SUMMARY REPORT

MATHEMATICAL MODELING OF FLOW OVER GILLESPIE DAM

By

HARZA Engineering Co.

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EXECUTIVE SUMMARY

Gillespie Dam, built in 1921, is a multiple arch and buttress dam spanning the Gila River about 40 miles southwest of Phoenix. The reservoir initially impounded by the dam filled with sediment soon after construction of the dam. The dam is primarily composed of 79 arches forming an overflow spillway section, 1,657 feet in length and 20 feet high above the downstream concrete apron. A sluiceway, about 40-feet wide is located at the east abutment. Abutments at each end of the dam are 10 feet higher than the overflow spillway section.

A section of Gillespie Dam failed on January 9, 1993, just after the peak of a flood had passed. Although estimates of the peak flow have varied, values within the reliable range of estimates should not change the basic findings presented herein. The adopted peak flow for January 9, 1993 as used herein is 178,000 ft^3/s, which is only slightly less than the estimated 50-year flood of 186,000 ft^3/s. The dam failure resulted in a breach 206 feet wide between Arch 11 and Arch 21. Arch 1 is located at the east abutment and Arch 79 is at the west abutment of the dam. Failure of the arches began at the east side of the breach and progressed toward the west.

The purpose of this study is to determine the distribution of flow along the crest of Gillespie Dam during the 1993 flood and place this information in context with events prior to the 1993 flood. Michael Stevens and John Haapala performed this study, under the supervision of Glenn Tarbox. A flow distribution that is concentrated (focused) increases the force of water on the dam and its downstream apron and causes increased scour in the riverbed at the end of the downstream apron. The primary factors affecting the distribution of flow along the crest of the dam are topography, which includes the size and configuration of channels, and the ground cover, which includes trees, fields, cleared floodplain, and areas normally covered with water (channels).

The history of flooding at the dam is also relevant. From 1942 through 1977, there was a period without any large floods with only one flood exceeding 20,000 cfs (64,200 cfs in 1966). In water years 1978, 1979, and 1980, the peak flows were 92,900 cfs, 125,000 cfs, and 178,000 cfs, respectively. Because of the similarity of the 1980 peak flow to the 1993 peak flow, the 1980 flood was included in this study in some detail. Understanding the changes that occurred between 1980 (when the dam survived a large flood) and 1993 (when the dam failed in a flood of similar magnitude) contributes to understanding the factors leading to the dam failure.

In the years prior to 1993, significant ground cover changes were made upstream from Gillespie Dam. The sediment-filled reservoir area would naturally support a thick growth of trees, primarily salt cedar, but the land is also attractive for farming. Following the series of floods in 1978-80, the Flood Control District of Maricopa County (FCD) cleared a 1,000-foot wide corridor for 36 miles upstream from Gillespie Dam to reduce the severity of damages attributed to flooding. Where the existing low-flow channel was not within the 1,000-foot wide corridor, a 100-foot wide pilot channel was excavated. The 1,000-foot wide cleared corridor and pilot channel were completed prior to the 1993 flood. A series of aerial photographs is presented in this report to document the significant changes in ground cover upstream from Gillespie Dam that occurred from 1975 through 1993.

A two-dimensional finite element hydrodynamic numerical model was the primary tool used to analyze the 1993 flood. The model is depth averaged and is two-dimensional in the horizontal plane, providing the capability to determine the flow distribution along a cross-section. The model computes water surface elevations, depths, and velocities, from which the discharge at any location can be determined. Two separate two-dimensional models were developed, one covering about seven miles upstream from the dam, a second model covering the last mile upstream of the dam in more detail. The seven-mile model provided the upstream boundary conditions for the one-mile model. An additional one-dimensional model was developed to determine the effects of flood wave attenuation in the modeled river reach, which were found to be negligible.

Modeling was performed for five conditions that included:

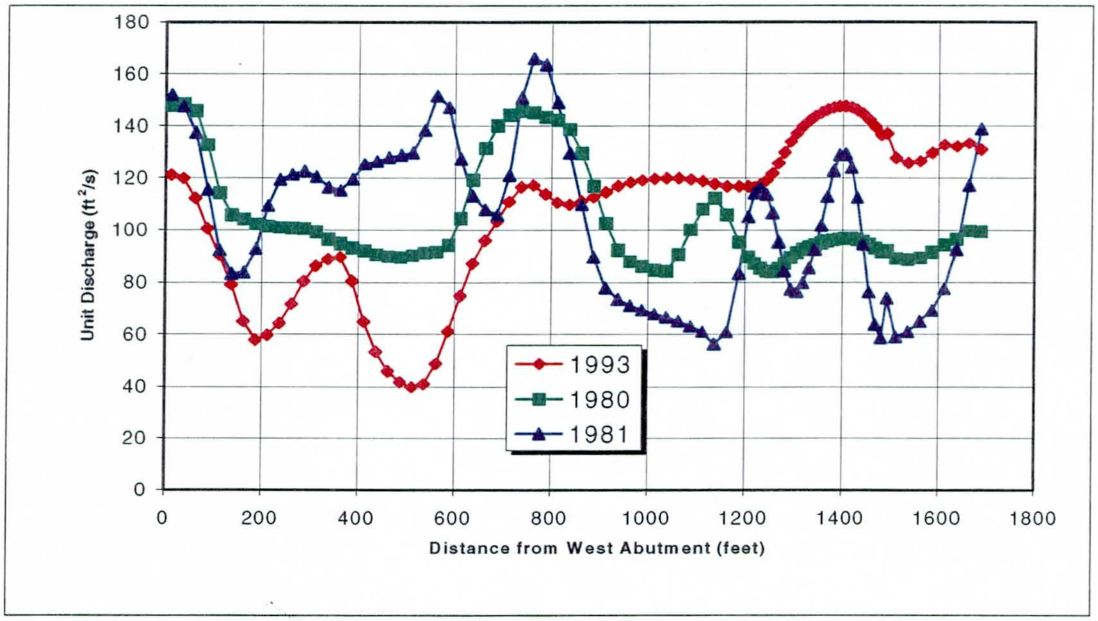
1) A 1993 Model which simulated conditions during the 1993 flood that resulted in dam failure.
2) A 1980 Model which simulated conditions during the 1980 flood which the dam survived.
3) A 1981 Model that simulated conditions just before the 1,000-foot wide corridor was cleared.
4) A Trees Model that simulated conditions with trees fully established upstream from Gillespie Dam.
5) A Bare Model that simulated conditions with trees completely removed upstream from Gillespie Dam. The Bare Model also approximates conditions if the FCD had decided to completely clear the floodplain for some distance upstream from Gillespie Dam.

For the 1993 Model, the 1980 Model, and the 1981 Model, material cover (trees, channels, cleared floodplain, etc.) were assigned to the model based on aerial photographs. The Trees Model and the Bare Model represented assumed conditions with uniform material coverage.

The 1991 topography was used in all models. The simulated concentration of flow in channels is probably underestimated in the modeling because channel depth below the low-flow water surface was not included, nor were the effects of scour, which should be greatest in the channels. The same flow rate (178,000 cfs) was also used in all of the models. Without changing the topography or flow rate, the variation in results among the models was due to changes in material cover, such as clearing of the 1,000-foot wide corridor by the FCD.

