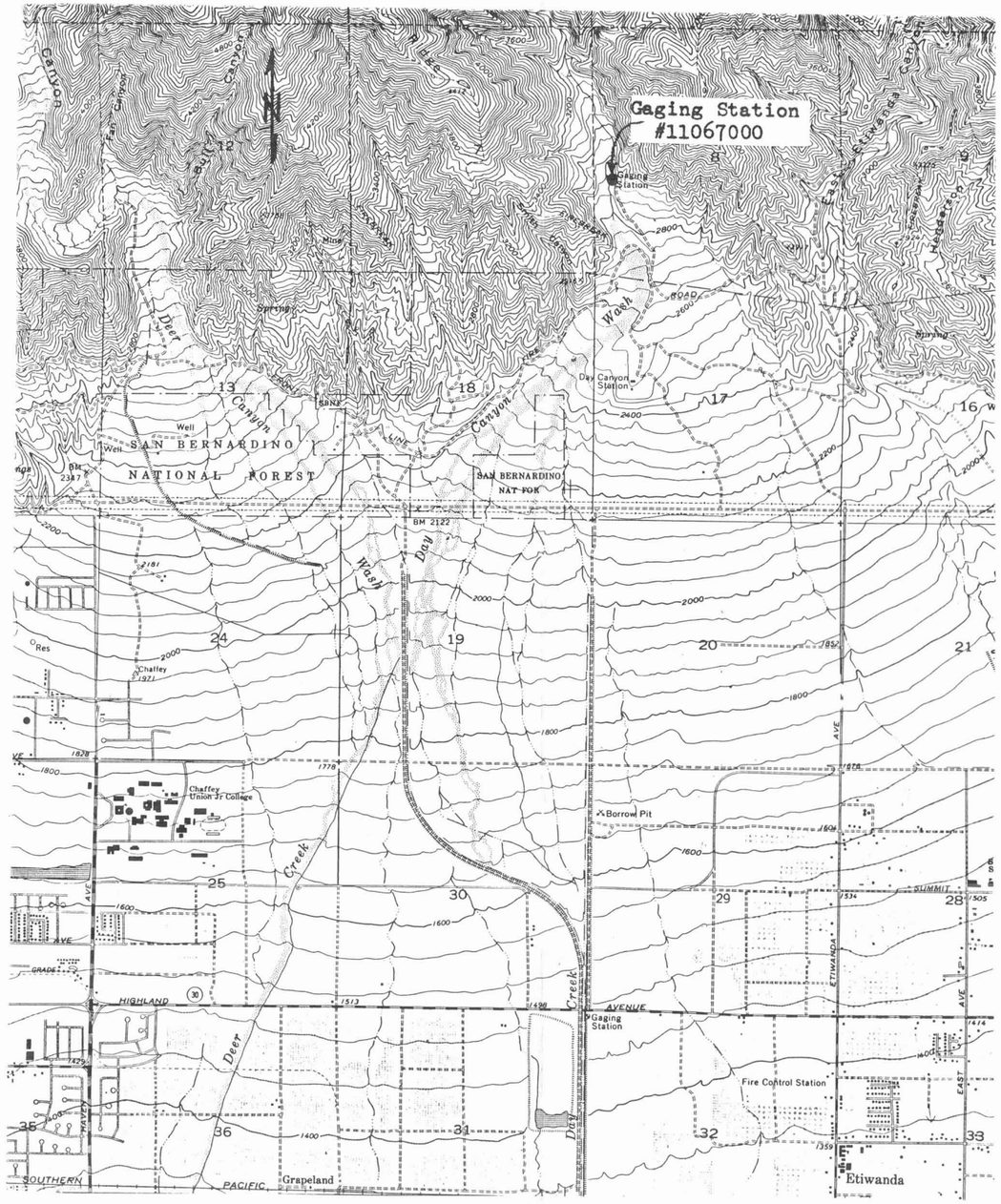


FIGURE 10
Topographic Map and Aerial Photograph of the Alluvial Fan below Day and Deer Canyons near Etiwanda, California

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Comparison of the aerial photographs of 1966 and 1969 also showed that the flood of January 25, 1969 flowed essentially in the channels developed by previous floods.

The above findings on the flood channel patterns tends to indicate that the flood channels in this case are rather stable even when subjected to a wide range of flood discharge.

Deer Creek near Guasti, California

Deer Creek alluvial fan is located west of and adjacent to Day Creek alluvial fan at the southern foothills of the San Gabriel Mountains. Deer Canyon has a slope of 0.168 and drains an upstream watershed of 3.4 square miles and is covered with sparse forests. The alluvial fan below Deer Canyon has an expansion angle of 90 degrees and a slope of 0.109 near the fanhead. There is no gaging station installed at Deer Canyon. However, it is reasonable to assume that the same winter storms that caused floods to the adjacent Day Creek would also cause floods on Deer Creek. Therefore, the aerial photographs used to determine the flood channel pattern for Day Creek could be used for Deer Creek as long as they covered the Deer Creek area (See Figure 10).

Examination of aerial photographs indicated that at about 600 feet immediately below the mouth of the canyon the flood flow changed from a single channel flow to a highly braided-sheet flow covering the eastern half of the alluvial fan. The flood water continued to flow southeastward until it was deflected back to the southwest direction at the boundary between the Deer and Day alluvial fans.

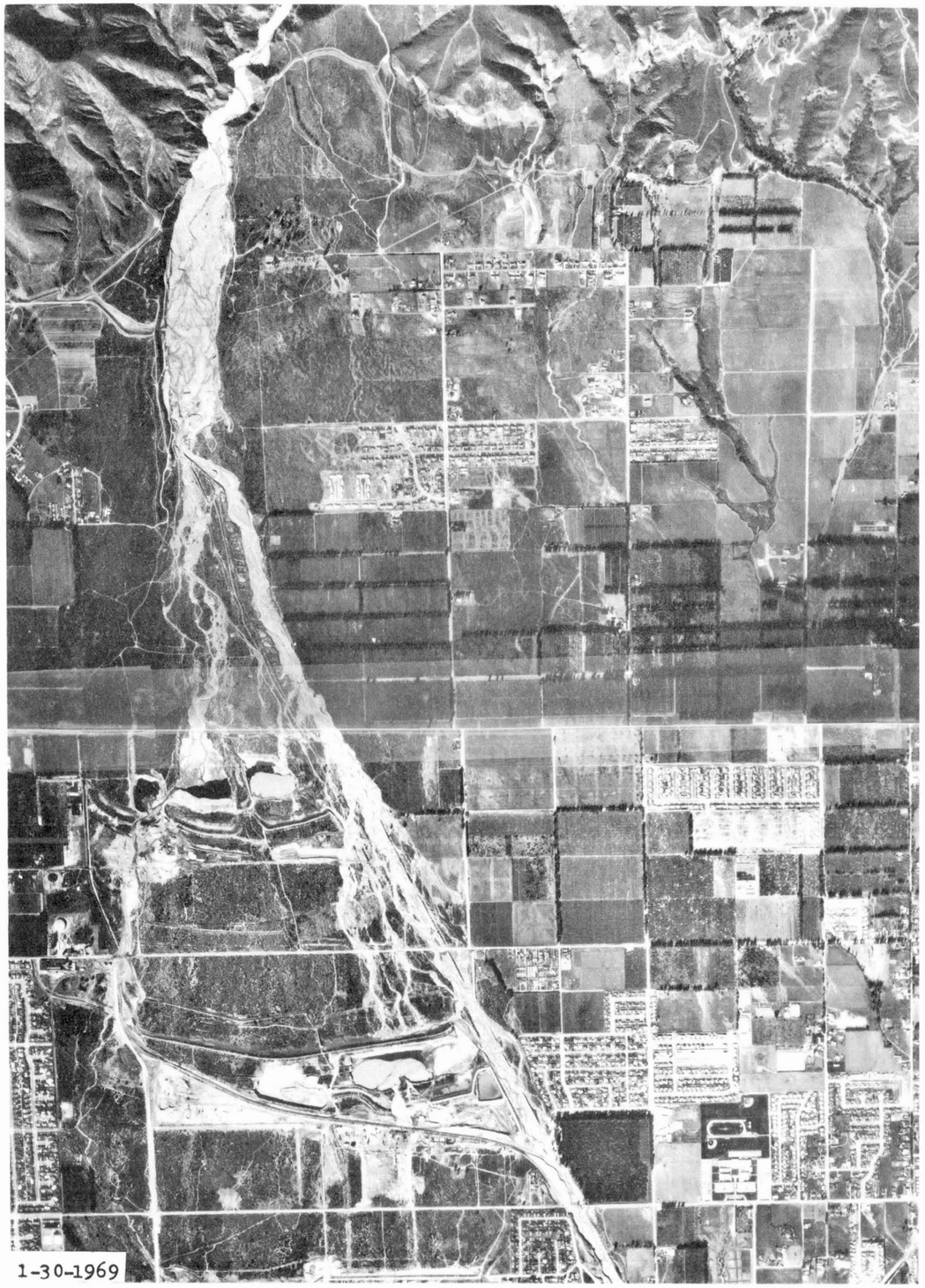
Comparison of aerial photographs for January 30 and February 27, 1969, indicated no apparent change in flood channels as a result of February 25, 1969 flood. The Deer Creek channels may be considered stable in this case.

Cucamonga Creek near Upland, California

Cucamonga Canyon, with a slope of 0.075, drains a sparsely forested upstream watershed of 10.1 square miles in the southern margin of the San Gabriel Mountains. The alluvial fan has a slope of 0.048 near the fanhead. An entrenched channel about 20 feet deep has developed within the 1.5 mile reach below the mouth of the canyon. A series of percolation basins has been built in this reach. For the next two miles, more percolation basins, incorporating levees, have been built to confine the flood water along the east side of the percolation basins. Further downstream, Cucamonga Creek is confined by levees on both banks to transport the flood water through the alluvial fan.

The discharge for Cucamonga Creek is usually less than 5 cfs for most of the year. Major floods, however, result from high-intensity short-duration winter storms. USGS gaging station #11073470, located at the mouth of the canyon, has recorded major floods with peak discharges of 10,300 cfs on March 2, 1938, 14,100 cfs on January 25, 1969, and 4,090 cfs on February 25, 1969.

The channel patterns for major floods were identified using the aerial photographs of March 10, 1938, January 30, 1969 (see Figure 11), and February 27, 1969, each taken shortly after a major flood event.



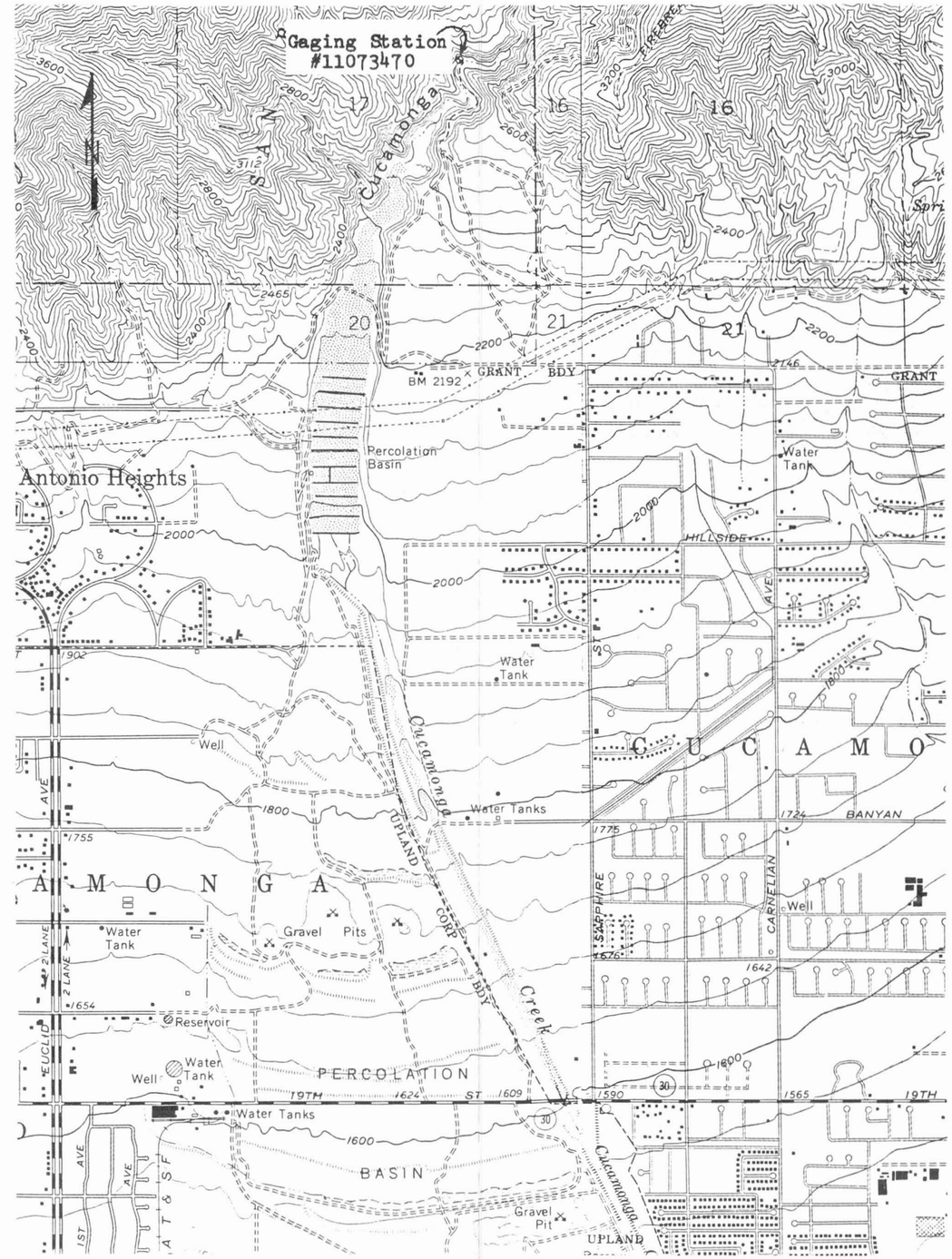


FIGURE 11
Topographic Map and Aerial Photograph of the Alluvial Fan below Cucamonga Creek near Upland, California

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Examination of aerial photographs indicated that the flood water occupied the entire channel within the 1.5 mile reach below the canyon mouth probably as a result of the obstruction by percolation basins. Below that reach the flood water was mainly transported by the channel located east of the lower percolation basins. When flood water exceeded the channel capacity it spilled over the levees to form small braided-sheet flows in the lower percolation basins and split-braided flow along Cucamonga Creek. Channel patterns remained essentially unchanged except for those areas being affected by new structures constructed after 1938, and for a slightly wider flooded area for the larger flood of 1969. Aerial photographs of January 30 and February 27, 1969, indicated that the flood water for the smaller flood of February 25, 1969 essentially followed the old channels developed by the previous flood of January 25, 1969. The above findings on the flood channel patterns tend to support the conclusion that the flood channels are relatively stable in this case.

San Antonio Creek near Claremont, California

San Antonio Creek alluvial fan is located near Claremont, California. San Antonio Canyon has a slope of 0.055 and drains a sparsely forested upstream watershed of 26.2 square miles in the southern margin of the San Gabriel Mountains. The alluvial fan expands from the apex with a 90 degree angle and has a slope of 0.046 for the upfan area. San Antonio Dam, a flood-control reservoir with a capacity of 7,620 acre-feet, is located at the mouth of the canyon. A spillway is situated at the west end of the dam to release flood water to San Antonio Creek. Percolation basins are built on either side of the channel for

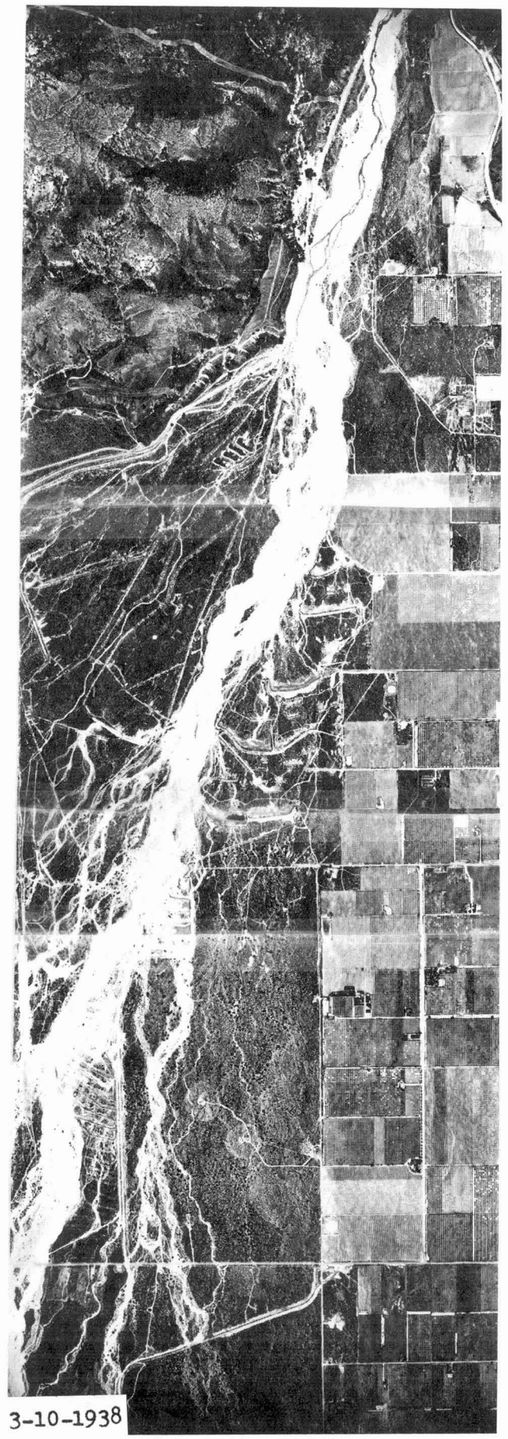
groundwater recharge. The major fan floods here are usually caused by winter storms. USGS gaging station #110730000, located about 4 miles above the mouth of the canyon, recorded a peak discharge of 21,400 cfs for the flood on March 2, 1938. USGS gaging station #11073200, located at the outlet channel of San Antonio Dam, recorded a maximum flood water release of 8,420 cfs on January 25, 1969, the largest since the initial operation of the gaging station in 1962.

The only set of aerial photographs available to identify the flood channel pattern on San Antonio alluvial fan were taken on March 10, 1938 (see Figure 12), about one week after the major flood of March 2, 1938. San Antonio Dam had not yet been built. The aerial photographs show that the flood water flowed in a single channel, restricted along the east bank by a series of percolation basins and levees for about 8,200 feet below the mouth of the canyon. Below this reach the channel bifurcated. The variation of channel width with distance measured from the mouth of the canyon is as follows:

DISTANCE IN FEET	0	1200	3400	4950	7900
WIDTH IN FEET	810	355	690	410	550

<u>Tahquitz Creek near Palm Springs, California</u>

Tahquitz Canyon drains an upstream watershed of 43.5 square miles in the San Jacinto Mountains with a slope of 0.111. It is well vegetated in the highlands but barely vegetated in the lowlands. The alluvial fan, with a slope of 0.046, has experienced development as part of the growth of the city of Palm Springs.



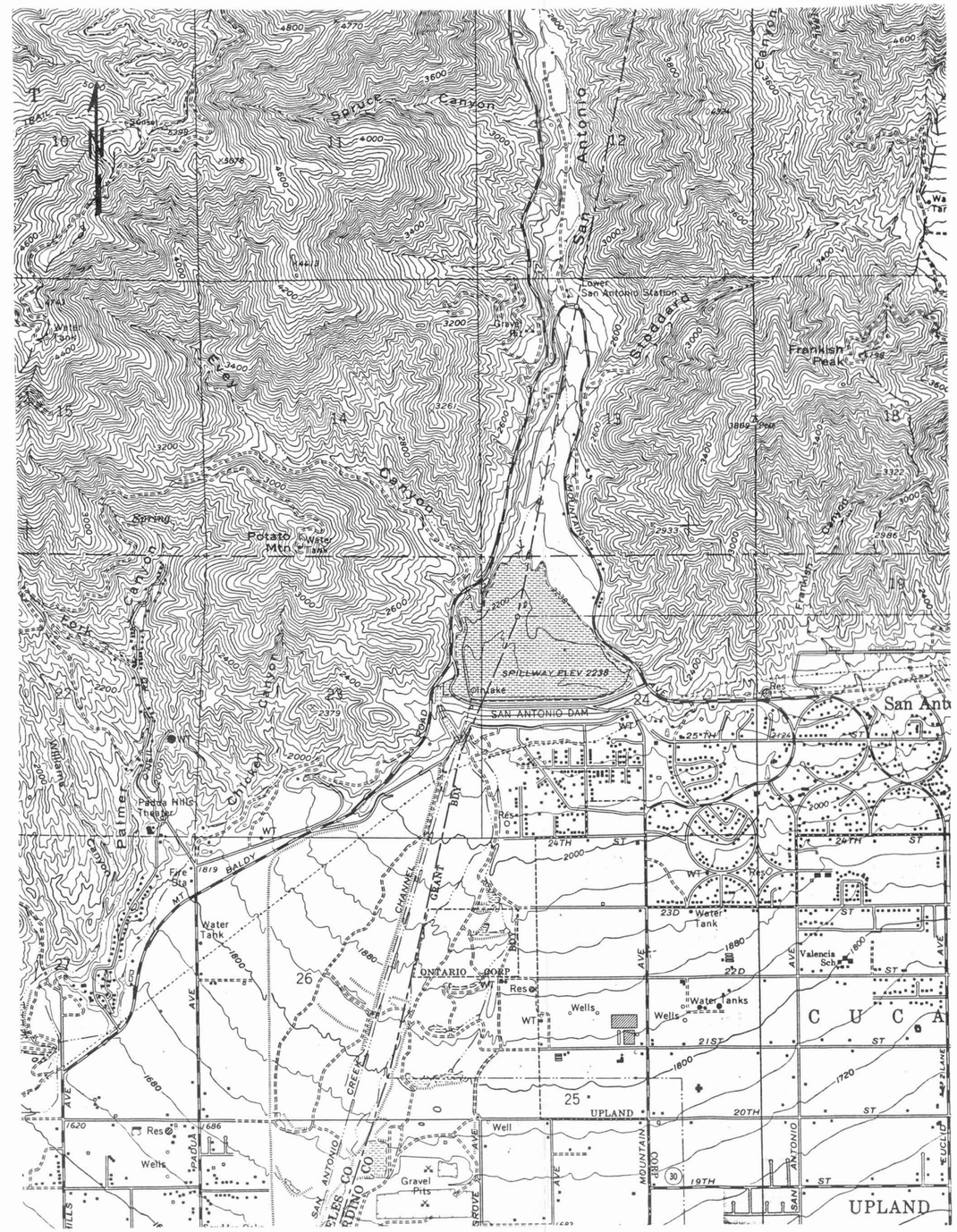


FIGURE 12
Topographic Map and Aerial Photograph of the Alluvial Fan below San Antonio Creek near Claremont California

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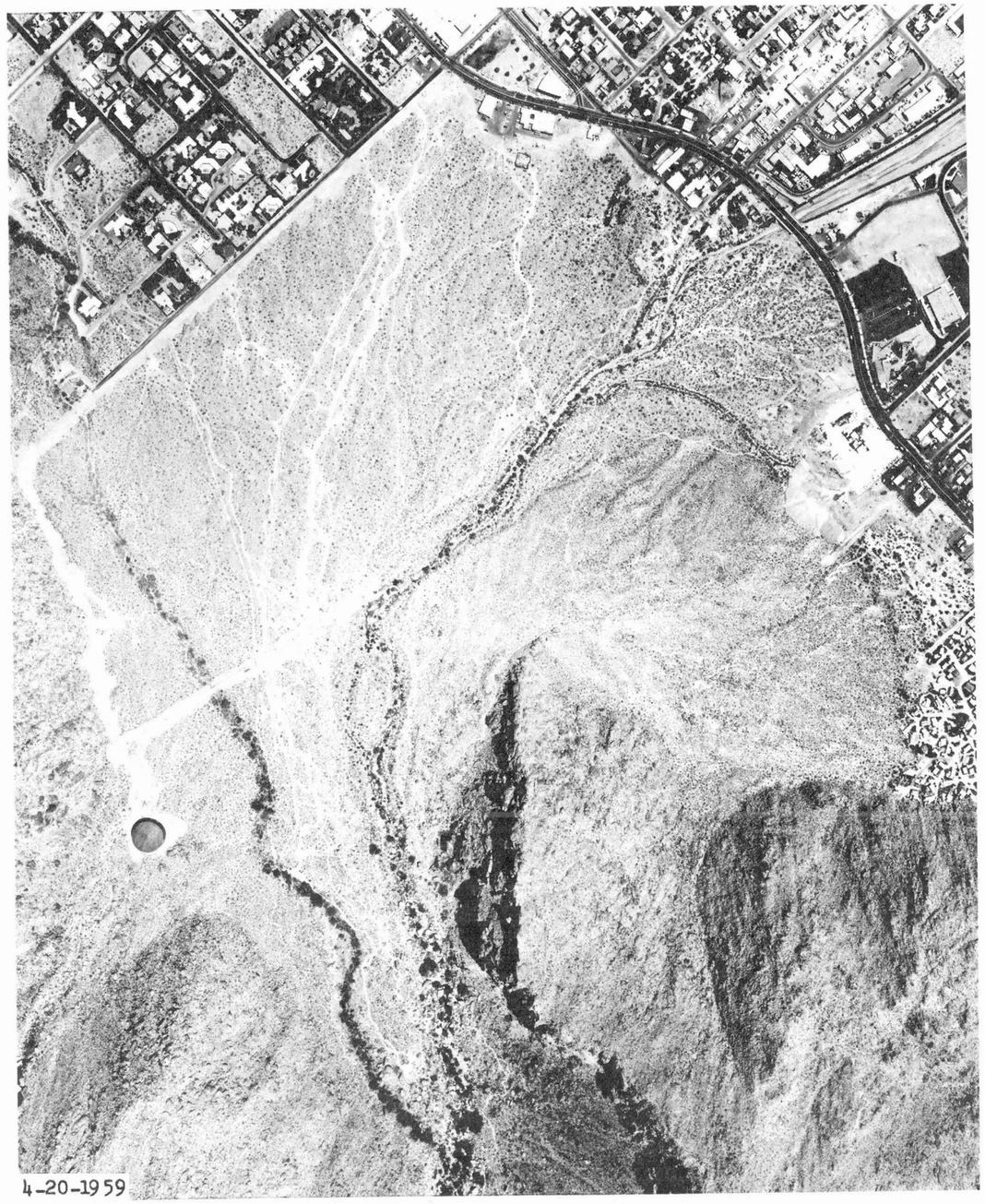
Floods on the fan result from winter storms, although most of the year the creek is completely dry. A peak discharge of 2,900 cfs was recorded on November 22, 1965, and on January 25, 1969. The only set of aerial photographs available to identify the flood channel pattern was taken on April 20, 1959 (see Figure 13). A peak discharge of 1570 cfs occurred on August 31, 1954. The aerial photograph showed that the flood water flowed in a northeastern direction and bifurcated at a point about 2,000 feet above the mouth of the canyon. The south channel turned toward the east at a location about 600 feet below the mouth of the canyon to lead to a lined channel to pass Palm Springs. The north channel flowed in a northerly direction to meet the flood flow from an adjacent fan. The channel banks for both channels seemed naturally stabilized with trees. Numerous abandoned small braided channels, however, were developed between those two channels. Currently the alluvial fan has been densely developed and is protected by levees on the upfan area.

Palm Canyon near Palm Springs, California

Palm Canyon originates from the San Jacinto Mountains and flows in a northerly direction to develop Palm Canyon Wash, on which part of Palm Springs is now located. It has a slope of 0.058 and drains an upstream watershed of 93.3 square miles. The watershed is covered with sparse forests above 4000 feet in elevation and is lightly vegetated below. Below the canyon mouth, two small alluvial fans have been developed by the easterly flowing Murray and Andreas Canyons against the northerly flowing Palm Canyon flow. This forced the alluvial channel below Palm Canyon to develop along the eastern wall of the valley. The alluvial



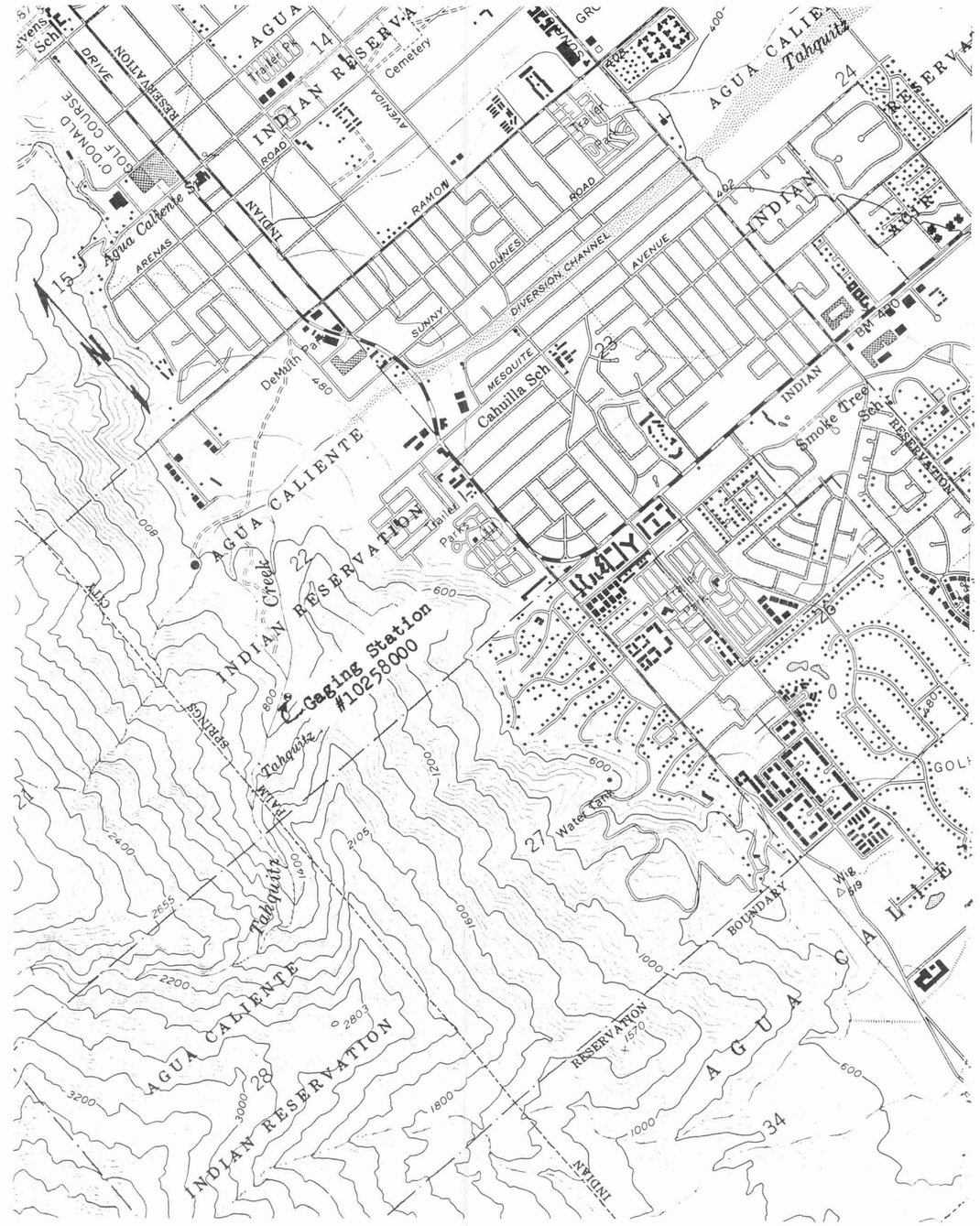


FIGURE 13
Topographic Map and Aerial Photograph of the Alluvial Fan below Tahquitz Creek near Palm Springs, California

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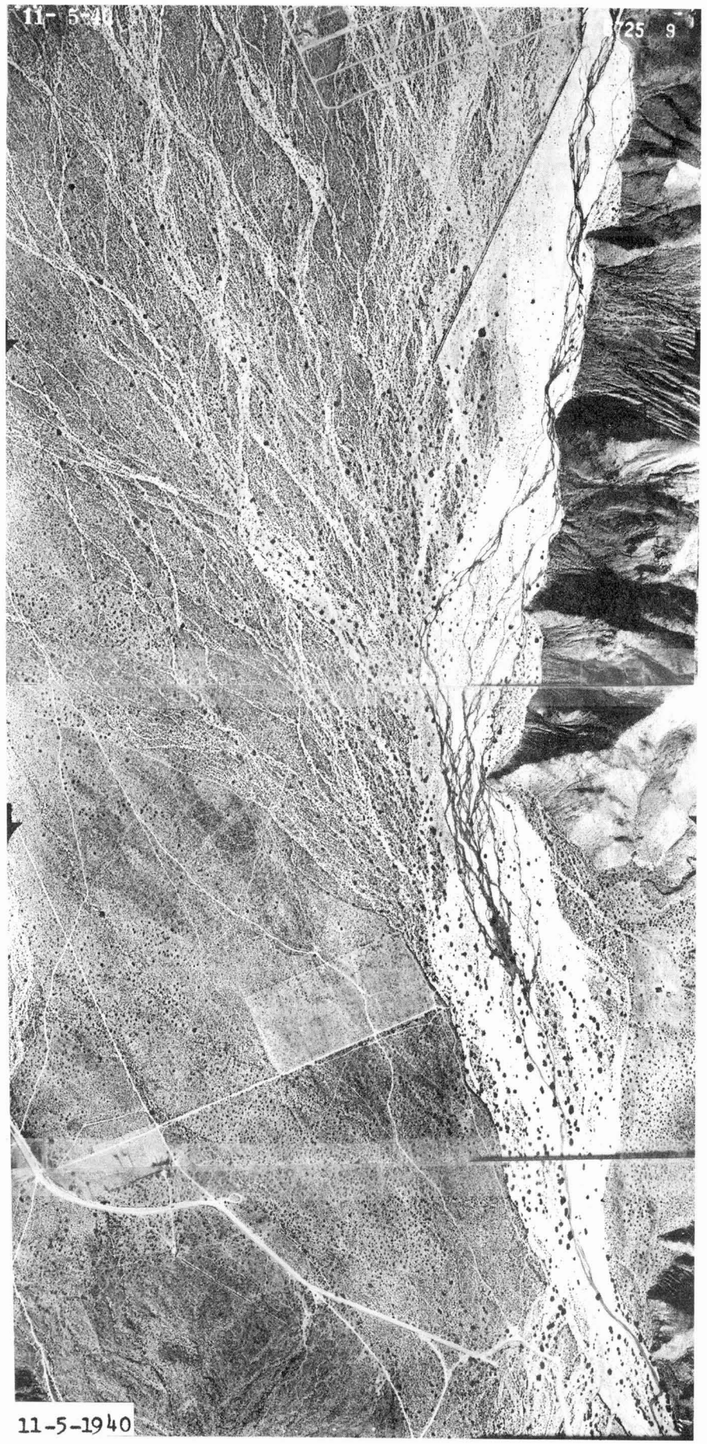
fan has an expansion angle of 25 degrees and a slope of 0.055. The floods are usually caused by winter storms. USGS gaging station #10258500 has recorded peak discharges of 3,850 cfs on February 6, 1937, 2,380 cfs on March 2, 1938, and 2,900 cfs on December 24, 1941.