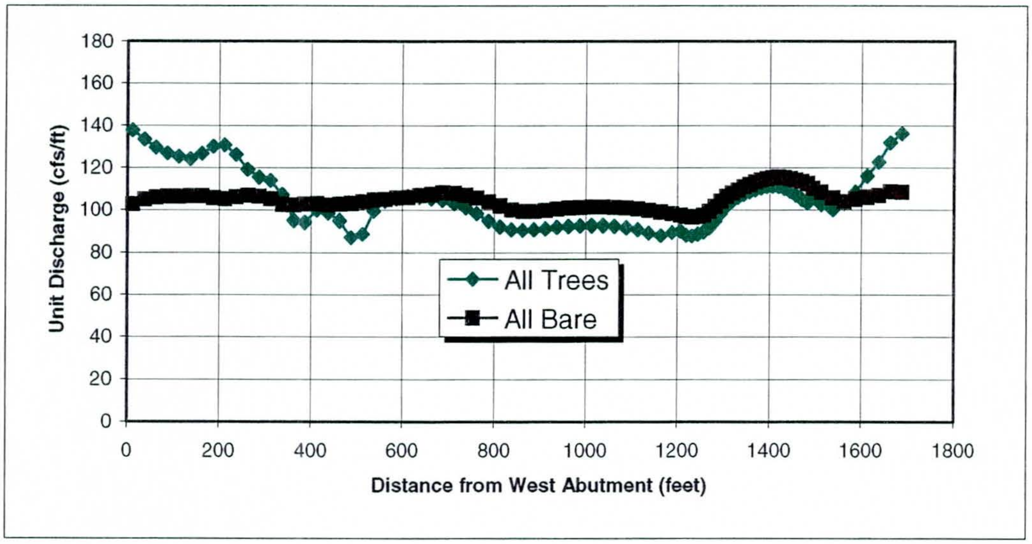
Prior to the February 1980 flood, farming and a series of floods had resulted in a floodplain upstream of Gillespie Dam with a relatively sparse growth of trees. An aerial photograph of the 1980 flood shows a predominant flow path generally to the west of what would become the 1,000-foot cleared corridor, with focused flow near the center and at the west end of the dam. Aerial photographs from 1981 show that the remnant low-flow channel from the 1980 flood (outside the future FCD cleared corridor) had been diked and diverted to a narrow eastern low-flow channel (within the future FCD cleared corridor). However, this action of diking and diverting the low-flow channel between 1980 and 1981 should have had little effect on the 1993 flood. If the existing low-flow channel had been outside of the 1,000-foot cleared corridor in the mid-1980's, the FCD would have excavated a low-flow (pilot) channel within the cleared corridor.

Conditions existing in December 1981 (the 1981 Model) showed a complex pattern of trees and cleared areas near the dam. By the time of the 1993 flood, the FCD 1,000-foot wide cleared corridor had been completed. The following figure shows the distribution of flow along the crest of Gillespie Dam for the three models corresponding to conditions that existed in 1980, 1981, and 1993.



The flow distribution in the simulated 1980 flood corresponds well with the flow distribution visible in an aerial photograph of the 1980 flood; the most focused flow is near the center of the dam and at the west abutment. For conditions that existed in 1981, including diking and diversion of the natural low-flow channel, the highest flow concentration is near the center of the dam, with several other areas of focused flow corresponding to cleared or open areas among the trees near the dam.

The following figure shows the distribution of flow along the crest of Gillespie Dam for an upstream floodplain that is either all trees or all-bare floodplain.



The model with an all-bare floodplain shows the most even distribution of flow along the dam of any of the models. With the lowest roughness coefficients, lateral movement of the flow is the least constrained. In the model having all trees, the unit discharge is greatest near the abutments at each end of the dam. This is probably due to the narrowing of the floodplain near the dam. Results indicate that changing the type and distribution of vegetation upstream from the dam by itself can significantly alter the distribution of flow along the crest of Gillespie Dam and focus the flow at different points on the dam.

Without the clearing of the 1,000-foot wide corridor, it is likely that the approach to Gillespie Dam would have been predominantly trees in 1992. Then, the major focusing of the flow would have not been at the point at which failure occurred, but near the center of the dam.

The FCD 1,000-foot wide corridor created an uneven flow distribution at the dam in the 1993 Model, with flow concentrated within the cleared corridor. Furthermore, the area in which flow was most focused, approximately 1,400 feet from the west abutment of the dam, was the area of initial failure of the dam. The FCD cleared corridor developed focused flow conditions at the point of dam failure.

The reason that Gillespie Dam did not fail during the 1980 flood and did fail during the 1993 flood was most likely due to the location of the focused flow.

INTRODUCTION

Gillespie Dam. Completed in 1921, the Gillespie Dam is a multi-arch concrete structure spanning the Gila River with a rectangular crest overflow section of length 1,657 feet (Figure 1). Only 20-feet high above the downstream concrete apron, the dam functioned to raise and divert water from the river into the Gila Bend Canal at the east abutment. Soon after completion, the pond behind the dam filled with sediment so there was no room for the storage of water.

Figure 1. US Geological Survey photograph from the east side downstream of the Gillespie Dam taken in 1962. Note that sediment has been deposited to the top of the dam and there is a healthy growth of vegetation on it.

The dam's 80 concrete arches, each 21 feet long (measured between buttress centerlines), were held in place by 18-inch wide concrete buttresses, with additional partial arches incorporated at each abutment. The overflow section of the dam consists of 79 full arches. The original 1921 drawings number the buttress from east to west (left to right looking downstream). Herein, the full arches that form the overflow section of the dam are numbered from east to west.

The concrete abutments at the ends are vertical to a height of 10 feet above the dam crest. Any flood with a depth 10 feet or less at the dam passed completely over the dam crest. Thus, a very large flood peak can spill over the dam without overtopping the abutments – a peak much greater than any that are in the US Geological Survey's hydrologic record.

A sluiceway, about 40-feet wide, with two gates was constructed at the east abutment. Its purpose was to remove sediment from in front of the Gila Bend Canal intake by hydraulically flushing the sediment to the riverbed downstream.

The crest of the dam, at Elevation 755.3 feet (with variations of a few tenths of a foot over the 1,657 foot length), is flat for 6 feet in the direction of flow. In the 1996 survey, the crest level was found to vary in elevation a maximum of 0.18 feet (Loomis 1997, pp. 4-5). As designed, any water coming across the crest falls 20 feet to a concrete apron, and is then deflected into a 4-foot high concrete wall which directs the flow upward (Figure 2). Finally the water falls again onto the downstream part of the apron, runs along it, and then over the end wall, to the riverbed downstream.

Figure 2. Flow over the Gillespie Dam before the breach on 9 January 1993 (PILP 09939). The photograph was taken from the east abutment looking to the west.

Pre-failure Photograph. The aerial photograph taken at 10:07 am on 9 January 1993, at the peak of the flood (Figure 3), defines the flow approaching and spilling over the dam about three hours before the breach. Many features portrayed in the photograph are helpful in assessing the reasons for the failure.

The wide expanse of water approaching the dam on the east side is the Flood Control District of Maricopa County's (hereinafter "FCD") 1,000-foot wide corridor. Trees and small channels dominate the west side of the approach to the dam. Water passing over the dam and over the apron wall entrained air, which gives the surface of the water downstream a white appearance on the photograph. The extent that this white water appears beyond the end of the dam is an indication of the water's speed and hence its discharge.

Starting at the west abutment of the dam, the white water downstream indicates the following:

1. At the west abutment the flow was low.
2. The flow became larger where there is a long opening back into the trees.
3. It was reduced again where there was a wide row of trees upstream.
4. Where the 1,000-foot wide corridor had been created, the flow was larger than anywhere on the west side.

5. In the midst of the 1,000-foot wide corridor, nearer the east abutment, there was a spot on the apron and downstream with very little white water – the spot where the dam was to fail some three hours later. This area is about 230 feet to 330 feet from the east abutment.

Two hypotheses can explain the existence of this spot with very little white water. One is that the flow was so large here that the influence of the wall became inconsequential. Another is that the wall was not there at the time the photograph was taken.