There is one set of aerial photographs available to correlate the flood channel patterns on the alluvial fan. This set of aerial photographs was taken on November 5, 1940 (see Figure 14), some three years after the flood on March 2, 1938. Examination of the aerial photograph indicated that the flood water flowed in a single channel 550 feet wide for about 3,825 feet below the mouth of the canyon. It then gradually widened to 3,000 feet at 1.92 miles below the mouth of the canyon. Below this point, numerous small channels branched out from the west bank of the flood channel to flow down the alluvial fan. The major portion of the floodwater, however, continued to flow in the main channel to its junction with Tahquitz Creek.

Devil Canyon near San Bernardino, California

Devil Canyon, near San Bernardino, California, has a slope of 0.085 and drains a sparsely vegetated upstream watershed of 5.61 square miles. The alluvial fan has a radius of 6,400 feet and an expansion angle of 33 degrees. The fan slope is 0.062 at the upfan area. Below the mouth of the canyon are three percolation basins, with levees to guide flood water into the basins. Downstream of those percolation basins levees are built to further divert the flood water through the opening of an elevated cross-fan ridge at the fan toe to a lined channel leading to Cajon Creek. A percolation basin is also located at the eastern side



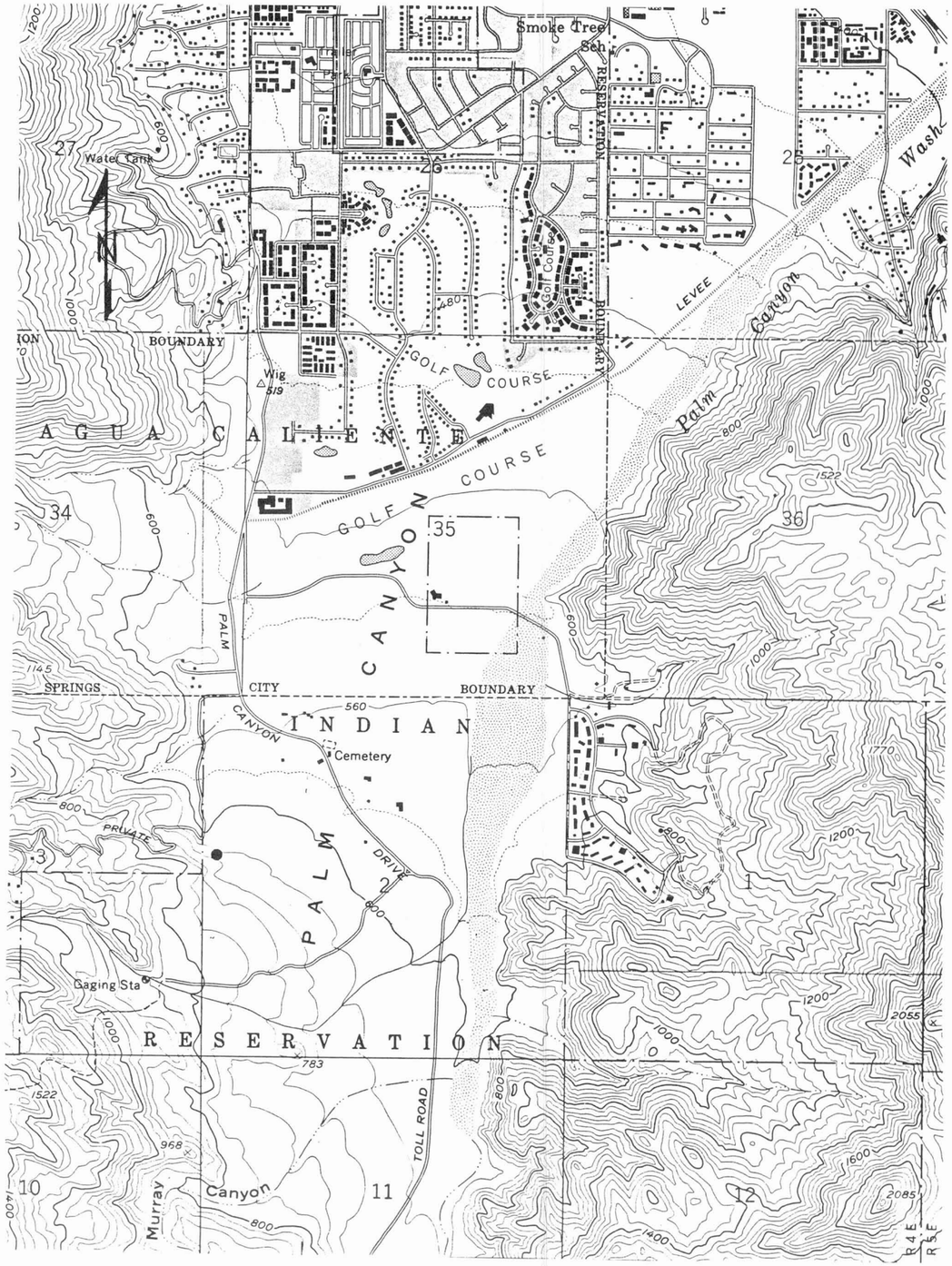


FIGURE 14
Topographic Map and Aerial Photograph of the Alluvial Fan below Palm Canyon near Palm Springs, California

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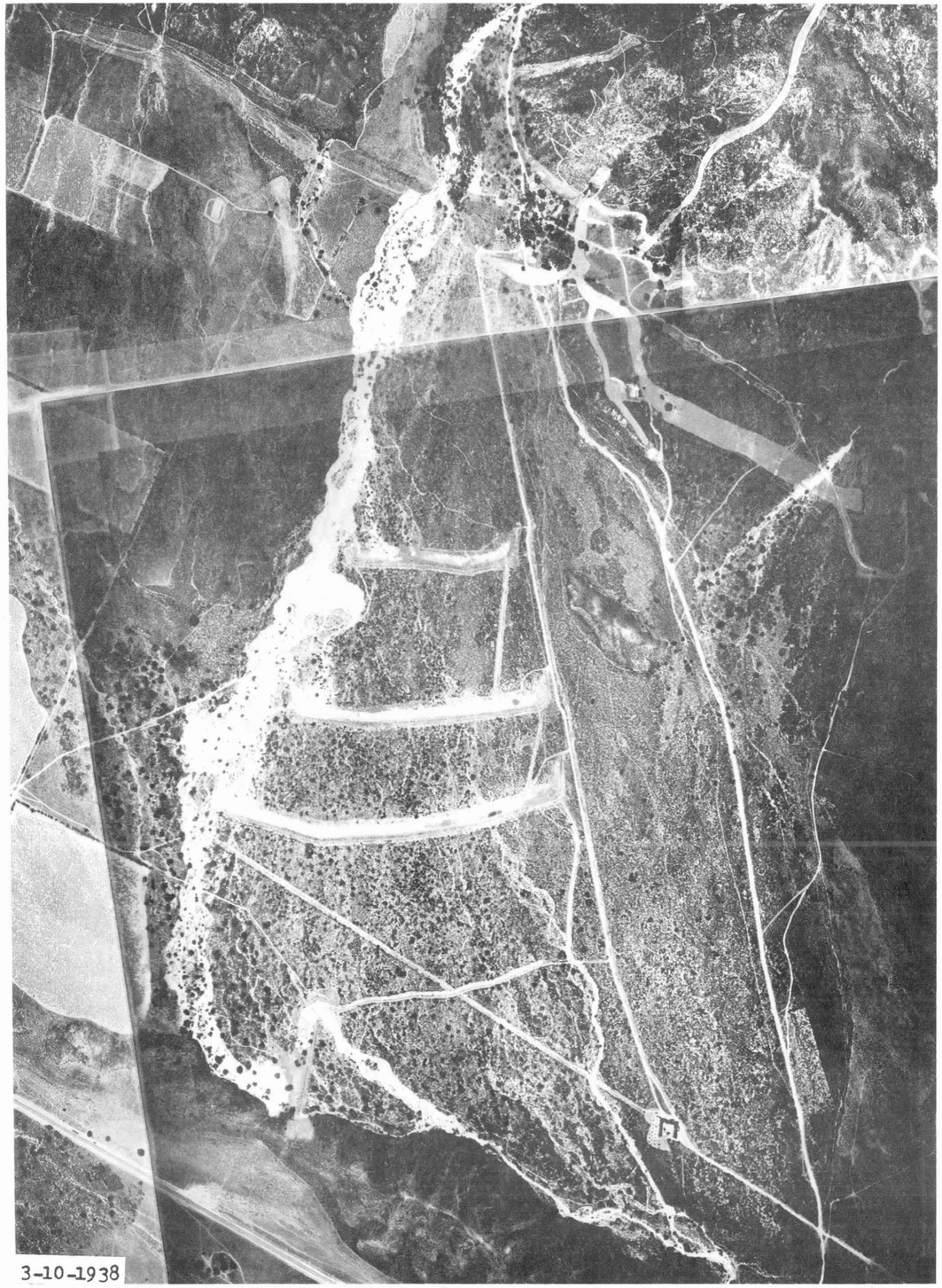
of the fan toe immediately above the cross-fan ridge.

Flooding is generally caused by winter storms. USGS gaging station #11063680, situated at the mouth of the canyon, recorded peak discharges of 3,320 cfs on March 2, 1938, 3,720 cfs on January 25, 1969, and 1,800 cfs on February 25, 1969. The flood channel pattern on the alluvial fan was identified using aerial photographs taken on February 17, 1937, and March 10, 1938 (see Figure 15), respectively, before and after the flood on March 2, 1938.

Comparison of the above two sets of aerial photographs indicated that the flood water of March 2, 1938, essentially flowed in the old channels developed by previous floods. The flood water, which entered the percolation basins, however, overtopped the downstream levees of the basins to develop a sheet flow pattern below the levees. The flood water eventually discharged into the percolation basin at the eastern side of the fan toe. Discharges of the magnitude of the 1938 peak are apparently controlled by the man-made structures.

Whitewater River near Whitewater, California

The Whitewater River flows in a north-to-south direction, discharging onto an alluvial fan just upstream of its junction with the San Gorgonio River. Near the toe of the fan, the Whitewater River collects the flow from the San Gorgonio River and then turns eastward downstream. The upstream watershed is sparsely vegetated in the highlands. The river has an average slope of 0.034 and a width of about 1500 ft. USGS gaging station #102560000, operated from 1948 to 1981, was located near Whitewater with a drainage area of 57.4 square miles. The river



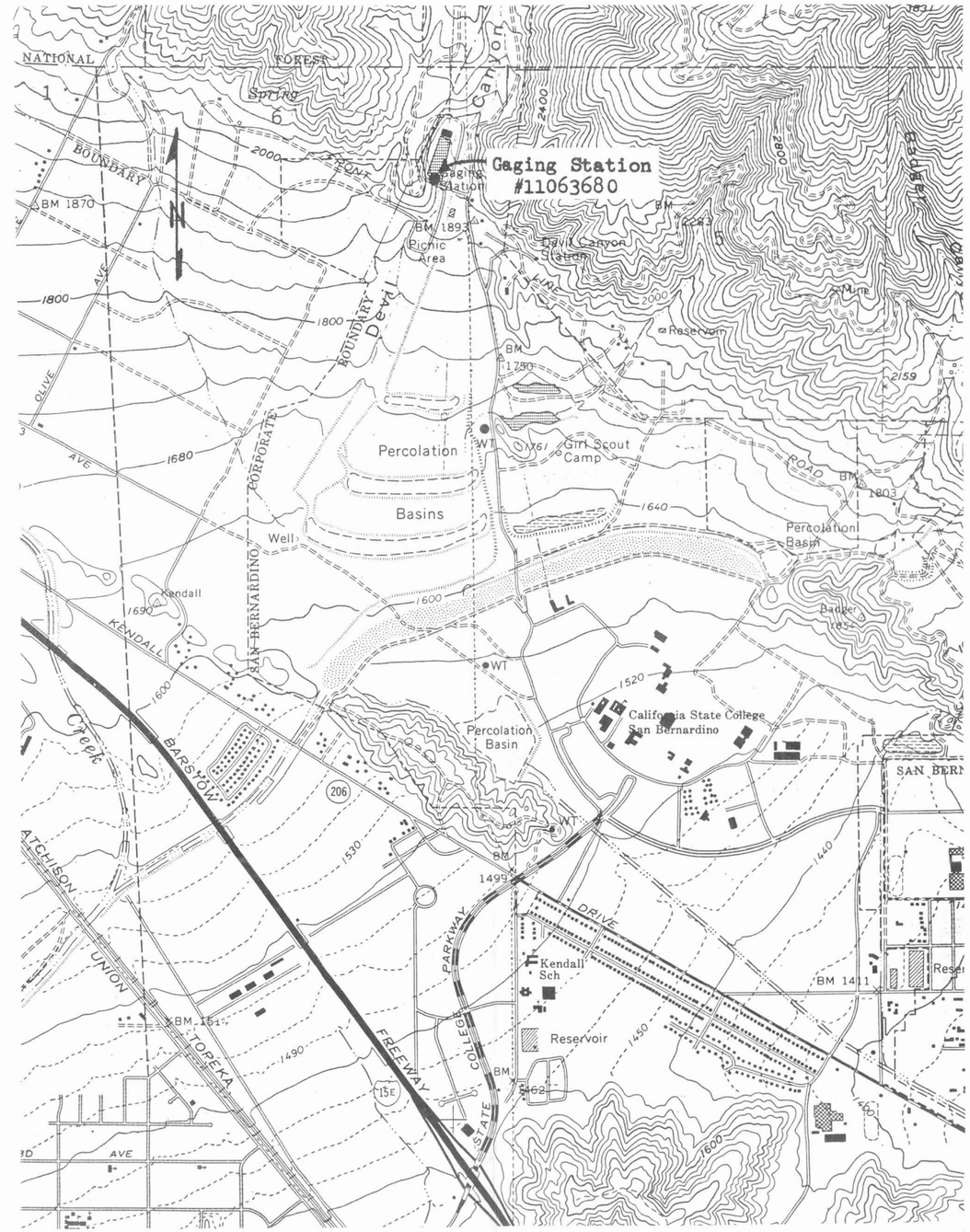
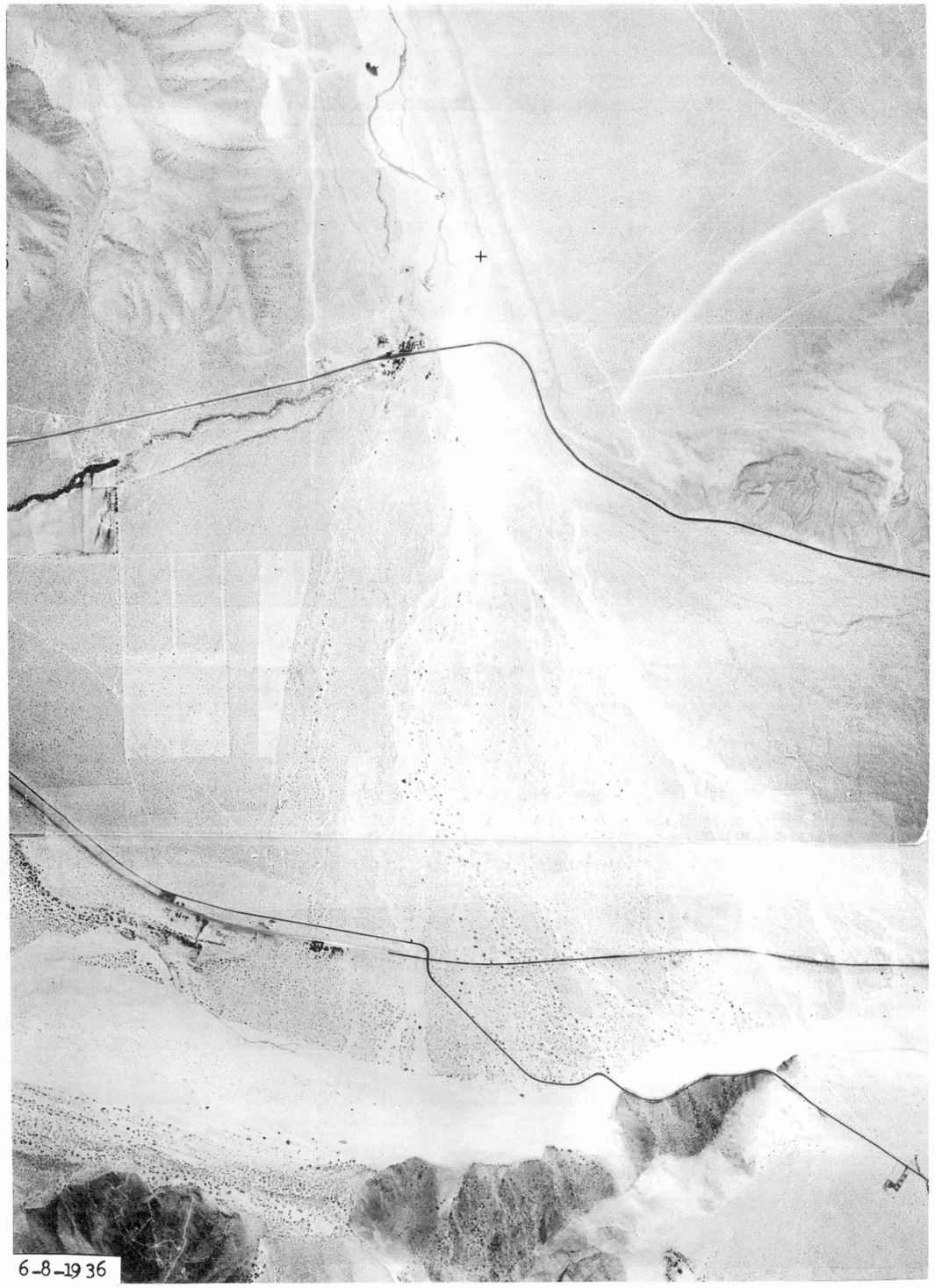


FIGURE 15
Topographic Map and Aerial Photograph of the Alluvial Fan below Devil Canyon near San Bernardino California

discharges are generally derived from winter rainstorms. Peak discharges were recorded of 42,000 cfs on March 2, 1938, 24,000 cfs on November 22, 1965, 16,200 cfs on January 25, 1969, and 13,500 cfs on February 25, 1969. The alluvial fan below the river mouth has an expansion angle of 70 degrees and a radius of 1.7 miles from the apex, the fan slope is 0.030. The alluvial fan is undeveloped, however, Interstate Highway 10 crosses the fan near the apex, and State Highway 111 and the Southern Pacific Railroad cross the fan near the toe.

The flood channel patterns on the alluvial fan was identified using an aerial photograph taken on June 8, 1936 (see Figure 16). No major peaks prior to that date were available. State Highway 111 had not yet been built and Highway 66, the predecessor to Highway 10 crossed the Whitewater River, at a location slightly above the river mouth. The flow approach to the bridge was constricted by upstream dikes and the embankments of the bridge. The flow passed under the bridge in a single channel, which gradually widened to 640 feet at a location about 880 feet below the bridge. Below this point, the flow bifurcated to form one large and one small channel. The large channel again bifurcated within a distance of 800 feet to two channels of approximately the same width. Further downstream, numerous small channels branched out from those three channels to form a complex braided channel pattern before meeting the flow from the San Gorgonio River.

There is only one set of aerial photographs available for the present study, therefore, no comparison of aerial photographs of different dates were made to detect if the channel locations were random. However, judging from the shallow flood channels and the braided channel pattern it is likely that shifting of channels might occur for different floods.



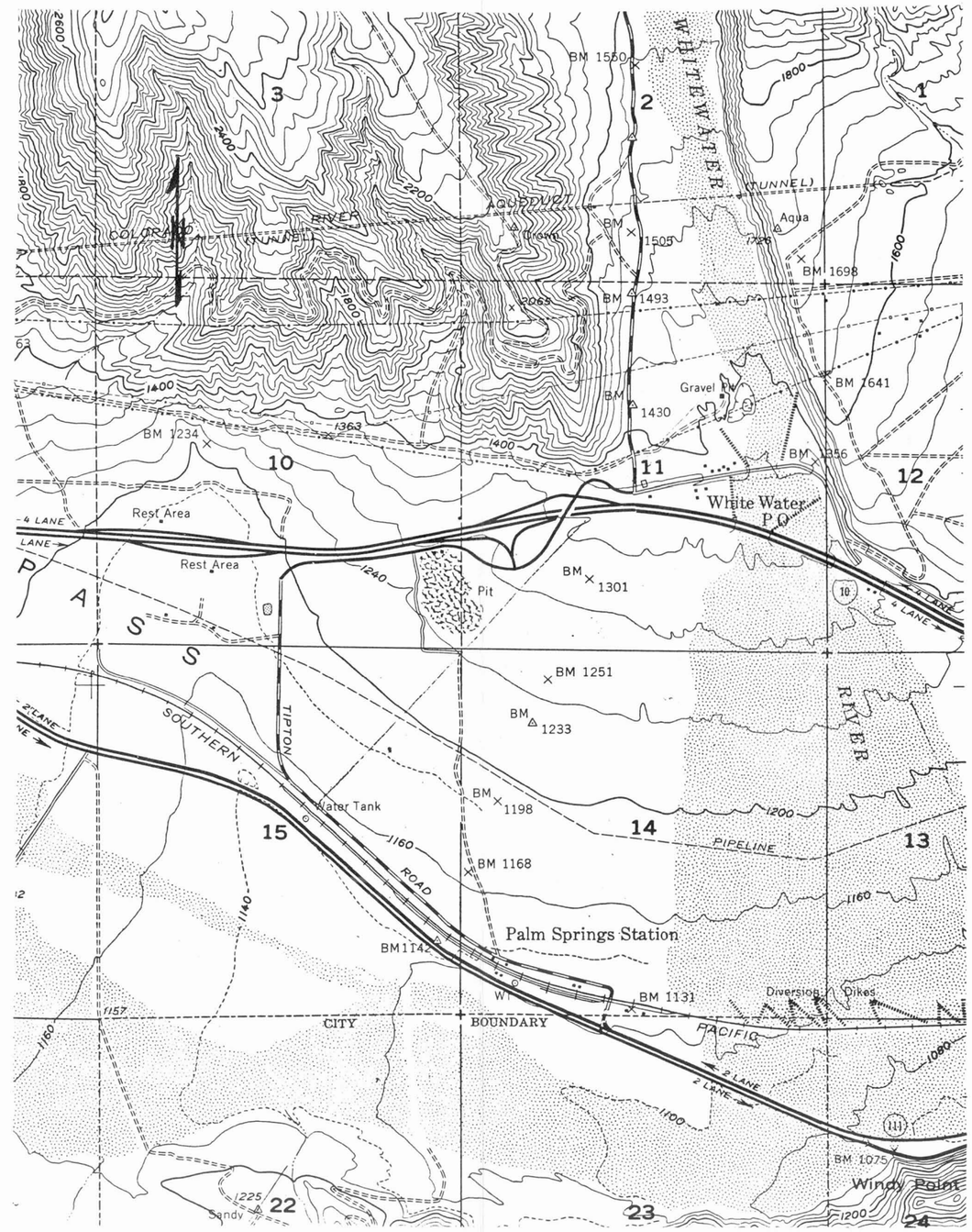


FIGURE 16
Topographic Map and Aerial Photograph of the Alluvial Fan below Whitewater River near Whitewater, California

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3.2.3 Results of Case Studies

Case studies have been conducted to cover alluvial fans in California and Nevada. The characteristics of flood channel patterns included single channels, split channels, and braided channels. The factors that may affect the fan flood including upstream watershed drainage area, canyon slope, alluvial fan slope, angle of expansion and radius of alluvial fan, were also determined using aerial photographs and USGS topographic maps. Table 2 summarizes those characteristics of alluvial fans in the present study.

The results of the present case studies can be summarized as follows:

<u>Channel Pattern</u>

The flood channels on alluvial fans were found to occur in three patterns, namely; single channel, split channel, and braided channel. The flood channel generally was found to be a single channel immediately below the mouth of the canyon, followed by a split channel segment, and finally terminating in a braided channel.

<u>Channel Location</u>

Treating the studied alluvial fans as a group, the relative location of a single channel immediately below the mouth of the canyon on an alluvial fan was found to be random as shown in Figure 17. Each data point in Figure 17 represents the relative location of a single channel on an alluvial fan, defined as the

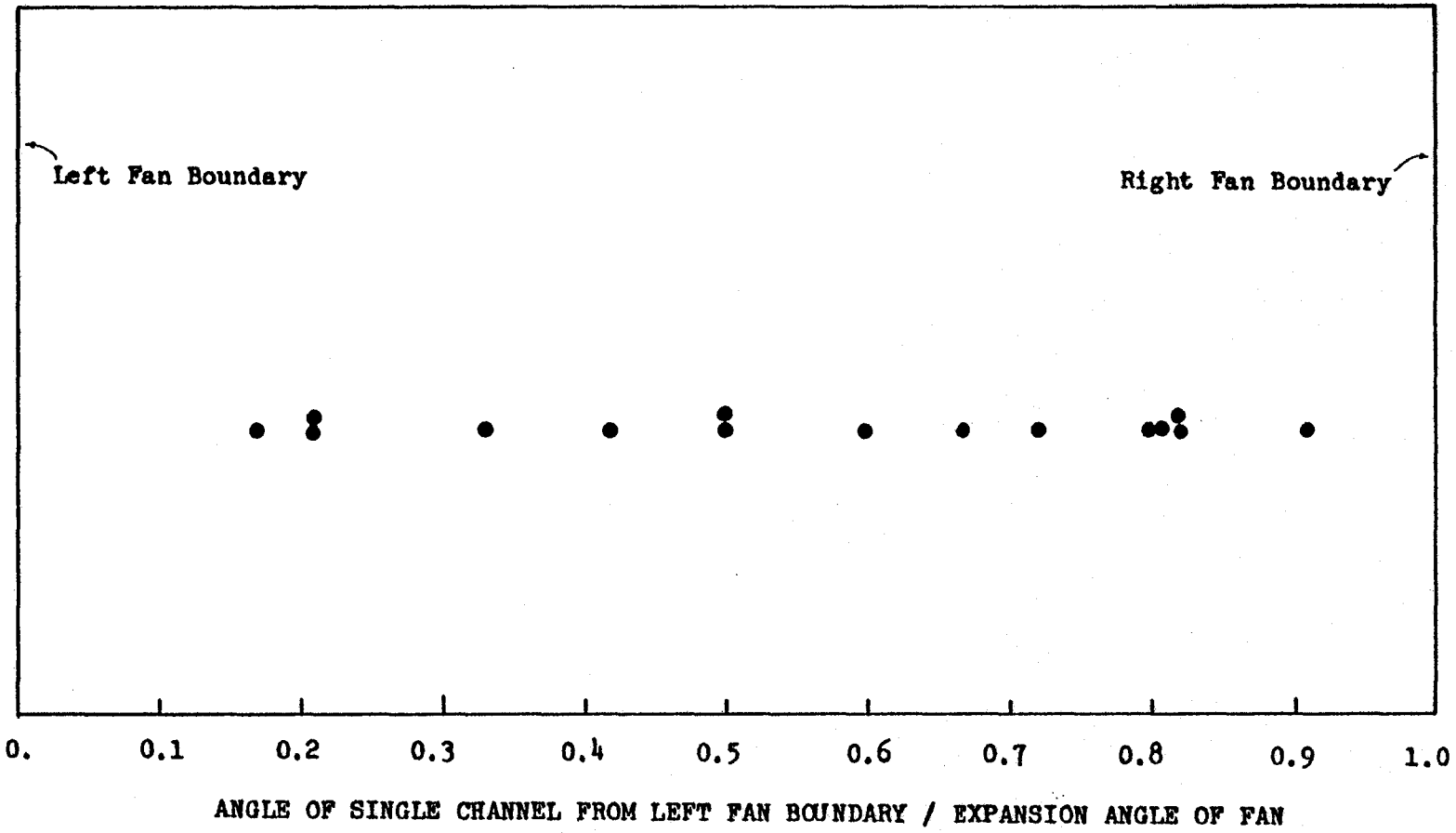

FIGURE 17
Normalized Locations of Single Channels on Alluvial Fans

ratio of the angle between a single channel and left fan boundary, when looking downstream, to the expansion angle of an alluvial fan. The relative locations of the single channels on alluvial fans are summarized in Table 2. It can be seen from Figure 17 that the data points spread rather uniformly over the entire range of relative single channel location from 0.0, which represents left fan boundary, to 1.0, which represents right fan boundary. This finding indicates that there is no preferential location for forming a single channel on an alluvial fan when compared with the relative locations of the single channels on other alluvial fans.

The present FEMA method assumes a random location for the 100-year event. Therefore, the random distribution across the fan as shown in Figure 17 is germane only if the process is ergodic, that is, if the synoptic view in space holds in the time domain at a fan. Figure 17 thus presents supportive evidence of the present method.

Although the locations of the flood channels were found to be stable for some of the alluvial fans which are subjected to urbanization and well vegetated upstream watersheds, such as those at Lytle, Day, and Deer Creeks in California, relocations of flood channels were evident for those undeveloped alluvial fans with barely vegetated upstream watersheds in Nevada. Based on the present study, the assumption of random channel location should be retained in the analysis.

Single Channel Pattern

The length of a single channel below the mouth of the canyon on an alluvial fan

TABLE 2

SUMMARY OF ALLUVIAL FAN AND FLOOD CHANNEL CHARACTERISTICS

ALLUVIAL FAN	DRAINAGE AREA SQ. MI.	CANYON SLOPE S_{cyn}	FAN SLOPE S_{fan}	EXPAN. ANGLE DEG	FAN RADIUS FT	OBSERVED SINGLE CHANNEL LENGTH FT	OBSERVED SINGLE CHANNEL WIDTH[a] FT	DIRECTION[b] OF CHANNEL DEG	S_{cyn}/S_{fan}	DATE OF PHOTO
Northumberland Cyn near Austin, Nv	15.1	.033[c]	.033	60	20000	14500	390	40	1.00	6-19-81
Mason Valley Trib. near Mason, NV	2.6	.058	.035	75	3500	--[g]	--[g]	--[g]	1.66	10-7-68
Humboldt River Trib. near Rye Patch, NV	.85	.110	.071	90	7300	1060	50	45	1.55	6-23-73
Rocky Canyon near Oreana, NV	4.05	.108	.058	110	12500	--[f]	--[f]	90	1.86	6-23-73
Humboldt River Trib. near Oreana, NV	.76	.124	.070	90	13000	--[f]	--[f]	38	1.77	6-23-73
Las Vegas Wash near Henderson, NV	.08	.058[c]	.050	50	3200	3075	68	30	1.16	7-4-80
Las Vegas Wash Fan A nr Henderson, NV	--	.061[c]	.056	40	6500	3250	183	20	1.09	7-4-80
Piute Wash Trib. at Searchlight, NV	3.40	.016[c]	.016	--[e]	--[e]	10500	90	--[e]	1.00	10-7-68
San Antonio Wash near Tonopah, NV	3.42	.070	.053	60	17700	--[f]	--[f]	10	1.32	8-29-73
Eldorado Valley Trib. nr Nelson, NV	1.40	.036[c]	.036	30	5800	2000	--[h]	--[h]	1.00	7-24-73
Lytle Creek near Fontana, CA	46.3	.031	.026	95	49000	4400	761	20	1.19	1-30-69
Day Creek near Etiwanda, CA	11.9	.149	.103	80	41200	2400	268	65	1.45	3-10-38
Deer Creek near Guasti, CA	3.4	.168	.109	90	37500	600	275	30	1.54	3-10-38
Cucamonga Creek near Upland, CA	10.1	.075	.048	55	42200	7900[d]	358[d]	45	1.56	3-10-38
San Antonio Creek near Claremont, CA	26.2	.055	.046	90	57800	8150[d]	370[d]	65	1.20	3-10-38
Tahquitz Creek nr Palm Springs, CA	43.5	.111	.046	90	7200	--[f]	--[f]	60	2.41	4-20-59
Palm Canyon nr Palm Springs	93.3	.058[c]	.055	25	16000	3825	550	20	1.05	11-5-40
Devil Canyon nr San Bernardino, CA	5.61	.085	.062	33	6400	1500[d]	216[d]	30	1.37	3-10-38
Whitewater River nr Whitewater, CA	57.40	.034[c]	.030	70	8980	880[d]	640[d]	15	1.13	6-8-36

a. Channel width was measured within a well-defined reach.

b. Direction of the single channel was measured as the angle between the single channel and the left fan boundary, when looking downstream. For an alluvial fan without a single channel region, it was approximated with the direction of a major channel.

c. Fan slope extends into canyon upstream of mountain front.

d. The channels on the alluvial fans were affected by levees, percolation basins, dikes, etc.

e. Not a well-defined alluvial fan, which is generally characterized by a rather uniform radial slope from the apex.

f. Without a single channel region on the alluvial fan.

g. No flood channels could be identified.

h. Width of a single channel not well-defined.

was found to be correlated to the ratio of canyon slope to fan slope as shown in Figure 18. It can be seen from this figure that the length of a single channel decreases with the ratio of canyon slope to fan slope. This indicates that flood flow can sustain a longer single channel when emerging from a canyon onto a fan of a similar slope than onto a fan of a smaller slope. An empirical relationship between the single channel length and the ratio of canyon slope to fan slope is proposed in Figure 18 based on the data of the present case studies.