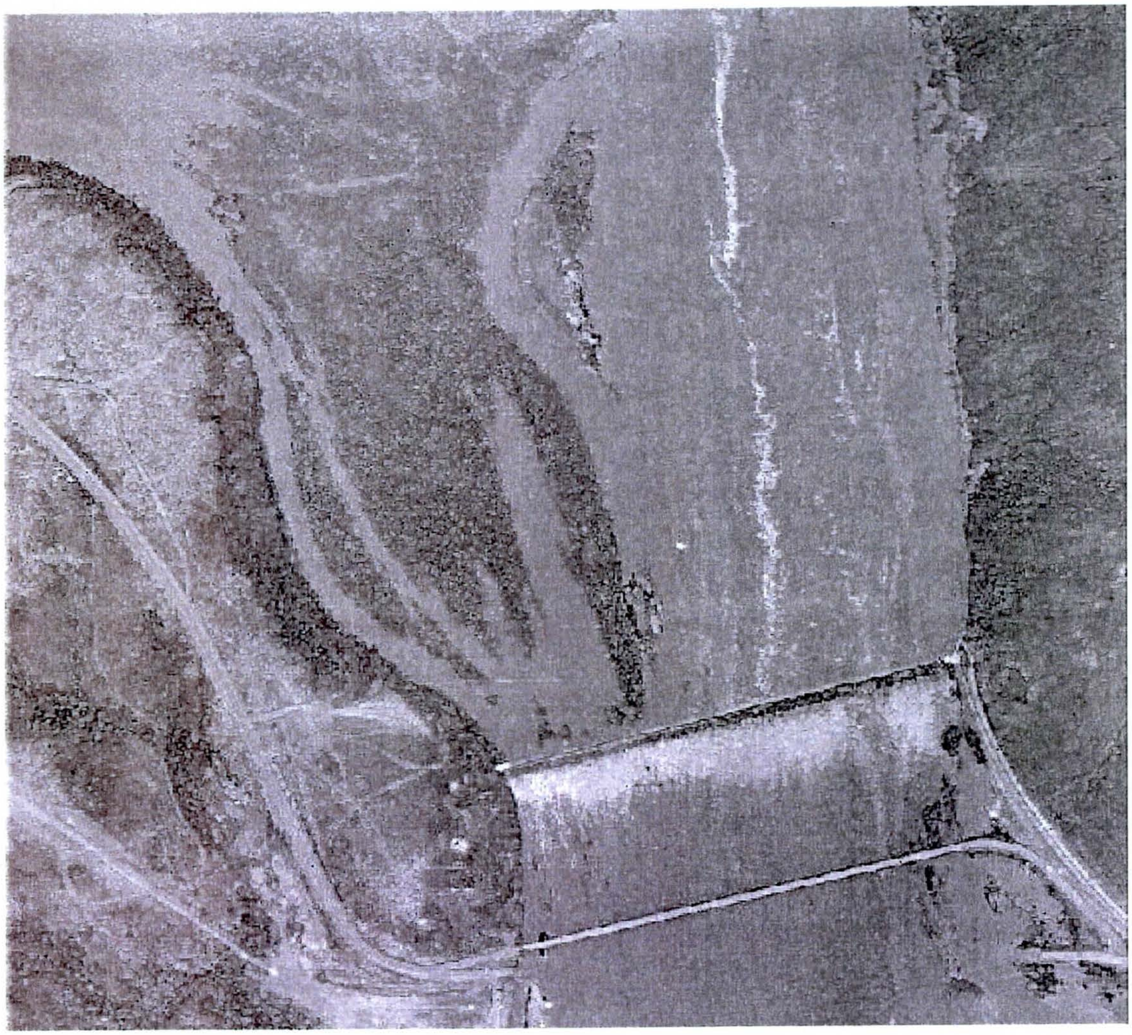


Figure 3. Aerial photograph of flow over Gillespie Dam taken at 10:07 am on 9 January 1993, approximately 3½ hours prior to the breach. Flow is from north to south (top to bottom). The Old Highway 80 bridge crosses the river approximately 700 feet downstream from the dam.

The white streak down the FCD's corridor is another interesting feature on the photograph. This occurrence is explained with the aid of the two-dimensional mathematical models of the flood flow.

Failure. At approximately 1:25 P.M. on 9 January 1993, the Gillespie Dam was breached just after the peak of the flood passed the dam (Barker 1997, p.3). It was reported that the initial breach was 20-25 feet wide (S.D. Coen, Sept. 8, 1993), or about the width of one arch. The progression of the breach was from east to west across the dam. The breach widened as follows:

Table 1. Schedule of arch failures (Wyman, unpublished notes, 1997).

Day	Time	Number of Broken Arches
9 January	1:30 pm	1
	2:14 pm	3
	3:10 pm	4
11 January	12:26 pm	7
	1:54 pm	9
Final		11

The July 1996 survey (Loomis 1997, p.5) put the final opening 206 feet wide beginning 223 feet from the east abutment (Figure 4). Accordingly, the first 10 arches from the east abutment remained. Arch 11 was partially damaged; Arches 12 through 20 were gone without a trace; Arch 21 was partially damaged; and the rest (22 to 79) remained intact and undamaged.

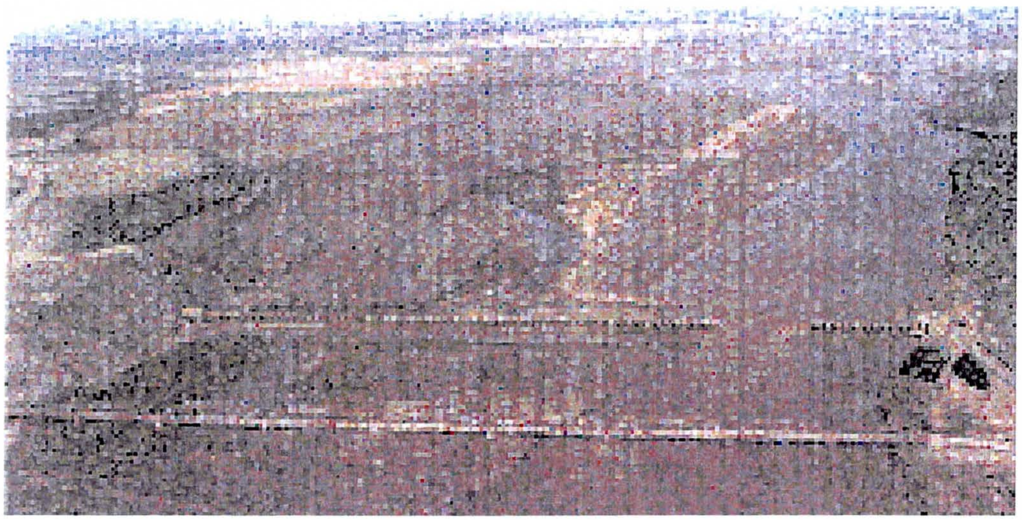


Figure 4. Oblique aerial view showing the breached Gillespie Dam in March 1993 (PILP 10122).

From this it could be assumed that the initial failure occurred at or near Arch 12, also taking part of Arch 11 in the initial failure. The east side of Arch 12 is 230 feet from the east abutment and 1,427 feet from the west abutment. The failure zone could be considered to be 230 feet to 330 feet from the east abutment, which is 1,327 feet to 1,427 feet from the west abutment and includes all of Arches 12 – 15 and most of Arch 16, essentially the east half of the final breach. However, the most probable zone of failure would be 230 to 251 feet from the east abutment (Arch 12), which is 1,406 feet to 1,427 feet from the west abutment. Arch 12 is subsequently referred to as the breached arch.

PURPOSE

The purpose of this study is to determine the distribution of flow along the crest of the Gillespie dam during the peak of the 1993 flood, just hours before the dam was breached and place this information in context with the events prior to the 1993 flood. The concentration of flow in 1993 was the result of conditions upstream from the dam. In this report, conditions that concentrate the flow are said to "focus" it. Focused flow increases the force of water on the dam, its apron, the 4-foot high wall, and the end sill. It can also cause increased scour in the riverbed at the end of the sill. Details of the effects that focused flow could have had on the dam structure and on riverbed scour are beyond the scope of this report.

The conditions upstream from the dam affecting focusing the flow include:

1. Topography, especially the configuration and size of channels.
2. Amount and location of vegetation, most importantly trees.
3. Amount and location of farmers' fields and any other bare land.
4. Existence of levees, dikes, and other embankments.

Focusing of the 1993 flood is placed into context by looking at the events that caused the focusing conditions. These include previous floods, the growth and destruction of vegetation, the damming of channels with embankments, and specifically the undertakings of the Flood Control District of Maricopa County.

Finally, "Why did Gillespie Dam not fail during the 1980 flood which had a peak flow equal to or greater than the 1993 flood that caused the breach?"

METHOD

The distribution of flow across the length of Gillespie Dam during the peak of the 1993 flood was determined with two-dimensional mathematical modeling. The model employs Newton's Second Law of Motion to determine where the water goes, how fast, and how deep.