The width of a single channel on an alluvial fan can be reasonably predicted by the FEMA method. Figure 19 shows the relationship between the fan slope and the ratio of calculated width using the FEMA method to observed width for a single channel. The calculated single channel widths and the ratios of calculated width to observed width for alluvial fans are summarized in Table 3. It can be seen from this figure that most data points are scattered around the line of perfect agreement between the calculated and observed widths, except for the data points associated with questionably high flood discharges for Las Vegas Wash and Humboldt River tributary near Rye Patch in Nevada. Based on the flood discharges reported by the USGS, the amounts of peak discharge contributed by a unit area of upstream watershed were 10,517 cfs per square mile for the tributary of Humboldt

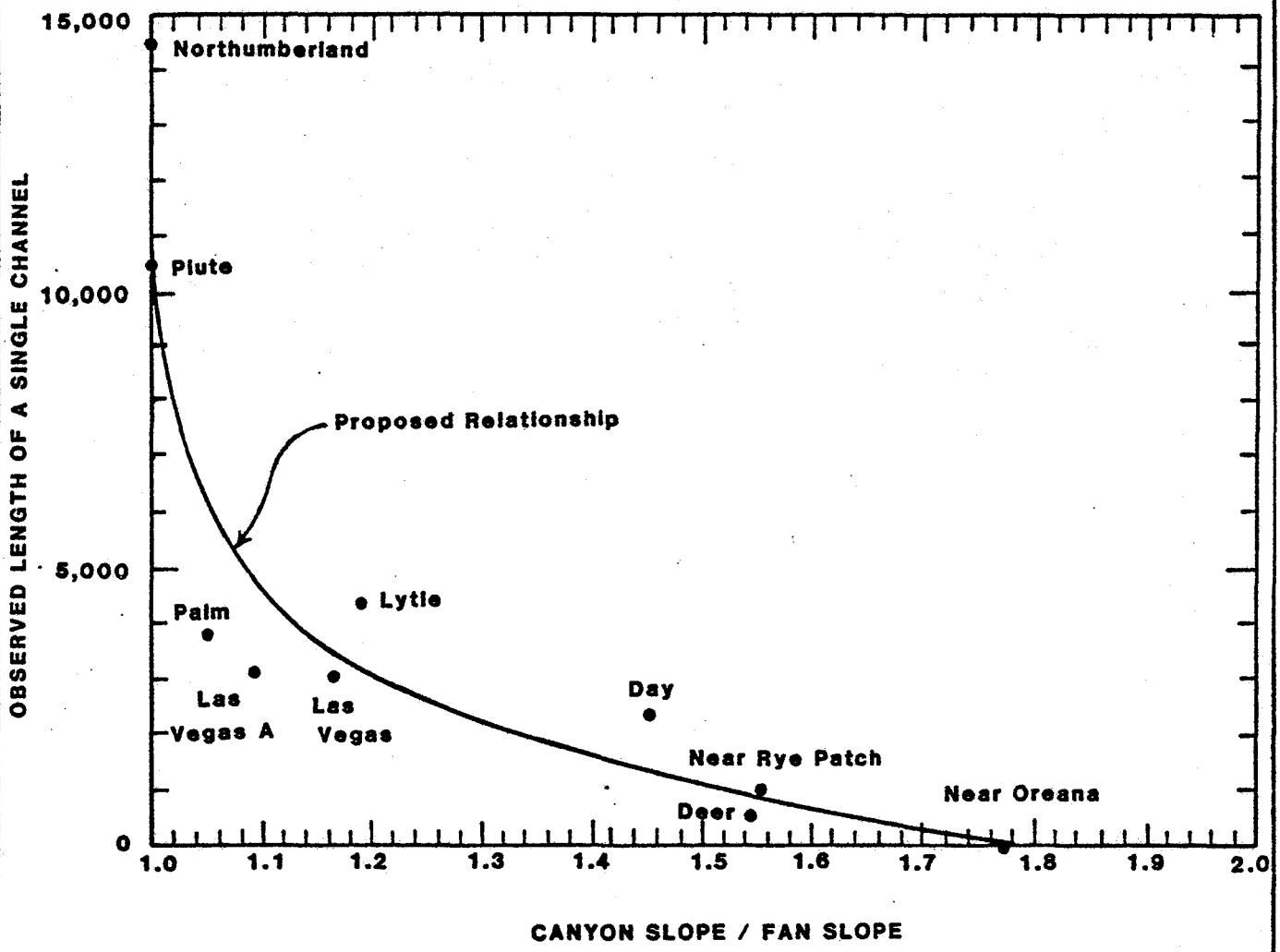

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FIGURE 18
Relationship Between Observed Length of a Single Channel and the Ratio of Canyon Slope to Fan Slope

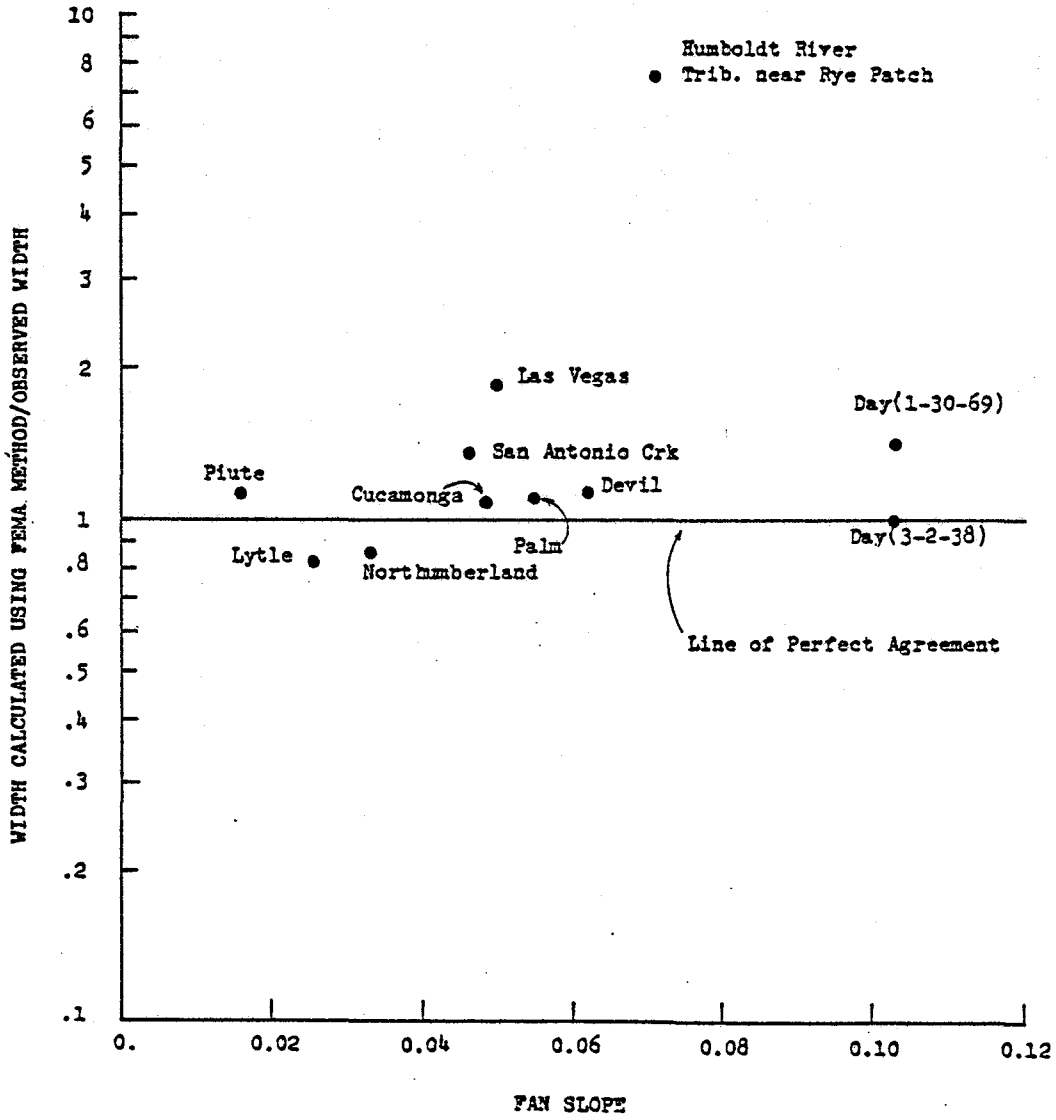

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FIGURE 19
Relationship Between Fan Slope and the Ratio of Width Calculated Using the FEMA Method to Observed Width for a Single Channel

TABLE 3

SUMMARY OF THE SINGLE CHANNEL WIDTHS CALCULATED USING THE FEMA AND EDWARDS & THIELMAMM'S METHODS

ALLUVIAL FAN	DRAINAGE AREA, A SQ. MI.	CANYON SLOPE S_{cyn}	FAN SLOPE S_{fan}	OBS. CHANNEL WIDTH, Wo FT	S_{cyn}/S_{fan}	DISCH. Qp CFS	DATE FLOOD	Q_p/A	CAL. WIDTH (FEMA), Wc FT	W_c/Wo	CAL. WIDTH (EDWARDS & THIELMANN), FT n=.25	n=.30	n=.35
Northumberland Cyn near Austin, NV	15.1	.033	.033	390	1.00	7680	8-7-79	50	340	.87	233	250	265
Humboldt River Trib. near Rye Patch, NV	.85	.110	.071	50	1.55	8940	5-31-73	10517	361	7.48	214	229	243
Las Vegas Wash near Henderson, NV	.06	.058	.050	68	1.16	655	7-30-68	10917	127	1.86	85	92	97
Piute Wash Trib. at Searchlight, NV	3.40	.016	.016	90	1.00	370	9-11-76	108	101	1.12	86	92	97
Lytle Creek near Fontana, CA	46.3	.031	.026	761	1.19	35900	1-25-69	775	630	.83	435	466	494
Day Creek near Etiwanda, CA	11.9	.149	.103	263	1.45	9500	1-25-69	798	370	1.41	204	219	232
Day Creek near Etiwanda, CA	11.9	.149	.103	268	1.45	4200	3-2-38	353	267	1.00	150	161	171
Cucamonga Creek near Upland, CA	10.1	.075	.048	358	1.56	10300	3-2-38	1019	382	1.08	243	260	276
San Antonio Creek near Claremont, CA	26.2	.055	.046	370	1.20	21400	3-2-38	817	512	1.38	322	345	366
Palm Canyon near Palm Springs, CA	93.3	.058	.055	550	1.05	3850	2-6-37	41	258	1.09	164	175	186
Devil Canyon near San Bernardino, CA	5.61	.085	.062	216	1.37	3320	3-2-38	592	243	1.12	151	162	172

River near Rye Patch on May 31, 1973, and 10,917 cfs per square mile for Las Vegas Wash on July 30, 1968.

It is also to be noted in Figure 19 that the observed single channel width for Day Creek stayed almost unchanged for the floods with peak discharges of 4,200 cfs on March 2, 1938, and of 9,500 cfs on January 25, 1969. This indicated that the single channel width did not vary with flood discharge, perhaps, because of the relatively stable channel banks of Day Creek. In this case, if the flood of 1938 flowed at bank full, the flood in 1969 deepened the channel to increase the channel capacity in order to accommodate the flood discharge.

Split Channel Pattern

The total width of multiple channels across the fan width for a given radius from the apex in a split channel region was found to be approximately 3.8 times the channel width in a single channel region as shown in Figure 20. This finding was derived based on the detailed accounts of multiple channel widths for the alluvial fans of Rocky Canyon and Las Vegas Wash Fan A in Nevada and Day Canyon and Deer Canyon in California, which displayed well-defined multiple channels on aerial photographs used in the present case studies. The detailed accounts of the multiple channel widths for the alluvial fans shown in Figure 20 are included in Appendix A. This assumes that all split channels were flowing in a set pattern during the peak flow which formed them. On the other hand, they may have resulted in some cases from an avulsion, or an "almost avulsion", in that near the peak one of the channels formed and robbed most of the flow from the previously main channel. If the flow split evenly between two branches, the combined width would

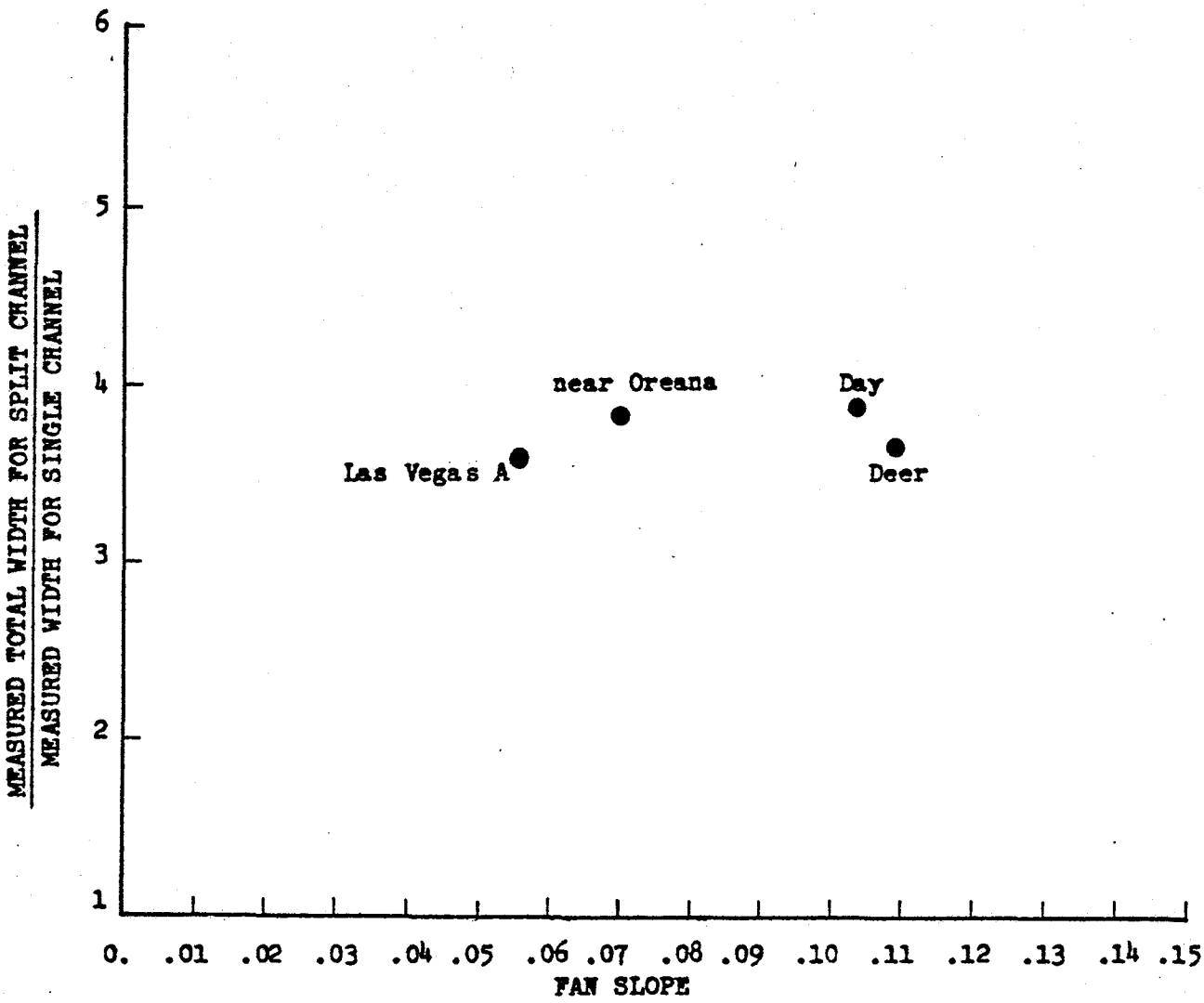

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FIGURE 20
Relationship Between the Ratio of the Total Width for a Split Channel to the Width for a Single Channel and the Fan Slope

be predicted by the present method to be 1.5 times the width prior to branching, and four equal channels would have a combined width 2.3 times the single flow channel. Unequal branches would produce smaller expected combined widths.

Avulsion Coefficient

The present method assumes that a new channel is formed with every other occurrence of a 100-year flood, on the average. Some of the fan floods caused relocation of the channels as a result of the floods, and some of the floods studied were probably not 100-year floods. More flood occurrences and an analysis of their return periods are necessary before the assumption of 1.5 for an avulsion coefficient can be better defined. On the basis of the present study, no change should be made.

4.0 FAN FLOOD ANALYSIS METHODOLOGY

In this chapter, the current methods for the analysis of fan floods are discussed first. Then alluvial fans are classified according to their characteristics from the standpoint of flood analysis. Finally, the practical considerations for fan flood analysis are presented.

4.1 Current Methods For Fan Flood Analysis

There are two methods published for the calculation of alluvial fan floods, namely, the standard FEMA method and Edwards and Thielmann's modification.

4.1.1 FEMA Method

The FEMA method is based primarily on the following assumptions:

1. The fan flood is in a critical flow condition. Therefore the flow velocity can be calculated from the flow depth.
2. An alluvial channel will continue to widen by lateral erosion with a corresponding decrease in flow depth until the point is reached where a decrease in depth results in a two hundred fold increase in width.

Therefore for a given peak discharge of a fan flood, the flow depth, channel width, and the flow velocity can be calculated. To calculate the risk of a fan flood at a particular location on the fan, it is further assumed that the probability of a flood channel occurring at any location across the fan width at the same radial distance from the apex is equal. The equations for the

calculation of channel width, W, flow velocity, V, and flow depth, D, are as follows:

$$W = 9.5\ Q^{0.4}$$

$$V = 1.5\ Q^{0.2}$$

$$D = .07\ Q^{0.4}$$

4.1.2 Edwards and Thielmann's Modification

Edwards and Thielmann (1982) modified the FEMA method by assuming that the flood water would flow at normal depth as described by Manning's equation, instead of at critical depth. The modification results in the following equation for the calculation of channel width, flow depth, and flow velocity:

$$W = 17.16\ \frac{Q^2}{S}\frac{n^2}{}^{3/16}$$

$$D = 0.14\ \frac{Q\ n}{S^{1/2}}^{3/8}$$

$$V = 0.14\ \frac{Q^{1/4}\ S^{3/8}}{n^{3/4}}$$

In the above equation, n is Manning's roughness coefficient, S is the fan slope, W is the width of a single channel, D is the flow depth, and V is the flow velocity. It may be shown that under most situations, the width of a single channel calculated using Edwards and Thielmann's modification is smaller than that calculated using the FEMA method (see Figure 21 and Table 3). For the comparison shown in Figure 21 and Table 3, Manning's roughness, n, is taken as 0.020, 0.025, and 0.030 respectively. It is noted in Figure 21 that the data points for the tributary of Humboldt River near Rye Patch and Las Vegas Wash in

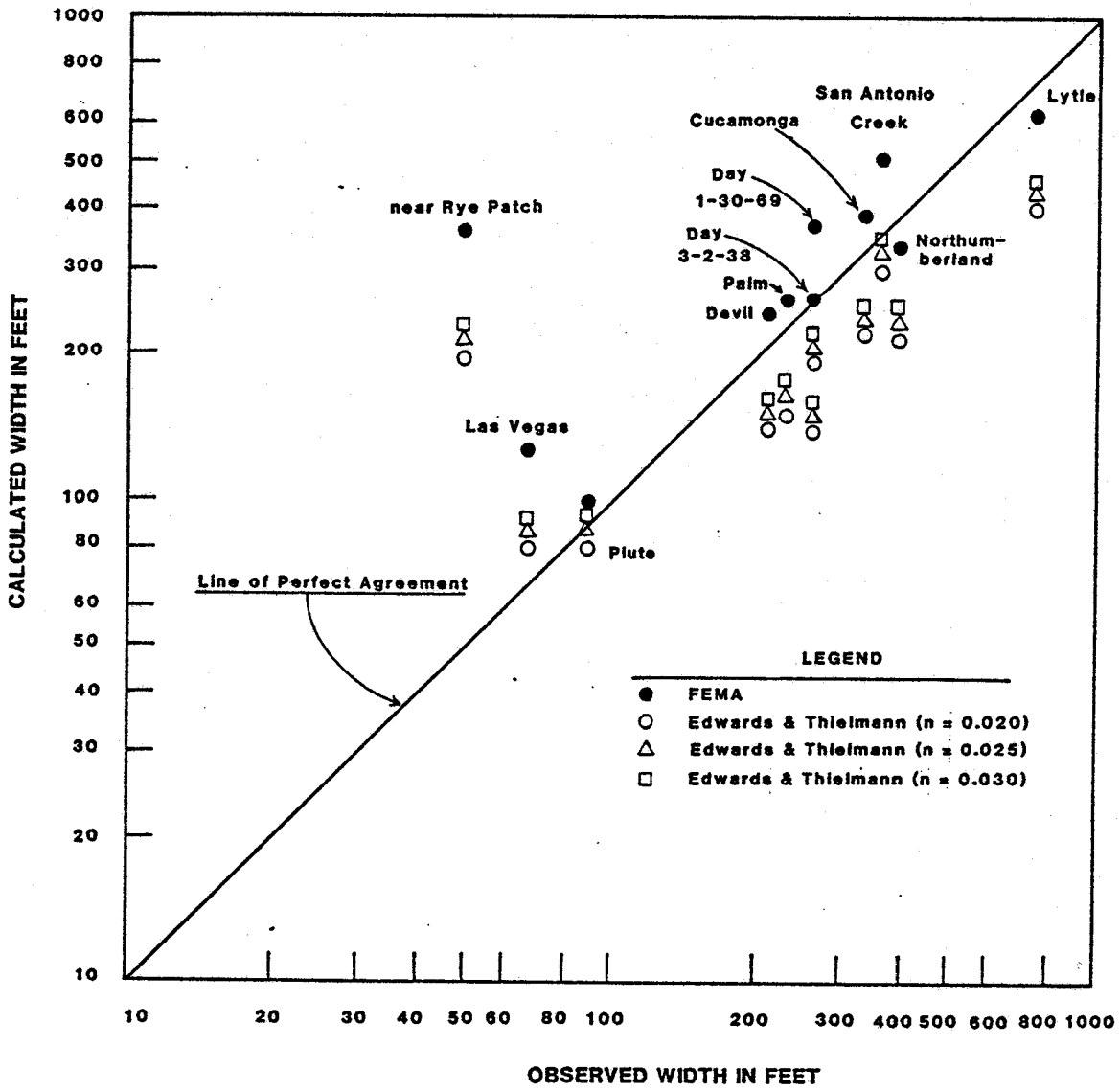

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FIGURE 21
Comparison of Observed Widths Against Calculated Widths for Single Channels Using FEMA and Edwards & Thielmann's Methods

Nevada are a considerable distance from the line of perfect agreement. The reported peak discharges were 10,517 cfs per square mile for the Humboldt River tributary near Rye Patch on May 31, 1973, and 10,917 cfs per square miles for Las Vegas Wash on July 30, 1968, as mentioned earlier these values are questionably high.