A review of the flooding history in the Gila River at Gillespie Dam and places close by was made to compare the 1993 flood, up to the time of breaching, with floods of the past.

A study of aerial photographs was made to judge how the area upstream from the dam responded to flooding in the past. There have been changes in the amount and location of the vegetation and in the size and locations of the main channels.

The history of the FCD's efforts to mitigate flooding in the area from Powers Butte to Gillespie Dam was reviewed to determine how the District had affected the flow to and over the Gillespie Dam.

With the above information in hand, the mathematical models were run on other configurations of the area upstream of the dam. A comparison of the results of modeling was made to estimate the degree to which the FCD had focused the 1993 flood at the section of Gillespie Dam that failed.

FCD CORRIDOR

The floods of February and March 1978 and December 1978 to January 1979 were the impetus for the development of the 1,000-foot wide corridor along the Gila River from 91st Avenue to Gillespie Dam, a distance of 35.8 miles (FCD 1994). The purpose of the project was "... to facilitate higher than normal flow in the river and away from the surrounding properties" (Perreault 1998). The project's purpose has also been described as "A corridor of low hydraulic resistance and improved riverbed stability that reduces the severity of damages attributed to flooding in the Salt-Gila River between 91st Avenue and Gillespie Dam" (FCD 1994). The thick growth of salt cedar on the floodplain had created a significant impediment to flood waters moving through. The initial contract was for clearing away these trees upstream of Gillespie Dam but this was terminated in June 1980 due to the February 1980 flood.

Within the corridor, most non-native phreatophyte growth, predominately salt cedar (Tamarix chinensis) was to be removed while preserving native stands of cottonwood and willows. The project was amended in the mid-1980s to include a pilot channel in areas where the existing low flows were outside the 1,000-foot-wide clearing (FCD 1993). The 100-foot wide pilot channel was centered in the clearing, had a variable depth and could carry an average from 800 to 1,000 cubic feet per second (hereinafter "ft^3/s").

Clearing commenced again near the dam in 1981 and continued in 1982. Maintenance work on the corridor is evident on the 8 November 1986 aerial photograph. The cleared corridor extended to with 30 feet of the dam where the ground became too swampy for the clearing machinery to work. No pilot channel was needed on the flat deposits near the dam. A short section of pilot channel terminated about 2.8 miles from the dam (Perreault 1998, Exhibit C).

The 1,000-foot wide corridor was considered "...a prudent flood control strategy..." (Graf et al. 1995, p.30). We have not found any comment by FCD or its consultants as to how the corridor might affect Gillespie Dam. In fact, the Chief Engineer and General Manager of the FCD had previously proclaimed Gillespie "...probably the safest dam in the world" (Donald 1979).

FLOOD HISTORY

Floods in the Gila River are the natural agents of change. The floodwaters erode new channels, fill old ones, scour soils and vegetation, and spread sediment and debris on the floodplain. The changes in channels and vegetation in the region immediately upstream from the Gillespie Dam influence how the water flowed over the dam in the past. Thus these floods are of interest here – to put the breaching flood in context with the past.

Measurement of flow in the Gila River at Gillespie Dam began in 1920, about the time the dam was completed. The annual maximum instantaneous discharge downstream from the dam has varied widely in the some 80 years of record (Figure 5). In many years there was no flood, the water not getting out of the channels onto the floodplain. In 1956 and 1962, there was no flow at all over the dam during the entire Water Year (1 October of the previous year to 30 September). The peaks are affected by diversions at the dam into the Gila Bend and Enterprise Canals. Also, there are many dams upstream. Theodore Roosevelt Dam on the Salt River, completed in 1910, is the largest and most influential in storing floodwaters

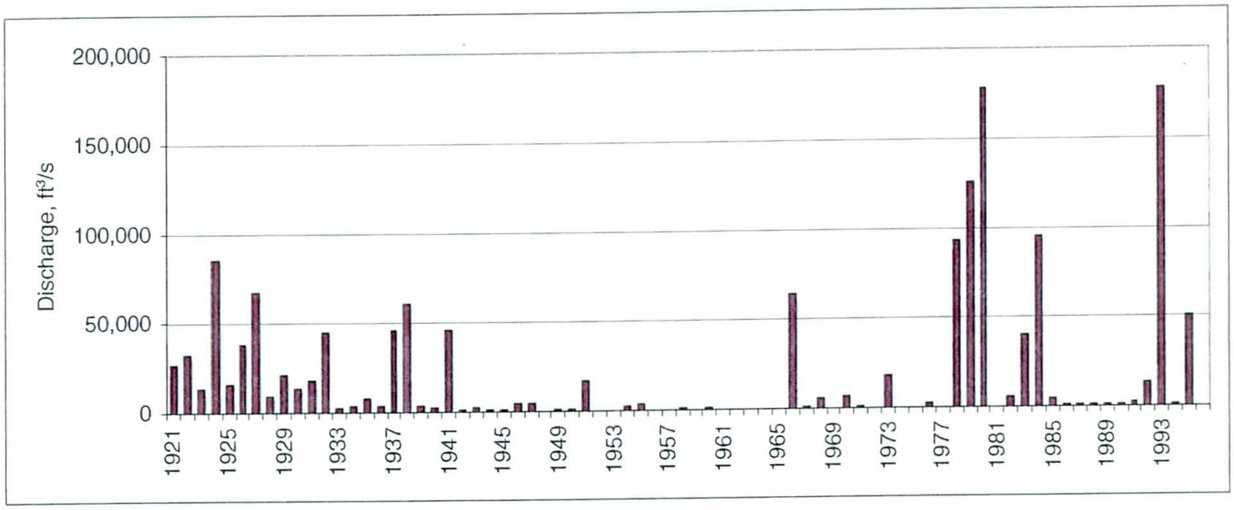


Figure 5. The sequence of annual maximum instantaneous flows in the Gila River below Gillespie Dam.

During the 25 years beginning in the early 1940s, the lack of floods could have been encouragement for farmers to encroach onto the sediment deposited immediately upstream due to the influence of the Gillespie Dam.

The US Geological survey lists a peak flow of 250,000 ft^3/s for February 1891. This is the largest in the historic record. Otherwise, floods have been lower than 100,000 ft^3/s until 1979.

The flow series for all peaks above 1,000 ft^3/s just downstream of Gillespie Dam (Figure 6) reveals a succession of flows near and above 100,000 ft^3/s between 1978 and 1984. The earlier ones in 1978 and 1979 were the impetus for the FCD's 1,000-foot wide corridor project, which began near the Gillespie Dam in 1981.

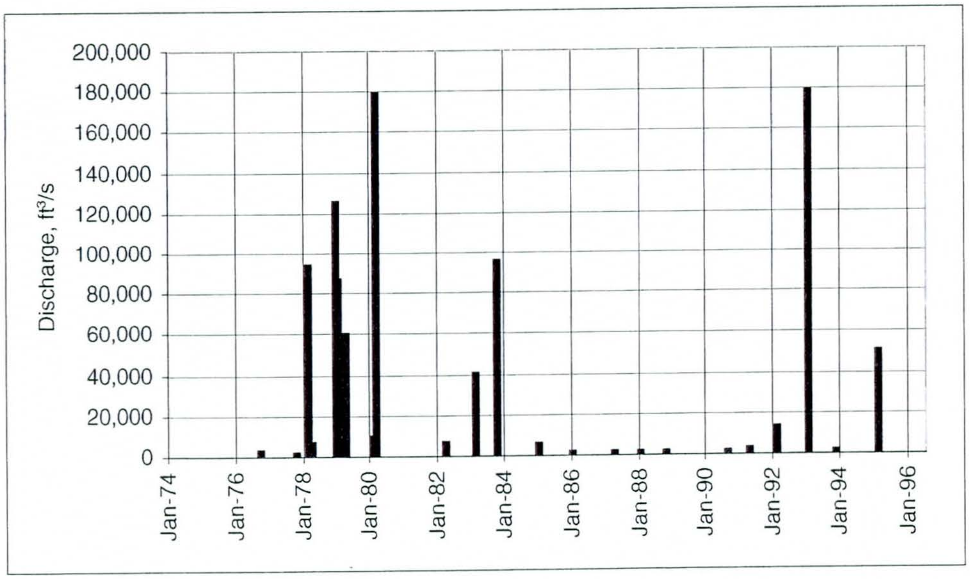


Figure 6. Instantaneous peak flows greater than 1,000 ft^3/s in the Gila River below Gillespie Dam since 1974.

On 9 January 1993, a flood flow in the Gila River breached the Gillespie Dam. That flood is reconstructed and discussed next.

1993 FLOOD

The winter flood of 1993 was one of the largest in terms of runoff and duration ever experienced at Gillespie Dam (Sabol 1997, p.5). However, here the prime interests are in the peak discharge on 9 January at Gillespie Dam and as well the Gila River hydrograph on the same day.

The two US Geological Survey water level gages on the Gila River at Gillespie became inoperable during the period of interest. One was immediately upstream from the dam at the east abutment (No. 09518000). The other was on an Old US Highway 80 bridge pier approximately 700 feet downstream from the dam (No. 09519500). The water level recorder on the Enterprise Canal did function. Also, it gives the indication that the Gillespie Dam failed at 1:30 P.M. on the 9th of January. The level in the Enterprise Canal reached a peak at 10:00 am on the same day (Hjalmarson 1997, Figure 8).

Some 27 miles upstream from the dam at Estrella Parkway, the US Geological Survey water level recorder on the Gila River (No. 09514100) failed about 1.3 hours after the peak of the flood arrived there at 2:30 am on 9 January (see Bookman-Edmonston 1995, Table 1).

Some 18 miles downstream from Gillespie Dam, the US Army Corps of Engineers water-level record at Painted Rock Reservoir captured the entire rise of the reservoir during the long flood. The Estrella Parkway and Painted Rock Reservoir records are the essence of the measured information for the flood.

Various estimates of the flood peak at Gillespie Dam (Table 2) are available. All are subject to criticism. The values of the flood peak up and down the river vary widely.

Table 2. Estimates of flood peaks on the Gila River during the 1993 flood.

Location	Source	Discharge ft^3/s	Status
Estrella Parkway	USGS	162,000 (instantaneous)	Published value
Gillespie Dam	USGS	130,000 (mean daily)	Published estimate
Gillespie Dam	Hjalmarson	132,000 (instantaneous)	Computed
Gillespie Dam	Hjalmarson	122,000 (mean daily)	Computed
Painted Rock	USCOE	204,000 (mean hourly)	From reservoir contents

Inflows to the Gila River by the Hassayampa and other smaller tributaries between Estrella Parkway and Painted Rock Reservoir on 9th January were minor compared to the flow in the Gila River.

Earlier the USGS had provided a provisional peak discharge of 180,000 ft^3/s for the Estrella Parkway gage (WEST Consultants 1993, p. 5). Later, the published value for this gage was lowered to 162,000 ft^3/s.

Judging that the Estrella Parkway gage "may be inaccurate," Hjalmarson (1997 p.1) routed recorded discharges from the upstream Gila River and its tributaries to Gillespie Dam and Painted Rock Reservoir. In addition to those in Table 1, his findings were that routed flows were larger in volume that those measured by the US Army Corps of Engineers (ibid. Figure 5).

The US Army Corps of Engineers' (1996) estimate is subject to three main errors. The first is the accuracy in which the reservoir volume was measured. The second is that over the years sediment has been deposited in the reservoir reducing the initial volume. The third is the effect of backwater on the amount of water in the reservoir. The second error usually results in too small an estimate of flow into the reservoir. Not accounting for backwater makes the estimate too small. Concerning the accuracy of the first survey, the estimate could be either way. It would require considerable fieldwork to improve the Corps' estimate.

The peak of the flood hydrograph at Gillespie Dam chosen for the one-dimensional modeling study is nominally 175,000 ft^3/s. This value is between that provided by the USGS at Estrella Parkway upstream and by the Corps of Engineers downstream. There is at least a measurement of peak water level at these two sites. The reconstructed hydrograph for the flood at Gillespie Dam (Figure 7) is that of the Corps of Engineers (1996) reduced by a factor of 0.83 and moved to have the peak at 1:15 P.M. on the 9th. This reconstructed hydrograph has the same 24-hour flow (130,000 ft^3/s) as that estimated by the US Geological Survey.

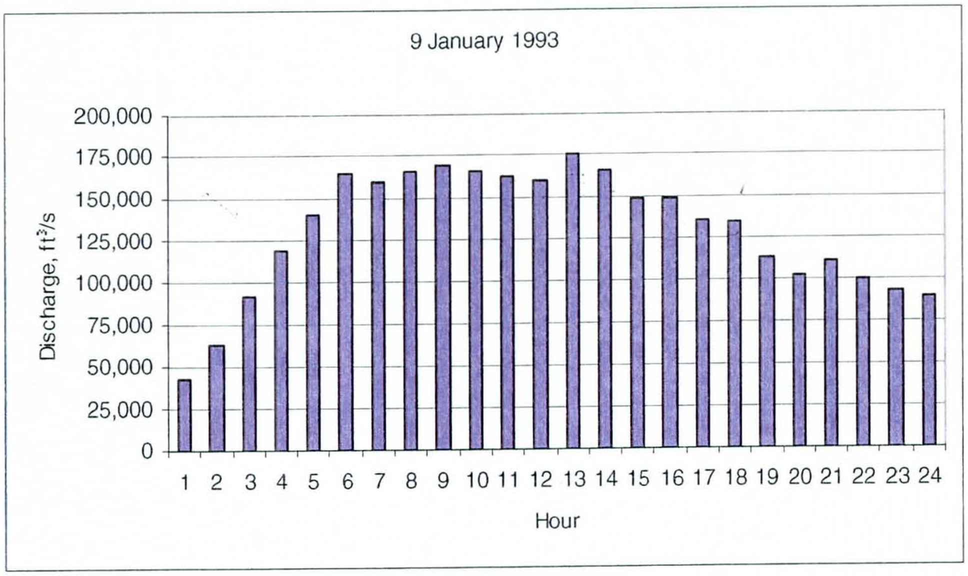


Figure 7. Hourly hydrograph of reconstructed Gila River flows at Gillespie Dam.

This Gila River peak of 175,000 ft^3/s is only 3,000 ft^3/s less that the flood peak that occurred in 1980. The rise from low flow to the peak was nearly the same in 1980 and 1993 (Sabol 1997, Figure 1).

At the time of the flood peak passage at Gillespie, it was estimated that 4,700 ft^3/s of flow was passing through the gates of the sluice at the east abutment of the dam (Loomis 1997, p. A9)

The selection of the flood hydrograph and its peak are not critical to the work in this study. Use of either the smaller or larger peak would lead to the same conclusions. By way of comparison, the 50-year flood peak estimated for the Gila at the Gillespie Dam is 186,000 ft^3/s (FEMA 1995).

AERIAL PHOTOGRAPHS

An assemblage of photographs (Table 3 and Appendix A) has been studied to assess what has gone on in the last few miles above Gillespie Dam in the years from 1975 to 1993. The former was at the end of a long period with only one flood, that being 64,200 ft^3/s on 2 January 1966. In 1978, there occurred a flood greater than any other previously in the century. This was the beginning of a series of large flows at the dam.

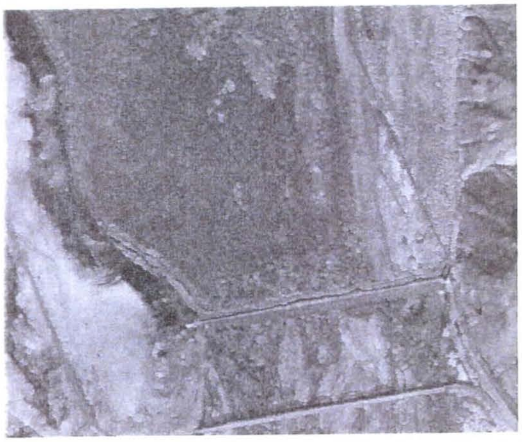
Table 3. Sequence of aerial photographs along with significant flood peaks.