4.1.3 Discussion of the Current Methods

The major assumptions used in the FEMA method and Edwards and Thielmann's modification, are discussed as follows:

1. Assumption of single channel pattern: The results of the present case studies indicate that the flood channel remains in a single channel for a distance below the mouth of the canyon. The length of the single channel can be estimated by use of Figure 18. Below the single channel region, there is a split channel segment and then a braided channel pattern forms.

2. Assumption of random channel location: The results of the present case studies reveal evidence of channel relocations for the undeveloped alluvial fans with sparesly vegetated watersheds in Nevada, even though channel locations were found to be stable within the study period for some of the alluvial fans in California, which tend to have well-vegetated watersheds. The present study data base does not provide sufficient evidence to indicate that channel relocations will not occur during the FEMA regulatory 100-year flood.

4.2 Major Factors Affecting Alluvial Fan Floods

The major factors that shape the flood flow on alluvial fans include the alluvial fan characteristics, canyon flow characteristics, and watershed characteristics. They are briefly discussed as follows:

Alluvial fan characteristics:

1. Fan slope: The fan slope is the natural topographic feature that guides the flood flow. The distinct feature of an ideal alluvial fan is that the slopes in all radial directions from the apex are approximately the same. Therefore an initial channel direction at the fanhead may very well determine the general direction for the rest of the fan flood. In addition, the fan slope represents the relative efficiency of an alluvial fan to transport the flood water to the area below the fan.

2. Man-made structures on alluvial fans: Levees, dikes, and lined channels, when able to withstand the major floods on alluvial fans, will guide the floodwaters to follow the designated paths, unless overtopped by the floods exceeding the design capacity. Man-made structures where they exist determine the boundaries of alluvial fan flooding during the fan floods.

Canyon Flow Characteristics:

Canyon Slope: The flow conditions at the mouth of the canyon may

significantly affect the flood channel pattern at the upfan area. The canyon flow characteristics may be represented by the canyon slope. For instance, a flood flow can sustain a longer single channel when emerging from a canyon onto an alluvial fan of a similar slope than onto an alluvial fan of a much smaller slope.

Upstream Watershed Characteristics:

1. Water discharge hydrograph: A hydrograph describes the rate and time distribution of flood water delivered from the upstream watershed onto the alluvial fan. A hydrograph with a longer duration and more gradual discharge increase will allow more time for the flood to adjust the existing channels to accommodate any flood which exceeds the existing channel capacity than a hydrograph with a short duration and sharp increase in discharge. This will reduce the possibility of channel avulsion. Floods which result from frontal storms will tend to be less flashy than those which result from summer thunderstorms. In addition, a water discharge hydrograph reflects the general vegetative coverage condition of the upstream watershed. A well-vegetated upstream watershed tends to yield a hydrograph with a more smooth increase in discharge than a barely-vegetated upstream watershed.

2. Sediment discharge: Debris flow, resulting from rapid sediment deposition along flood channels, has been cited to be the major cause for channel avulsion. High sediment discharge is related to poor upstream watershed coverage. A well-vegetated upstream watershed tends to deliver less sediment onto the alluvial fan than a barely-vegetated upstream watershed.

4.3 Classification of Alluvial Fan Floods

Alluvial fans may be classified based on the major factors affecting fan flooding as discussed in the last section.

1. Urbanized vs. Unurbanized Alluvial Fans: The urbanized alluvial fans are often modified by man-made structures such as levees, dikes and lined channels to guide the flood waters; upstream water retention dams to reduce the peak water discharge; and debris basins to reduce the mud and debris entering the alluvial fan. The above structures all aim to, and, in some cases do confine the flood channels to be within designated portions of the alluvial fan. Many of the alluvial fans in California fit this category. For the unurbanized alluvial fans, the flood flows have less constraint in developing channels and therefore the flood channels may be more randomly located over the alluvial fans.

2. Alluvial fans with well-vegetated vs. barely-vegetated watersheds: The probability of debris flows from a well-vegetated watershed is generally smaller than from a barely-vegetated watershed. Thus factors to trigger the channel avulsion process are less likely to occur, and flood channels are more stable and less likely to shift location for an alluvial fan with a well-vegetated watershed than for one with a barely-vegetated watershed.

In summary, urbanization and a well-vegetated upstream watershed may be the main reasons why the flood channels on those alluvial fans located in the southern San

Gabriel Mountains area show a high degree of stability.

4.4 Practical Considerations for the Analysis of Alluvial Fan Flooding

Practical considerations in the development of a valid method for the analysis of alluvial fan floods are as follows:

Stability of Flood Channels

The channels developed by previous floods, especially deeply entrenched channels, may be used by future floods. The smaller flood tends to develop thalwegs within the existing channels while a larger flood tends to widen and deepen the existing channels, or develop additional channels to accommodate the flood waters. The stability of flood channels for some of the alluvial fans in California, which are subjected to urbanization and well-vegetated watersheds, support these findings.

Some evidence of random channel relocation exists for some of the alluvial fans in Nevada, which are not subject to urbanization and have barely-vegetated watershed. Channel relocation should result mainly from channel avulsion. It does not appear that channel avulsions associated with debris flow occur for every 100-year flood. (The present FEMA method uses an avulsion coefficient of 1.5, which implicitly assumes that half of the 100-year flood events create avulsions).

Probability of Channel Avulsion

The channel avulsion is the main factor responsible for the random nature of channel relocation for fan floods. Channel avulsion is triggered by the rapid deposition of sediment and debris along the flood channel or by rapid bank erosion. Thus, it can occur under the combination of high water and sediment discharges such as debris flow or under the condition of side scour creating or exposing a new or different path for flow. The sediment discharge is dependent on the erodibility of the upstream watershed. Therefore, one would conclude that debris flow, and consequently channel avulsion, is most likely to occur for an alluvial fan with a barely-vegetated watershed, or a watershed which has recently suffered a brush or forest fire and then is hit by a severe rain storm. However, there is insufficient evidence in the present study to better define the probability of an avulsion and its relation to causative factors.

Flood Channel Patterns

The flood channels for most of the case study alluvial fans exhibit three distinct patterns, namely, single channel, split channel, and braided channel patterns. The flood flows remain in a single channel for a distance below the mouth of the canyon. That distance may be estimated by use of Figure 18. Channel splitting, mostly by bifurcation, starts to occur along the channels at some point below the apex of the fan. Eventually, a braided channel pattern prevails at the toe of the fan. The applications of the existing methods, specifically, FEMA and Edwards and Thielmann's methods, are limited to the single channel reach. The extension of the current methods to the split and braided channel patterns is needed.

Boundaries for Alluvial Fan Floods

Man-made structures such as levees, dikes, and lined channels may restrict the flood channels to be within only portions of the alluvial fans. Therefore the boundaries of fan flood should be defined in the analysis of the FEMA 100-year regulatory flood by accounting for the effects of those man-made structures if they are considered capable to withstand the 100-year flood.

4.5 Proposed Modification of the FEMA Method

Although more studies are needed to identify the process of alluvial fan floods, modification of the present FEMA method may be made based on the present study results to improve the analysis of alluvial fan floods. The modifications are proposed as follows.

Single Channel Region

The present FEMA method should continue to be used in the single channel region of the fan, which is determined by the length of a single channel reach, and in turn is related to the canyon and fan slopes as shown in Figure 18.

Split Channel Region

The present FEMA method should be modified for the alluvial fan flood analysis in

the split channel region. An equivalent single channel with its width equal to 3.8 times the channel width in the single channel region may be substituted for the split channel region as indicated by Figure 20. This indicates that the major current is not necessarily constant, but migrates from sub-channel to sub-channel if the basic width formula still holds. Normal flow conditions may be assumed for the equivalent single channel flow. The fan slope usually decreases with the radial distance to result in a smaller fan slope in the split channel region than in the single channel region. Incorporation of the above assumptions into the present FEMA method yields the equations for channel width, W, velocity, V, and depth, D, as follows:

$$W = 36.1\ Q^{.4}$$

$$V = 0.303\ n^{-.6}\ S^{.3}\ Q^{.24}$$

$$D = 0.0917\ n^{.6}\ S^{-.3}\ Q^{.36}$$

Manning's equation was used in the derivation of the above equations. The width of the equivalent single channel may be used for the calculation of the probability of 100-year flood at any given location on an alluvial fan.

Braided Channel Region

The flooding process in braided channel regions is more complicated than that for split channel or single channel regions. More studies are needed in order to develop an accurate method for flood analysis in that region. For the present stage it is reasonable to propose that the method modified for the split channel region be extended to the braided channel region because the flooding process in

the braided channel region is more similar to the split channel region than the single channel region.

The proposed multiple-channel method (for both split-channel and braided-channel regions) of the present study was compared with the current FEMA method and two other alternatives chosen to test the robustness of the flow boundary prediction. The comparison is included in Appendix B.

5.0 STUDY FINDINGS AND RECOMMENDATIONS

In the present study, a literature review was made for alluvial fan floods. The report "Flood Plain Management Tools for Alluvial Fans," by Anderson-Nichols & Company of Palo Alto, California was reviewed in detail. Case studies were conducted to identify the geomorphic characteristics of fan floods using aerial photographs of alluvial fans in California and Nevada. Finally, the FEMA method for the determination of depth, velocity and frequency of flooding on alluvial fans was assessed using the data gathered from the present case studies. The study findings and recommendations for the present study are presented herein.

5.1 Study Findings

- The flood channels on an alluvial fan can be divided into three patterns, namely; single channel, split channel, and braided channel. The occurrence of those patterns generally follow the above order from the fan apex to the toe of the fan.

- Based on the results of the present case studies, the length of a single channel immediately below the mouth of the canyon is related to the ratio of canyon slope to fan slope as shown in Figure 18. The width of a single channel can be reasonably determined by the present FEMA method.

- In the split channel region, the total width of all channels across the fan width at a given radius from the apex is about 3.8 times the channel width in the single channel region.

- The flood channels appear to be more stable for the alluvial fans which are subject to urbanization and well-vegetated watersheds than the alluvial fans which are nearly undeveloped and originate from sparesly vegetated watersheds. However, on the basis of the present study, there is insufficient evidence to conclude that channel relocations will not occur on those apparently stable alluvial fans for future floods. The assumption of random channel location should continue to be used in the fan flood analysis.

- The present data base is insufficient to better define the value of the avulsion coefficient. Therefore the present value of the avulsion coefficient should continue to be used.

5.2 Recommendations

- The current FEMA method should continue to be used in the single channel region of alluvial fan floods. The single channel region, defined by the length of the single channel, may be determined using the relationship shown in Figure 18.

- The alluvial fan floods in split and braided channel regions may be analyzed by modifying the current FEMA method. An equivalent single channel may be used to substitute for the multiple channels in that region. The width of the equivalent single channel will be 3.8 times the channel width in the single channel region. The equations for the calculations of width, depth, and velocity for this equivalent single channel are included in Section 4.5. The width calculated in this manner may be used to evaluate the probability of 100-year flood occurring at any location on an alluvial fan.

- Avulsions and channel relocations result from debris flows. Further studies are needed to determine the frequency of debris flows on an alluvial fan, which, once determined, may be incorporated into the alluvial fan flood analysis to assess the randomness of channel relocation on an alluvial fan.

- Stability of existing flood channels should be given proper consideration in the analysis of the FEMA regulatory 100-year floods by analyzing the historical flood events using aerial photographs and conducting field inspection of flood channels. The occurrence of debris flows in a 100-year flood should be verified in a future study.

- Future study based on a broad range of alluvial fan conditions is needed in order to further develop the method for alluvial fan flood analysis.

- A proposed modification of the FEMA's FLOOD INSURANCE STUDY : "Guidelines and Specifications for Study Contractors -- Appendix 6. Alluvial Fan Studies" based on the present study is included in Appendix C.

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APPENDIX A

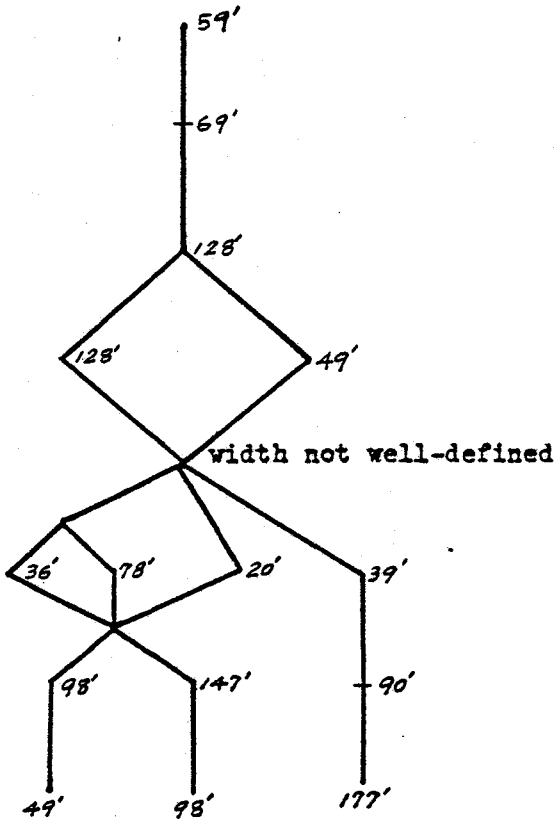
APPENDIX A

SELECTED OBSERVATIONS OF CHANNEL BRANCHING

TABLE A-1

OBSERVED CHANNEL BRANCHINGS FOR ROCKY CANYON

NEAR OREANA, NEVADA (USING AERIAL PHOTOGRAPHS OF JUNE 23, 1973)

CHANNEL BRANCHING	RADIAL DISTANCE, FT	SUM OF WIDTH, FT	SUM OF WIDTH/ SINGLE CHANNEL WIDTH
	340	59	1.00
	340	59	1.00
	570	69	
	1003	128	2.17
	1550	177	3.00
	2000		
	2500	167	2.83
	3500	335	5.68
	4250	324	5.49
		AVERAGE	3.83

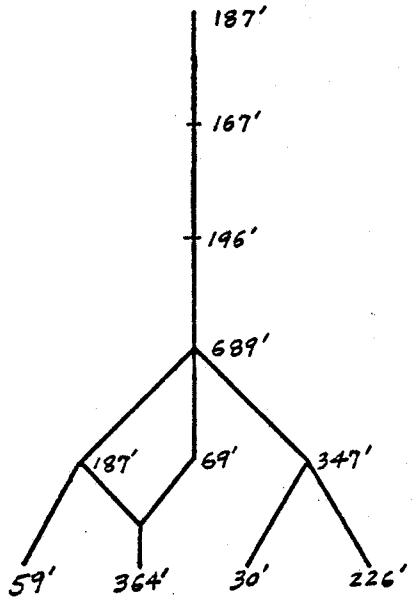
Remark: The channel bifurcated at a point above the mouth of the canyon with the north channel being wider than the south. The south channel was neglected in this analysis.

TABLE A-2

OBSERVED CHANNEL BRANCHINGS FOR LAS VEGAS WASH,

ALLUVIAL FAN A NEAR HENDERSON, NEVADA

(USING AERIAL PHOTOGRAPH OF OCTOBER 21, 1971)

CHANNEL BRANCHING	RADIAL DISTANCE, FT	SUM OF WIDTH, FT	SUM OF WIDTH/ SINGLE CHANNEL WIDTH
	1250	187	
	2000	167	
	2875	196	
	3250	689	3.77
	3625	603	3.30
	4375	679	3.71
		AVERAGE	3.59

Remark: The width of the single channel was taken as the average of the three 167 observed values, namely, (187 + 167 + 196)/3 = 183.

TABLE A-3

OBSERVED CHANNEL BRANCHINGS FOR DAY CREEK

NEAR ETIWANDA, CALIFORNIA (USING AERIAL PHOTOGRAPHS OF JANUARY 30, 1969)

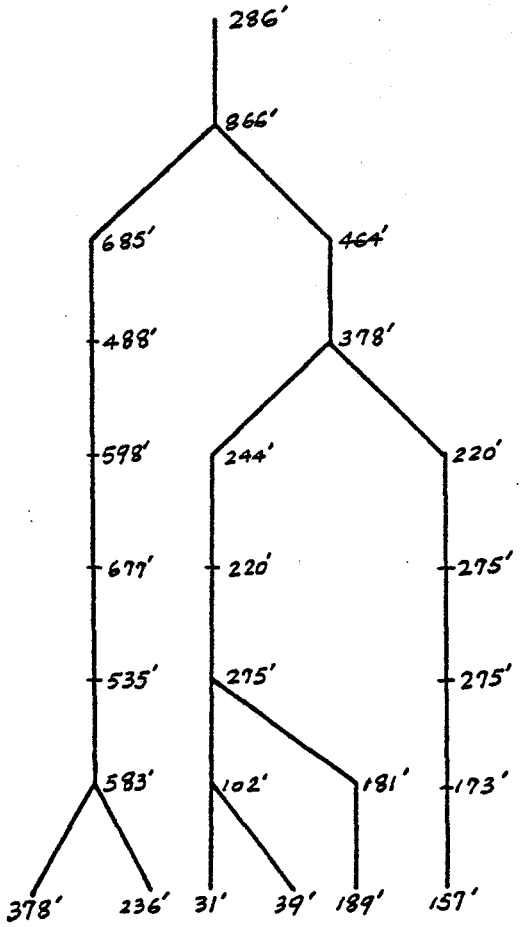
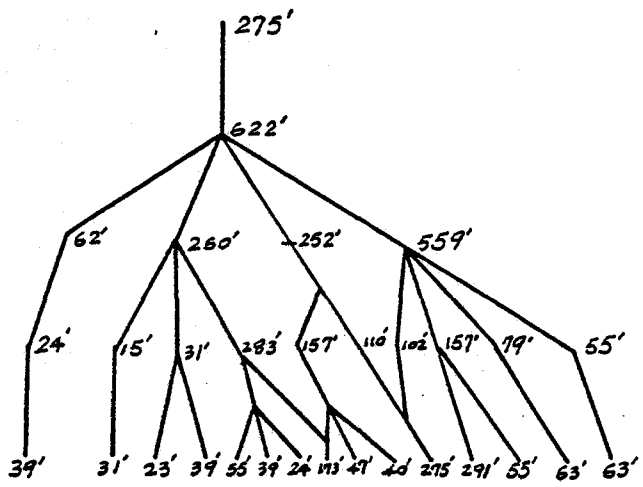
CHANNEL BRANCHING	RADIAL DISTANCE, FT	SUM OF WIDTH, FT	SUM OF WIDTH/ SINGLE CHANNEL WIDTH
	2400	286	1.00
	3660	866	3.24
	4400	1149	4.30
	4800	866	3.24
	5700	1068	4.00
	6200	1172	4.39
	6800	1085	4.06
	7200	1038	3.89
	9740	1030	3.86
		AVERAGE	3.87

TABLE A-4

OBSERVED CHANNEL BRANCHINGS FOR DEER CREEK

NEAR GUSTI, CALIFORNIA (USING AERIAL PHOTOGRAPHS OF JANUARY 30, 1969)

CHANNEL BRANCHINGS	RADIAL DISTANCE, FT	SUM OF WIDTH, FT	SUM OF WIDTH/ SINGLE CHANNEL WIDTH
	300	275	1.00
	600	622	2.26
	1600	1133	4.12
	2840	1013	3.68
	3900	1257	4.57
		AVERAGE	3.66

APPENDIX B

APPENDIX B

COMPARISON OF DIFFERENT ALLUVIAL FAN FLOOD ANALYSIS METHODS

APPENDIX B

COMPARISON OF DIFFERENT ALLUVIAL FAN FLOOD ANALYSIS METHODS

The proposed multiple-channel method of the present study was compared with the current FEMA single-channel method and two other alternatives (designated as Alternative I and Alternative II), chosen to test the robustness of the flow boundary predictions. Alternative I assumed critical flow conditions for the calculations of the flow velocity and depth in the multiple channel region. The method also assumed that the channel width for the multiple channel region is 3.8 times the channel width in the single channel region. Therefore, it is essentially the present FEMA method with a channel 3.8 times as wide. Alternative II assumed that, below the single channel region on the alluvial fan, the flood channel split into two sets of sub-channels of the same width, each being equal to 1.9 times the channel width predicted by the present FEMA single-channel method with two-thirds of the peak discharge creating the width of each set. Thus two-thirds of the peak discharge was assumed to shift alternatively between the two sub-channels during the flood. This results in a smaller flood causing a wider channel system because it migrates between channels. That smaller flood hypothetically flows in a set of channels 1.9 times the present FEMA method. The comparsion of the four alternative methods was based on the flood analysis for three hypothetical alluvial fans of different sizes, each being typical of a small, a medium, and a large alluvial fan. All three alluvial fans were assumed to have a 90 degree angle of expansion for the purpose of illustration. Log-Pearson III parameters assumed for the flood frequency distribution for the fans are shown in Table B-1.

TABLE B-1

LOG PEARSON III FLOOD FREQUENCY DISTRIBUTION PARAMETERS

ASSIGNED FOR THE HYPOTHETICAL ALLUVIAL FANS

Distribution Parameters	Fan #1	Fan #2	Fan #3
Log Mean, X	2.0	2.5	3.0
Log Standard Dev., S	0.5	0.5	0.5
Log Skewness, G	0.3	0.3	0.3
100-year Flood, cfs	1870	5920	18700

The transformed parameters for the log Pearson III distribution for the calculation of flood depth boundaries on those three alluvial fans are shown in Table B-2.

TABLE B-2

TRANSFORMED PARAMETERS FOR LOG PEARSON III DISTRIBUTION
FOR THE ALLUVIAL FANS IN THE COMPARISON

Transformed Parameters	Fan #1	Fan #2	Fan #3
$m = X-2S/G$	-1.333	-0.833	-0.333
$\alpha = 2/GS$	13.333	13.333	13.333
$\lambda = 4/G^2$	44.444	44.444	44.444
$a = \alpha - 0.92$	12.413	12.413	12.413
$C = \exp[0.92X + 0.42S^2]$	6.994	11.078	17.555
$Z = m + \lambda/a$	2.247	2.747	3.247
$S_z = \lambda^{1/2}/a$	0.537	0.537	0.537
$G_z = 2/\lambda^{1/2}$	0.300	0.300	0.300

Using the above transformed parameters for the log Pearson III distribution, the boundaries for various flood depths, in terms of radial distance from the apex to those boundaries, were calculated and compared for the proposed multiple-channel method, the FEMA single-channel method, and Alternatives I and II in Tables B-3 through B-6.

TABLE B-3

FLOOD DEPTH BOUNDARIES FOR THE HYPOTHETICAL ALLUVIAL FANS CALCULATED USING THE FEMA SINGLE-CHANNEL METHOD

FLOOD CHARACTERISTICS	Flood Depth	
	0.5 ft	1.5 ft
Flood Discharge, cfs	49.5	772.
Boundary for Fan #1, ft	5359.(1.07)	786.(1.60)
Boundary for Fan #2, ft	9879.(1.01)	3819.(1.14)****
Boundary for Fan #3, ft	15914.(1.00)*	11734.(1.00)

Note: see footnotes for Table B-6.

TABLE B-4

FLOOD DEPTH BOUNDARIES FOR THE HYPOTHETICAL ALLUVIAL FANS CALCULATED USING THEPROPOSED MULTIPLE-CHANNEL METHOD

FLOOD CHARACTERISTICS	Flood Depth	
	0.5 ft	1.5 ft
Flood Discharge, cfs	300.	1500.
Boundary for Fan #1, ft	7727.(1.02)	1196.(1.48)
Boundary for Fan #2, ft	25915.(1.00)*	7917.(1.02)****
Boundary for Fan #3, ft	46706.(1.00)*	32247.(1.00)

Note: see footnotes for Table B-6.

TABLE B-5

FLOOD DEPTH BOUNDARIES FOR THE HYPOTHETICAL ALLUVIAL FANS CALCULATED USING ALTERNATIVE I

FLOOD CHARACTERISTICS	Flood Depth	
	0.5 ft	1.5 ft
Flood Discharge, cfs	450.	7021.
Boundary for Fan #1, ft	5304.(1.07)**	96.(1.75)***
Boundary for Fan #2, ft	21015.(1.00)*	1069.(1.53)****
Boundary for Fan #3, ft	52302.(1.00)*	11271.(1.00)

Note: see footnotes for Table B-6.

TABLE B-6

FLOOD DEPTH BOUNDARIES FOR THE HYPOTHETICAL ALLUVIAL FANS CALCULATED USING ALTERNATIVE II

FLOOD CHARACTERISTICS	Flood Depth	
	0.5 ft	1.5 ft
Flood Discharge, cfs	218.	3400.
Boundary for Fan #1, ft	8480.(1.01)	298.(1.69)
Boundary for Fan #2, ft	29357.(1.00)*	4907.(1.09)
Boundary for Fan #3, ft	49613.(1.00)*	14767.(1.00)

( ) Slope ratio from Figure 18 for the calculated distance
* Multiple-channel method applicable
** 1-ft flood depth boundary at channel bifurcation point, if less than for single-channel method
*** Single-channel method applicable
**** For slope ratio less than 1.14,single channel method applies
For 1.14 < slope ratio < 1.53, single channel method applies to point of bifurcation, multiple-channel method applies downstream.
For slope ratio greater than or equal to 1.53, single-channel method applies to point of bifurcation, which defines the downstream extent of flood hazard.

For comparison, the computational results of flood depth boundaries for the above-mentioned methods are shown in Figure B-1. It can be seen from this figure that both 0.5-ft and 1.5-ft flood depth boundaries are longer for the proposed method than for the FEMA single-channel method, and the difference in the flood depth boundary between those two methods increases with the alluvial fan size. In comparison to Alternatives I and II, it can be seen from this figure that the 1.5-ft flood depth boundary for the proposed method is larger than those for Alternatives I and II. For the 0.5-ft flood depth boundary, the value for the proposed method is larger than that for Alternative I but smaller than that for Alternative II for the small and medium alluvial fans. For the large alluvial fan, the 1.5-ft flood depth boundary for the proposed method is smaller than those for Alternatives I and II.

It is also noted in Figure B-1 that the 0.5-ft flood depth boundary is almost the same for both Alternative I and the FEMA single-channel method for Fan #1. As the size of the alluvial fan increases, the flood depth boundary becomes longer for Alternative I than for the FEMA single-channel method. The 1.5-ft flood depth boundary, however, is shorter for Fan #1 for Alternative I than for the FEMA single-channel method. As the size of the fan increases, the difference in the flood depth boundary becomes smaller. The flood depth boundaries calculated using both methods are almost the same for Fan #3.

The 0.5-ft flood depth boundaries for Alternative II as shown in Figure B-1 is longer than for that for the FEMA single-channel method for all the fan sizes. The 1.5-ft flood depth boundary for Alternative II is, however, smaller than that for the FEMA single-channel method for the small fan but larger than that for the FEMA single-channel method for the large alluvial fan.

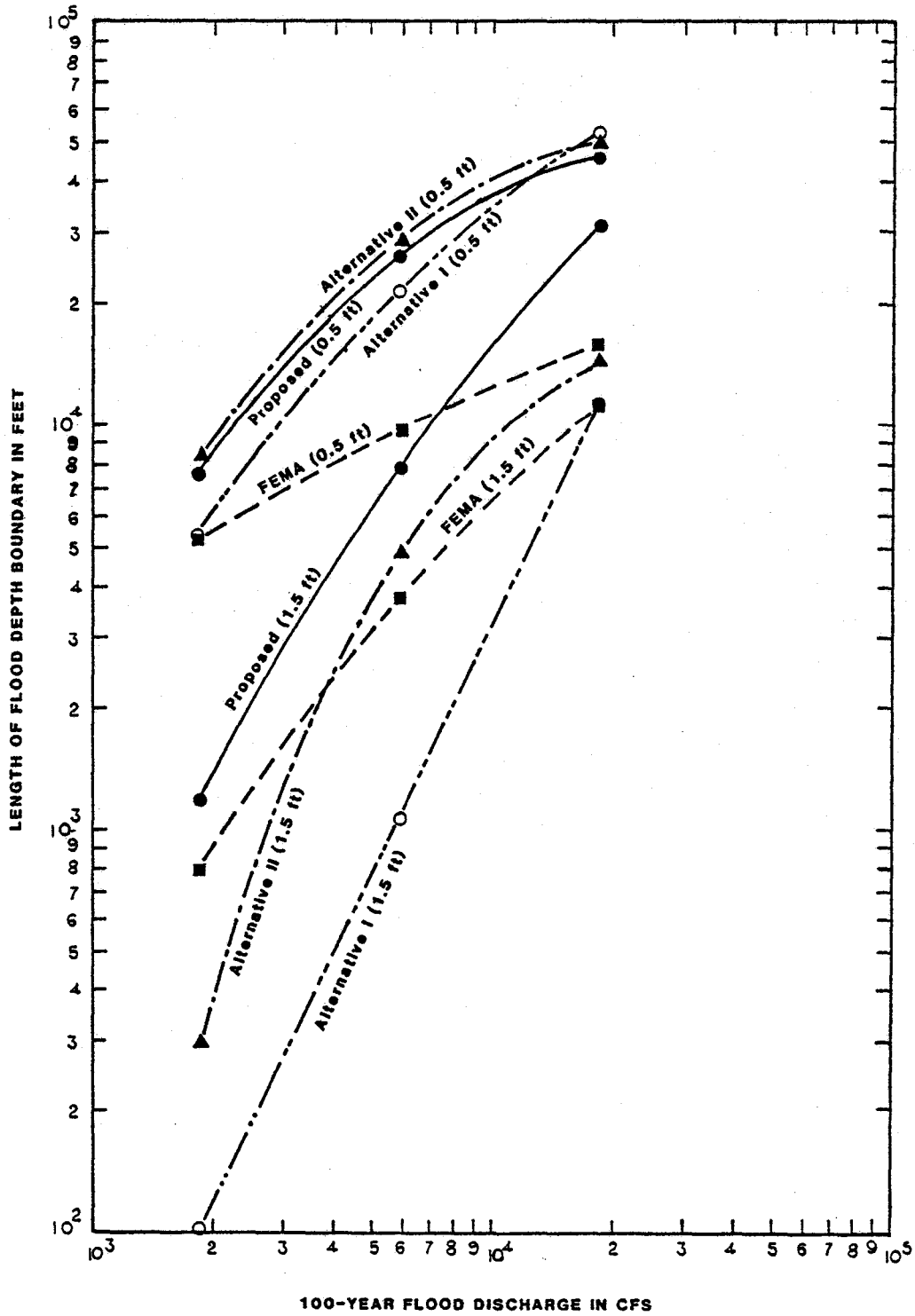


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FIGURE B - 1
Comparison of Flood Depth Boundaries Calculated Using Different Methods

In summary, the shapes of the three alternative methods are quite similar for the definition of the contour for 0.5 foot depth of flooding. That is the relation which would most often be used. Flooding will extend further down the fan. The definition of the contour for 1.5 feet of flooding will be less used, because the single channel equation would apply more often at that contour than at the contour further down the fan where the 0.5 foot depth is defined. For the 1.5 feet depth contour, the proposed method predicts its occurence further down the fan than any other methods considered for comparison.

All of the comparison are based on the hypothetical fans shown in Table B-1, and all were assumed to have an expansion angle of 90 degrees. Changes in those assumptions would change the points plotted in Figure B-1, but for a given fan the points for all the methods would change in a similar manner, so that the qualitative comparison described above will not change substantially.

APPENDIX C

APPENDIX C

PROPOSED MODIFICATION OF FEMA'S "GUIDELINES AND SPECIFICATIONS FOR STUDY CONTRACTORS: APPENDIX 6. ALLUVIAL FAN STUDIES"

A6-4 COMPUTATIONAL INSTRUCTIONS

e. Determine Discharges for Depth and Velocity Zones

The discharges, depths, and velocity zones for alluvial fan flooding can be determined by a combination of two methods. They are based on a single channel region and a multiple channel region in the analysis. The single channel region is defined by the length of the single channel measured from the mouth of the canyon to the point where the flood channel splits. The length of the single channel can be determined using Figure A6.1. Below the single channel region of the fan is the multiple channel channel region. The fan width along the boundary between the single channel and multiple channel regions can be measured from the topographic map, once the length of the single channel is known.

I. Single Channel Region

Within this region, discharge, Q (in cubic feet per second), that correspond to the various depth zone boundaries should be selected using the table below. This table was derived from the relationship

$$Q = 280\ D^{2.5}$$

where D is the total depth in feet due to pressure head and velocity head.