Photograph Date	Source	Approximate Scale	Flood peaks in interval ft³/s	
15 Dec 1975	ADOT	1" = 2,500 ft	3 Mar 78	92,900
			20 Dec 78	125,000
			19 Jan 79	86,600
15 Feb 1979	FCD	1" = 2,000 ft	30 Mar 79	59,900
			16 Feb 80	178,000
16 Feb 1980	FCD	1" = 1,000 ft	20 Feb 80	126,000
			22 Feb 80	117,000
26 Jan 1981	FCD	1" = 3,000 ft		
2 Dec 1981	ADOT	1" = 1,000 ft		
5 Dec 1982	Landiscor	1" = 3,000 ft	5 Oct 83	95,200
5 Mar 1985	Landiscor	1' = 3,000 ft		
8 Nov 1986	Landiscor	1" = 3,000 ft		
30 Jun 1989		1" = 800 ft		
5 May 1991	ADOT	1" = 4,000 ft		
9 Jan 1993	ADOT	1" = 800 ft	9 Jan 93	175,000
7 Feb 1993		1" = 1,600 ft		

The aerial photographs reproduced in the following pages indicate many features that affect the focusing of flow at the dam. These include size, location, and number of channels, the amount of bare ground (fields and otherwise) on the floodplain, and the location and density of the vegetation. More photographic detail is given in Appendix A.

Channels at the Dam. The main channel is the largest of the waterways to the dam. During floods the main channel most likely carries the highest unit discharge which is the product of the flow depth and velocity at any point in the flow. The unit discharge (ft^3/s per foot of width) is designated q in technical literature.

15 Dec 1975



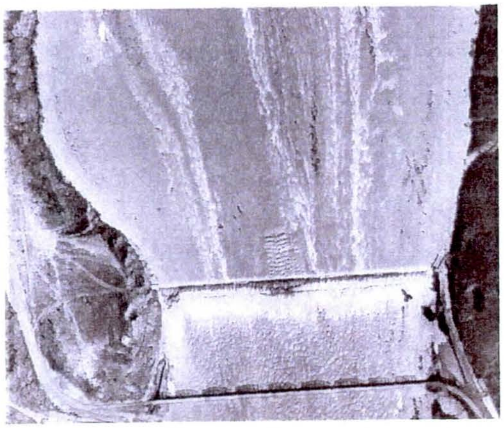
Approximately 150 feet wide, the main channel was about 400 feet out from the east abutment. There is a diagonal feature on the photograph indicating a small excavated channel from the main channel to the intake of the Gila Bend Canal at the east abutment of the dam. North is at the top of the photograph.

The channel running along the west edge of the valley to the dam is the Arlington Canal.

15 Feb 1979

After the series of three high flood peaks, the 1975 channel remained, but a bit to the west of the dam center, a new and larger main channel had formed, collecting much of the floodwater from the western side of the floodplain. Flow in the main channel had scoured a hole in the riverbed at the end of the apron. Part of the material from this scour hole was deposited in the wake of the central bridge pier at the highway bridge.

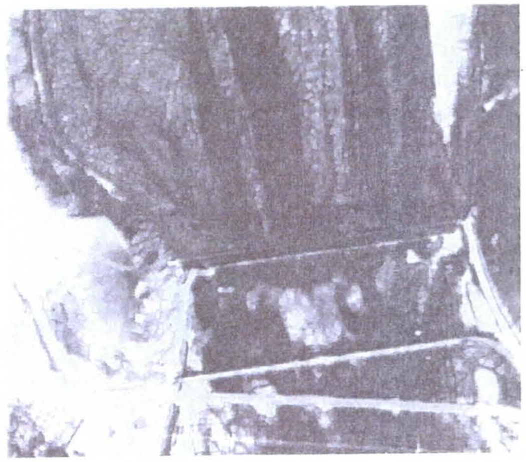
16 Feb 1980



At the height of the largest flood ever over Gillespie Dam, this same main channel of the previous year focused the flow at the dam. Evidence of this are the waves on the water surface just upstream from the dam crest and the extent and position of the water boiling up from the wall on the apron floor.

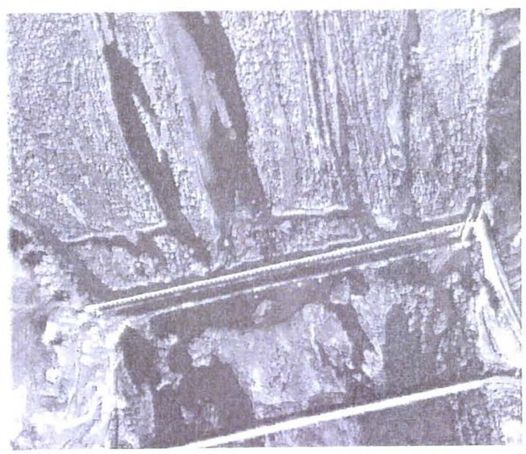
26 Jan 1981

By this time, the main channel during the 1980 flood had become a remnant, its water supply being cut off by an embankment about two miles upstream (see photograph of same date in Appendix A). The channel that was the main one in 1975 was carrying the low flow. A mound of sediment from scour at the end of the apron during the 1980 flood extended from the hole almost to the bridge. Some clearing of vegetation had been undertaken along the east side of the valley just upstream from the dam.



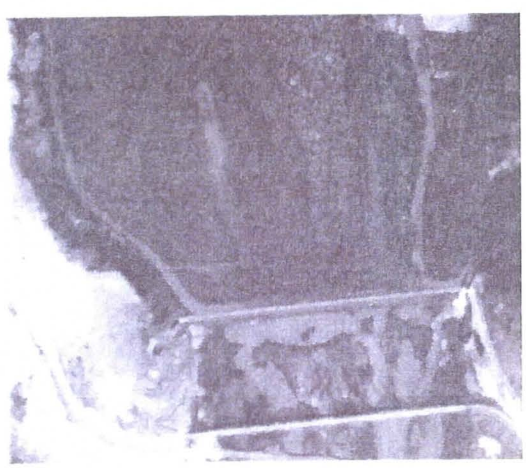
2 Dec 1981

By December, vegetation had almost closed off the low-flow channel of 10 months earlier. A poorly defined main channel had developed to the east, about 200 feet from the east abutment, the spot where the dam was to fail in 1993. One-half mile upstream vegetation had reduced this latest main channel to just a sliver on the photograph (see 3 photographs of same date in Appendix A). The area cleared of trees 10 months previously had become revegetated.



5 Dec 1982

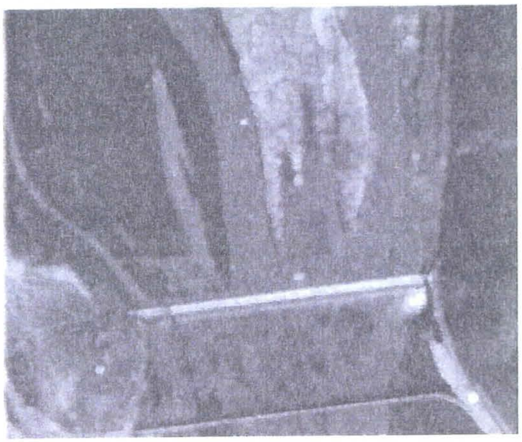
A year later, channel conditions remained the same. The 1,000-foot wide corridor had been cleared to within 1,500 feet of the dam. Some new trees were encroaching on the edges of the main channel



5 Mar 1985

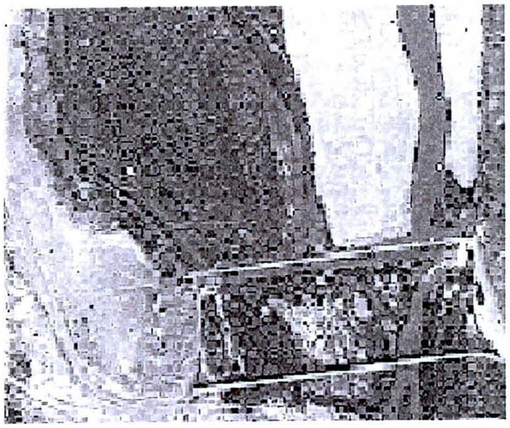
The flood of October 1983 had used FCD's 1,000-foot wide corridor to advantage and created two channels of about equal size at the dam. The west branch was in the location of the 1980 main channel and the east branch was an enlargement of the 1981 low-flow channel.