Q	49.5	772	2770	6420	12000
D	0.5	1.5	2.5	3.5	4.5

Depth zones are designated from zone boundaries as follows:

Depth of Zone	Depth of Lower Boundary	Depth of Upper Boundary
1	0.5	1.5
2	1.5	2.5
3	2.5	3.5
4	3.5	4.5

Discharges, Q (in cubic feet per second), that correspond to the various velocity zone boundaries should be selected using the table below. This table was derived from the relationship

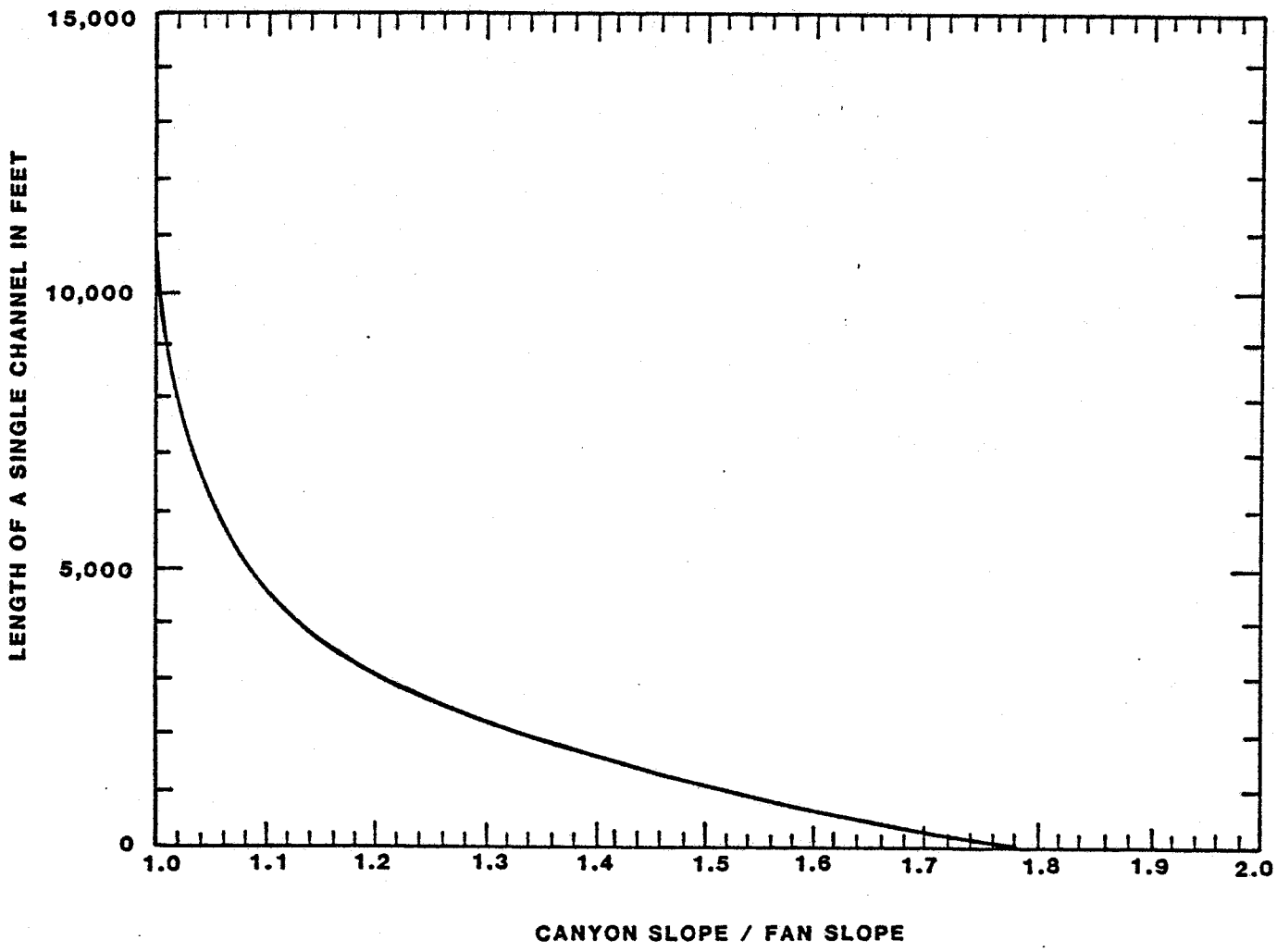
$$Q = 0.13\ V^{5}$$

where V is velocity in feet per second.

FIGURE A6-1

RELATIONSHIP BETWEEN LENGTH OF A SINGLE CHANNEL

AND RATIO OF CANYON SLOPE TO FAN SLOPE



Q	68	240	654	1510	3080	5770
V	3.5	4.5	5.5	6.5	7.5	8.5

Velocity zones are designated from zone boundaries as follows:

Zone Velocity	Velocity of Lower Boundary	Velocity of Upper Boundary
4.0	3.5	4.5
5.0	4.5	5.5
6.0	5.5	6.5
7.0	6.5	7.5
8.0	7.5	8.5

II. Multiple Channel Region

Within the multiple channel region, discharges, Q (in cubic feet per second), that correspond to the various depth zone boundaries may be calculated by iteratively solving the following equation:

$$D = 0.0917\, n^{.6}\, S^{-.3}\, Q^{.36} + 0.001426\, n^{-1.2}\, S^{.6}\, Q^{.48}$$

where D is the total depth in feet due to pressure head and velocity head, S is the fan slope, and n is Manning's roughness coefficient for the alluvial fan flood channel.

Discharges, Q (in cubic feet per second), that correspond to the various velocity zone boundaries should be calculated using the equation.

$$Q = 99314\, n^{4.17}\, S^{-1.25}\, V^{4.17}$$

where V is velocity in feet per second and S is the fan slope.

Depth zones and velocity zones are designated from zone boundaries in the same manner as shown in the analysis for the single channel region.

h. Compute Fan Widths for Zone Boundaries

The fan widths (i.e., arc lengths from one lateral limit of the fan to the other taken parallel to contours) that correspond to each upper and lower zone boundary depth and velocity listed in Section A6-4e should be computed both for the single channel region and the multiple channel region. The following formulas should be used.

I. Single Channel Region

Fan Width = 950 ACP

II. Multiple Channel Region

Fan Width = 3610 ACP

In the above two formulas, A is the avulsion coefficient, C is the transformation constant, and P is the probability of the discharge that corresponds to each given depth and velocity.

An avulsion coefficient (factor) greater than 1 should be selected by the Study Contractor in consultation with the Project Officer. A factor of 1.5 is recommended in the absence of other data.

In summary, the steps for the determination of the flood velocity and depth boundaries are listed as follows:

1. Compute all flood depth and velocity zone boundaries by the standard single channel method.

2. Determine point of bifurcation into multiple channel region through use of Figure A6.1 and the calculation of near fanhead canyon slope to fan slope ratio.

3. If the point of bifurcation is downfan from the lower boundary of the one-foot depth zone as computed by the standard single channel method, the standard single channel method will be used for the determination of all flood boundaries on the fan.

4. If the point of bifurcation is upfan from upper the boundary of the one-foot depth zone as computed by the standard single channel method, the one-foot depth zone boundaries will be changed to that computed for the multiple channel case.

5. If the point of bifurcation is upfan from the one-foot depth zone boundaries as computed by the standard single channel method, compute the depth and velocity at the point of bifurcation by the standard single channel method. Compute the velocity and depth boundaries for velocities and depth less than those determined for the point of bifurcation by use of the multiple channel method. Substitute those boundaries for the boundaries computed by the standard single channel method.

A6-7 SAMPLE STUDY

c. Determination of Discharges for Depth and Velocity Zones

The discharges that correspond to the various depth and velocity zone boundaries were selected from the tables for the single channel region and calculated by use of the equations for the multiple channel region shown in Section A6-4e of this Appendix. For Number One Canyon, with the fan slope of 0.03 and Manning's n of 0.02, these discharges are as follows:

I. Single Channel Region

Depth	Discharge
0.5	49.5
1.5	772.0
2.5	2770.0

Velocity	Discharge
3.5	68
4.5	240
5.5	654
6.5	1510

II. Multiple Channel Region

Depth	Discharge
0.5	310
1.5	3835

Velocity	Discharge
3.5	122
4.5	348
5.5	803
6.5	1611

d. Determine Probabilities of Transformed Discharges and Fan Widths at Zone Boundaries

The log-Pearson Type III standard deviates (K) were computed for the discharges (Q) that correspond to each depth zone boundary and each velocity zone boundary, using the equation

$$K = \frac{\log Q - \bar{Z}}{S_z}$$

The probability of occurrence (P) of the discharges for the required depth and velocity boundaries were determined by interpolation of the deviate values (K) listed in Appendix 3 of Bulletin 17B.

Fan arc widths (W) were computed for each special flood hazard zone boundary using the equation

$$W = 950\ ACP$$

for the single channel region and the equation

$$W = 3610\ ACP$$

for the multiple channel region.

An avulsion coefficient (A) of 1.5 was assumed for each case.

Computations for Number One Canyon were made as follows:

Based on the fan slope of 0.03 and near fanhead canyon slope of 0.036, the ratio of canyon slope to fan slope is calculated as 1.2. The single channel length of 3200 feet was determined from Figure A6.1 using the calculated ratio of canyon slope to fan slope of 1.2. The fan width along the boundary dividing the single channel region and multiple channel region was determined as 1680 feet from the topographic map based on the calculated value of the single channel length.

I. Single Channel Region

For the 0.5-foot depth boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 49.5 - 2.29}{0.4965} = \frac{1.695 - 2.29}{0.4965} = -1.199$$

$$P\{Q>49.5\} = P\{K> -1.199\} = 0.881$$

$$W = 950\ ACP = 950 \times 1.5 \times 7.4 \times 0.881 = 9290 \text{ feet}$$

For the 1.5-foot depth boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 772 - 2.29}{0.4965} = \frac{2.888 - 2.29}{0.4965} = 1.204$$

$$P\{Q>772\} = P\{K> 1.204\} = 0.118$$

$$W = 950\ ACP = 950 \times 1.5 \times 7.4 \times 0.118 = 1240 \text{ feet}$$

For the 2.5-foot depth boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 2770 - 2.29}{0.4965} = \frac{3.44 - 2.29}{0.4965} = 2.316$$

$P \{ Q > 2770 \} = P \{ K > 2.316 \} = 0.0104$

$W = 950 \text{ ACP} = 950 \times 1.5 \times 7.4 \times 0.0104 = 110$ feet

For the 3.5-feet per second (fps) velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 68 - 2.29}{0.4965} = \frac{1.83 - 2.29}{0.4965} = -0.926$$

$P \{ Q > 68 \} = P \{ K > -0.926 \} = 0.819$

$W = 950 \text{ ACP} = 950 \times 1.5 \times 7.4 \times 0.819 = 8640$ feet

For the 4.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 240 - 2.29}{0.4965} = \frac{2.38 - 2.29}{0.4965} = 0.181$$

$P \{ Q > 240 \} = P \{ K > 0.181 \} = 0.428$

$W = 950 \text{ ACP} = 950 \times 1.5 \times 7.4 \times 0.428 = 4510$ feet

For the 5.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 654 - 2.29}{0.4965} = \frac{2.816 - 2.29}{0.4965} = 1.059$$

$P \{ Q > 654 \} = P \{ K > 1.059 \} = 0.15$

$W = 950 \text{ ACP} = 950 \times 1.5 \times 7.4 \times 0.15 = 1580$ feet

For the 6.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 1510 - 2.29}{0.4965} = \frac{3.18 - 2.29}{0.4965} = 1.793$$

$P \{ Q > 1510 \} = P \{ K > 1.793 \} = 0.037$

$W = 950 \text{ ACP} = 950 \times 1.5 \times 7.4 \times 0.037 = 390$

II. Multiple Channel Region

For the 0.5-foot depth boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 310 - 2.29}{0.4965} = 0.4055$$

$$P\{Q > 310\} = P\{K > 0.4055\} = 0.3438$$

$$W = 3610 \text{ ACP} = 3610 \times 1.5 \times 7.4 \times 0.3438 = 13780 \text{ feet}$$

For the 1.5-foot depth boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 3835 - 2.29}{0.4965} = 2.6058$$

$$P\{Q > 3835\} = P\{K > 2.6058\} = 0.0047$$

$$W = 3610 \text{ ACP} = 3610 \times 1.5 \times 7.4 \times 0.0047 = 190 \text{ feet}$$

For the 3.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 122 - 2.29}{0.4965} = -0.4102$$

$$P\{Q > 122\} = P\{K > -0.4102\} = 0.6578$$

$$W = 3610 \text{ ACP} = 3610 \times 1.5 \times 7.4 \times 0.6578 = 26360 \text{ feet}$$

For the 4.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 348 - 2.29}{0.4965} = 0.5067$$

$$P\{Q > 348\} = P\{K > 0.5067\} = 0.3065$$

$$W = 3610 \text{ ACP} = 3610 \times 1.5 \times 7.4 \times 0.3065 = 12280 \text{ feet}$$

For the 5.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 803 - 2.29}{0.4965} = 1.2381$$

$$P\{Q > 803\} = P\{K > 1.2381\} = 0.1099$$

$$W = 3610\ ACP = 3610 \times 1.5 \times 7.4 \times 0.1099 = 4400 \text{ feet}$$

For the 6.5-fps velocity zone boundary:

$$K = \frac{\text{Log } Q - \bar{Z}}{S_z} = \frac{\text{Log } 1611 - 2.29}{0.4965} = 1.8471$$

$$P\{Q > 1611\} = P\{K > 1.8471\} = 0.0331$$

$$W = 3610\ ACP = 3610 \times 1.5 \times 7.4 \times 0.0331 = 1330 \text{ feet}$$

III. Fow Velocity and Depth at Bifurcation Point

The fan width at the bifurcation point is 1680 feet. The probability of occurrence (P) of the discharge for the velocity and depth at the bifurcation point can be calculated using the equations for the standard single channel method as follows:

$$P = \frac{W}{950\ A\ C} = \frac{1680}{950 \times 1.5 \times 7.4} = 0.1593$$

The standard deviate, K, is then determined to be 1.0207 by interpolation of probabilities and standard deviates, with skewness G equal to zero, listed in Appendix 3 of Bulletin 17B. The corresponding discharge, velocity, and depth may be calculated using the following formulas,

$$\text{Log } Q = \bar{Z} + K\ S_z = 2.29 + 1.0207 \times 0.4965 = 2.797$$

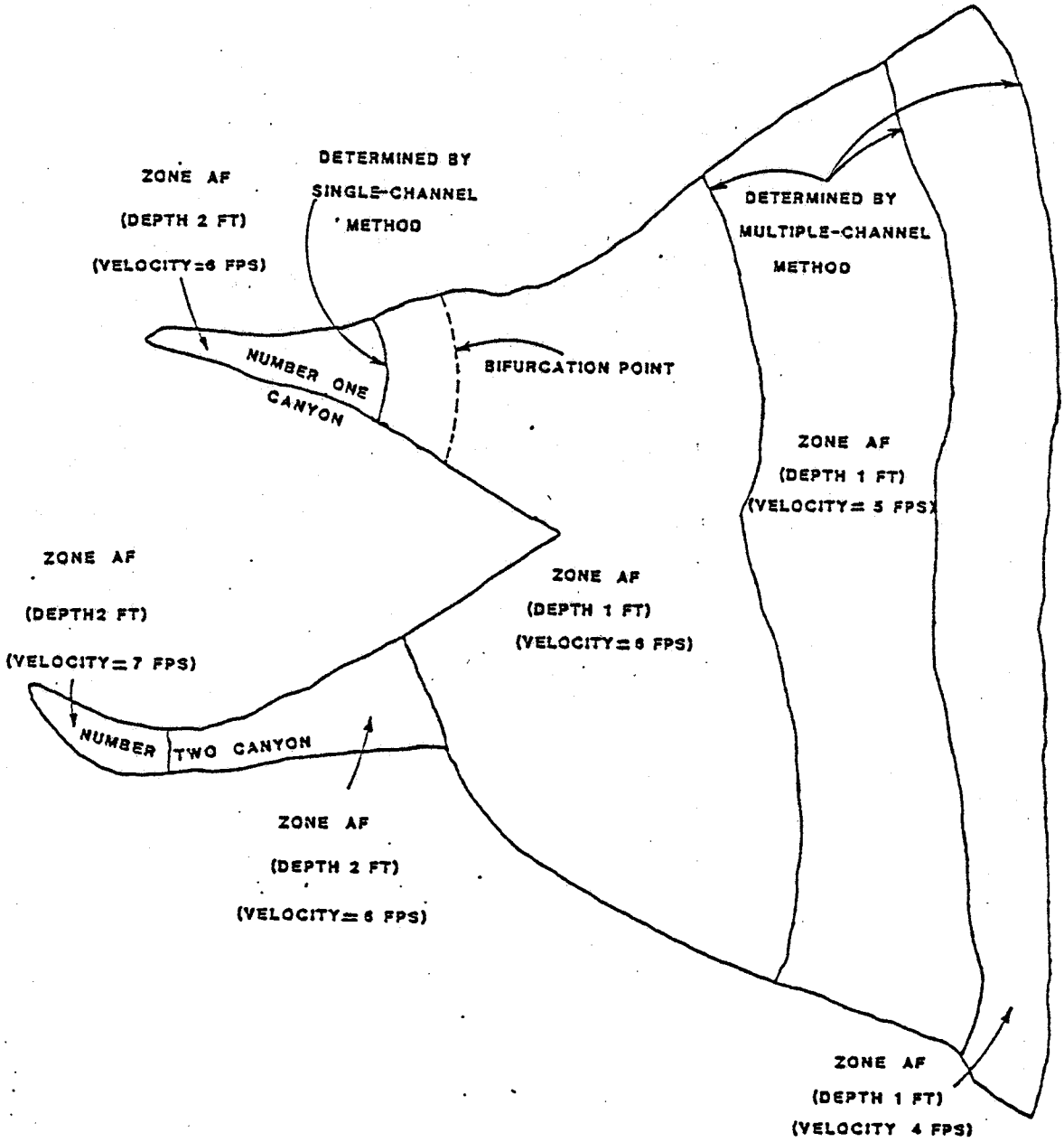
Thus $Q = 626$ cfs

$$V = 1.5\ Q^{0.2} = 1.5 \times (626)^{0.2} = 5.4 \text{ fps}$$

$$D = 0.10\ Q^{0.4} = 0.10 \times (626)^{0.4} = 1.3 \text{ feet}$$

So, the 0.5 foot depth contour and the 5.5, 4.5 and 3.5 ft/sec velocity boundaries are determined by the multiple-channel method. All other boundaries are determined by the single-channel method. Fan widths were computed independently for the fan originating from Number Two Canyon. The computed widths were then fit to the proper contours on the fans to produce the flood hazard zone boundaries as shown on the map (see Figure A6.2).

FIGURE A 6-2

DISTRIBUTION OF SPECIAL FLOOD HAZARDS ZONES

SAMPLE STUDY