The embankment that blocked the old main channel after the 1980 flood remained intact during the 1983 flood, most likely because the 1,000-foot wide corridor relieved the tendency for the water to move in that previous direction.



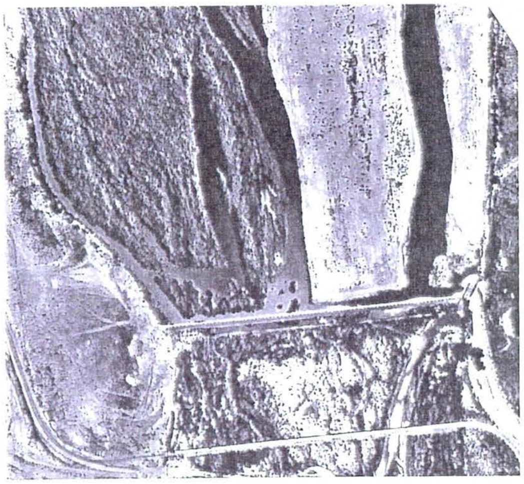
8 Nov 1986

The east branch of the two channels had moved to the east at the dam bringing low flows almost directly to the Gila Bend Canal intake. An embankment had been constructed across the west branch. Maintenance of the 1,000-foot wide corridor (light shade) was in progress right down to the dam.



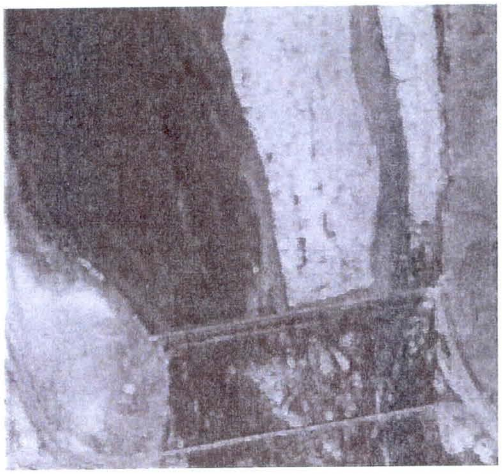
30 Jun 1989

The channels remained essentially the same as in 1986 with the west branch of the main channel blocked and the east branch carrying the low flows. In 1989, a growth of vegetation had become established on the apron of the dam, downstream from the wall.



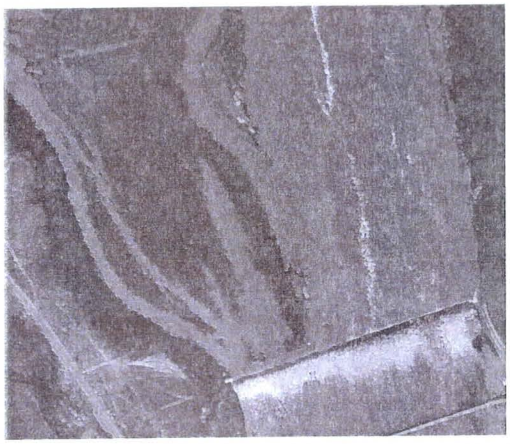
5 May 1991

The channels remained essentially the same as in 1989 with the west branch of the main channel blocked and the east branch carrying the low flows.



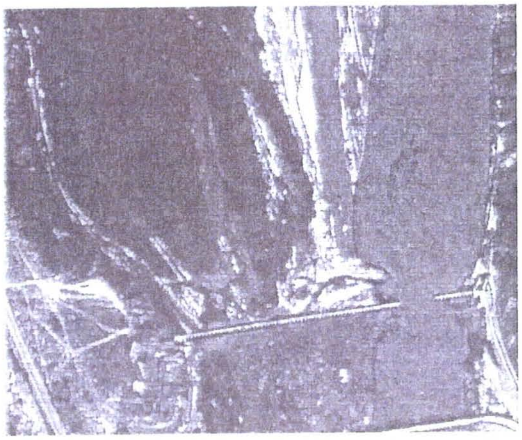
9 Jan 1993

During the flood that breached the dam, most of the floodwater came down the 1,000-foot wide corridor. The area of the apron near the east abutment where there was no white water is of special interest. Here the dam failed about three hours after the photograph was taken.



7 Feb 1993

On the recession of the flood, the flow carved a very deep channel from the breach upstream along the east valley wall. Approximately 14,000,000 cubic yards of sediment were eroded in 4.1 miles of river immediately upstream from the dam. (Stevens 1997)



Vegetation. Trees are very adept at slowing down the movement of water on the floodplain. Where there is a thick growth of trees, the velocity is low, the depth larger, and the unit discharge smaller. If the backwater area of Gillespie Dam were to become entirely and thickly vegetated with salt cedar, with no channels, there would be no focusing of the flow at the crest of the dam. For the 1993 flood peak, the unit discharge q would be 175,000/1,657 = 105 ft^3/s per foot width of dam – or nearly so.

Conversely, if the entire approach area were bare ground with no channels, the unit discharge q would also be 105 ft^3/s per foot width of dam. Again there is no focusing of the flow. Between these two extremes – all trees and no trees – the flow over the dam is focused to some degree.

The last 2,000 feet of floodplain immediately upstream from the dam is the most important in determining focusing of the flow. Farther upstream, the vegetation directs the flow to different areas of the floodplain and that has a lesser but also important effect.

Floodplain Near Gillespie Dam. Figure 8 is a copy of the US Geological Survey topographic map for Spring Mountain, AZ made in 1973 from information on 1972 aerial photographs. The Gila River is the almost straight line in the center of a 200-foot wide strip of vegetation. To the west, the large flat area of sediment deposited behind the dam (contour 750) was almost completely covered by vegetation. To the east of the river, there were trees only at the dam.

The distance from the dam to the north boundary of the west trees is approximately 2,000 feet. This bottom end of the floodplain and river has remained essentially treed since 1973 except for channels and remnants of channels as described previously with the photographs – and clearing by the FCD.

By 1975, the previously barren east side had been invaded by trees. This was followed by the 1978 floods that scoured the vegetation and opened the channel network to the dam. Hardly any of the trees show through the water during the peak of the 1980 flood. By January 1981, the FCD had some trees cleared along the east side of the floodplain for a distance of two miles up from the dam. The clearing did not extend quite to the face of the dam. Eleven months later, this clearing had grown up with trees again as well as a large area of the floodplain to the north. Except for two remnant channels the bottom end was almost completely treed. It was "grow and grub" in the 1,000-foot wide corridor along the Gila River.

By December 1982, the FCD had cleared the 1,000-foot wide corridor down to and a bit into the bottom end. Later the clearing was extended to the dam. As the low-flow channel was inside the 1,000-foot corridor, no pilot channel was constructed at or near the dam. However, as shown by the photographs in Appendix A, the low-flow channel existed within the 1,000-foot corridor because of the diking and diverting to the east of the low-flow channel remaining from the 1980 flood.

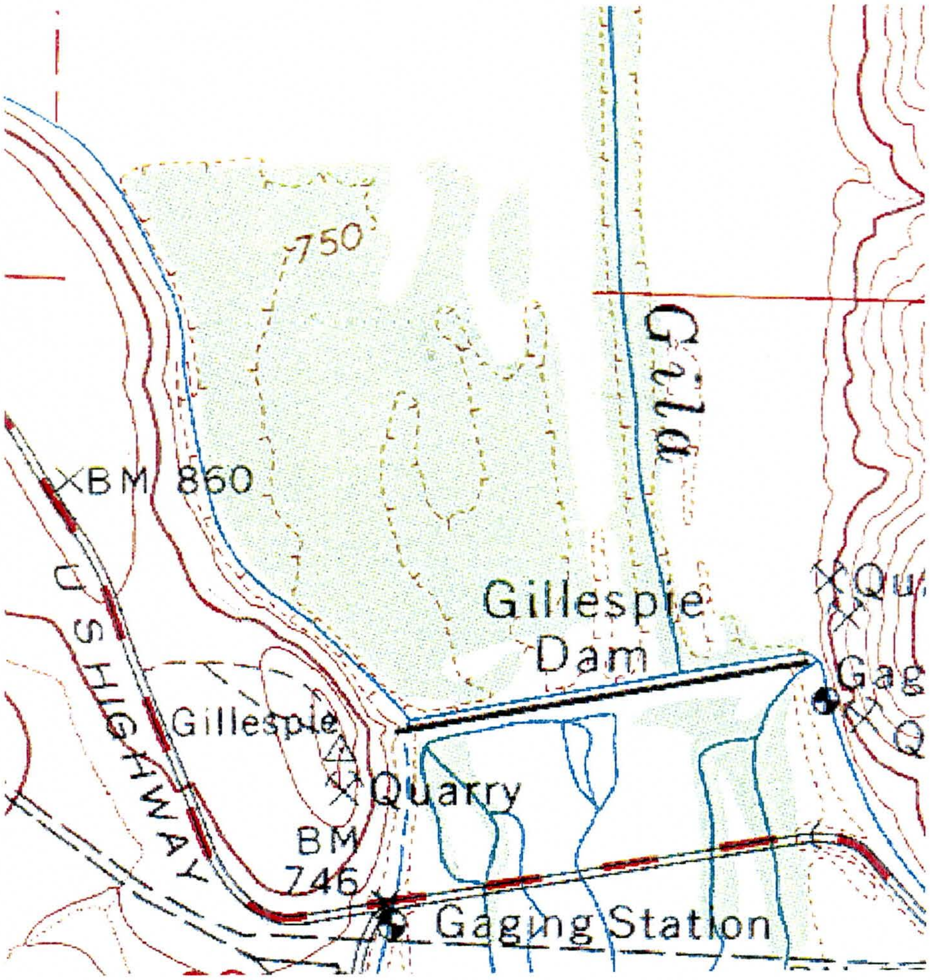


Figure 8. The 1973 US Geological Survey topographic map for the Gillespie Dam area.

The 1,000-foot wide corridor is clearly shown on the November 1986 aerial photograph (Figure 9). The main channel had taken on more definition and some sinuosity as the result of the 1983 flood. The dike used to divert the low-flow channel is still visible, although there is no water on the upstream side of the dike. Thereafter, the bottom end remained essentially unchanged until the 1993 flood.

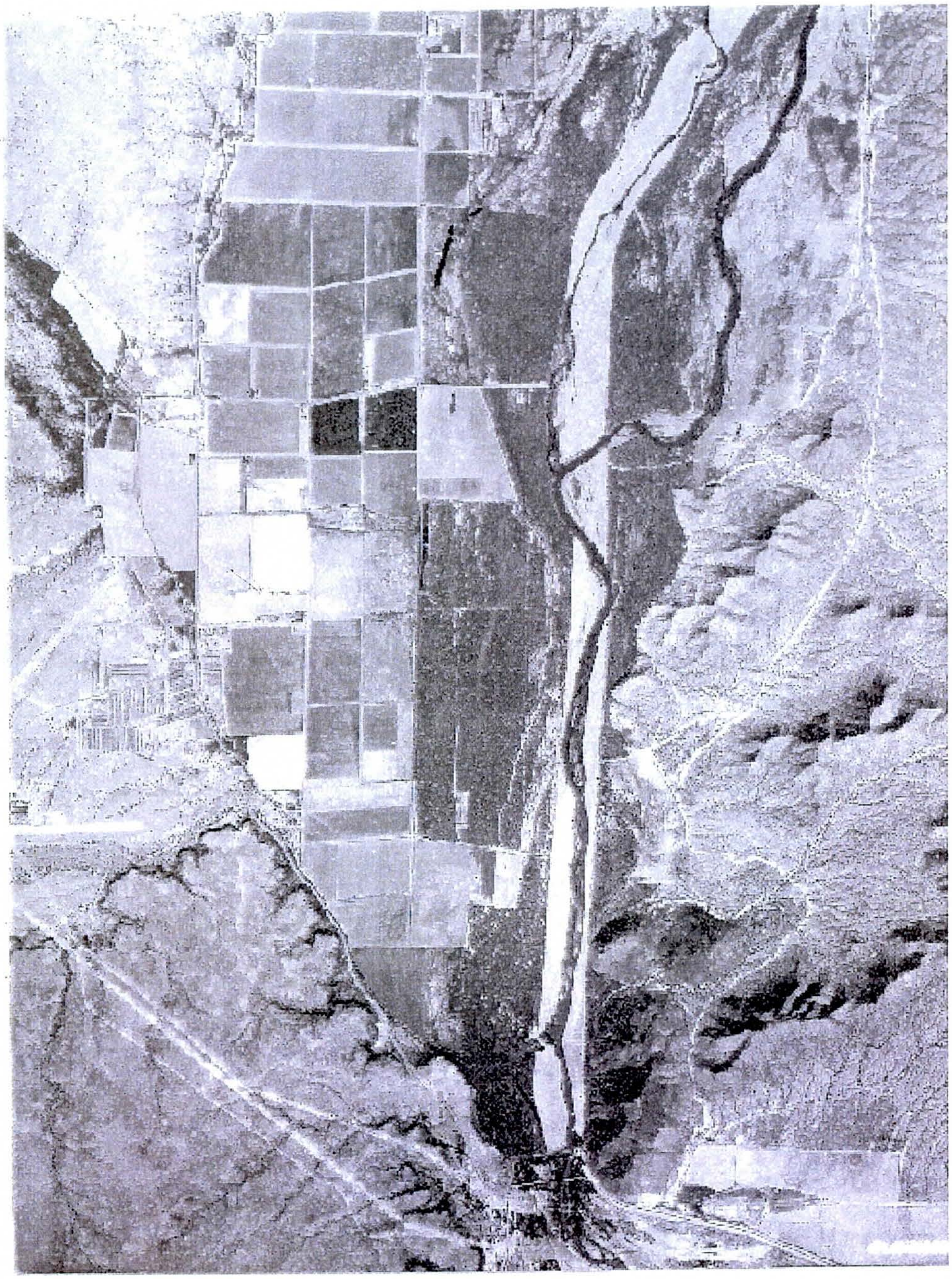


Figure 9. Aerial photograph taken on 8 November 1986 showing the 1,000-foot wide corridor (light shade) and the sinuous main channel within it (dark).

Upper Floodplain. Approximately seven miles upstream from Gillespie Dam (Figure 10), the Gila River passes Powers Butte flowing from east to west. Here the valley is only 3,000 feet wide. Immediately afterwards, the valley opens up, and the river turns directly to the south. At its widest extent, the valley is three miles wide. Two miles upstream from the dam, Buckeye Hills on the east force the last bit of water to turn south.

On this southern journey, the floodplain to the west of the Gila River was farmed in 1973, except for three ¼-sections in a row near the river. The most northern of these was cleared by 1975. The floodplain between the east and west branches of the Gila River was well treed. To the east of the river the vegetation was spottier.

The 1978 and 1979 floods scoured the vegetation in the two remaining treed quarter sections leaving the area at the bottom end with a sparest covering of trees. Growth was apparent because trees were above the flood level in the west half of Section 16 during the 1980 flood. Growth was rapid after this flood, trees moving into the area between Section 16 and the bottom end, and to 2,000 feet west of the river. By the end of 1981, the floodplain was heavily treed from the dam to three miles north (Section 9 in Figure 10). The notch in the trees for the field in Section 16 was the only new farming expansion towards the river.

As stated earlier, the FCD began its clearing project in this area in 1981. By 1985, the 1,000-foot wide corridor and a short reach of pilot channel were completed from Powers Butte to Gillespie Dam, the lower end of the flood mitigation scheme.

The field that was notched into the trees was enlarged between 1985 and 1986. Thereafter, floodplain vegetation remained the same, the tree-free corridor and trees to the west being the dominant features.

The notch played a prominent role during the 1993 attracting a meander of the river channel to it. The notch served to deliver floodplain flow during the peak of the flood back to the 1,000-foot corridor.

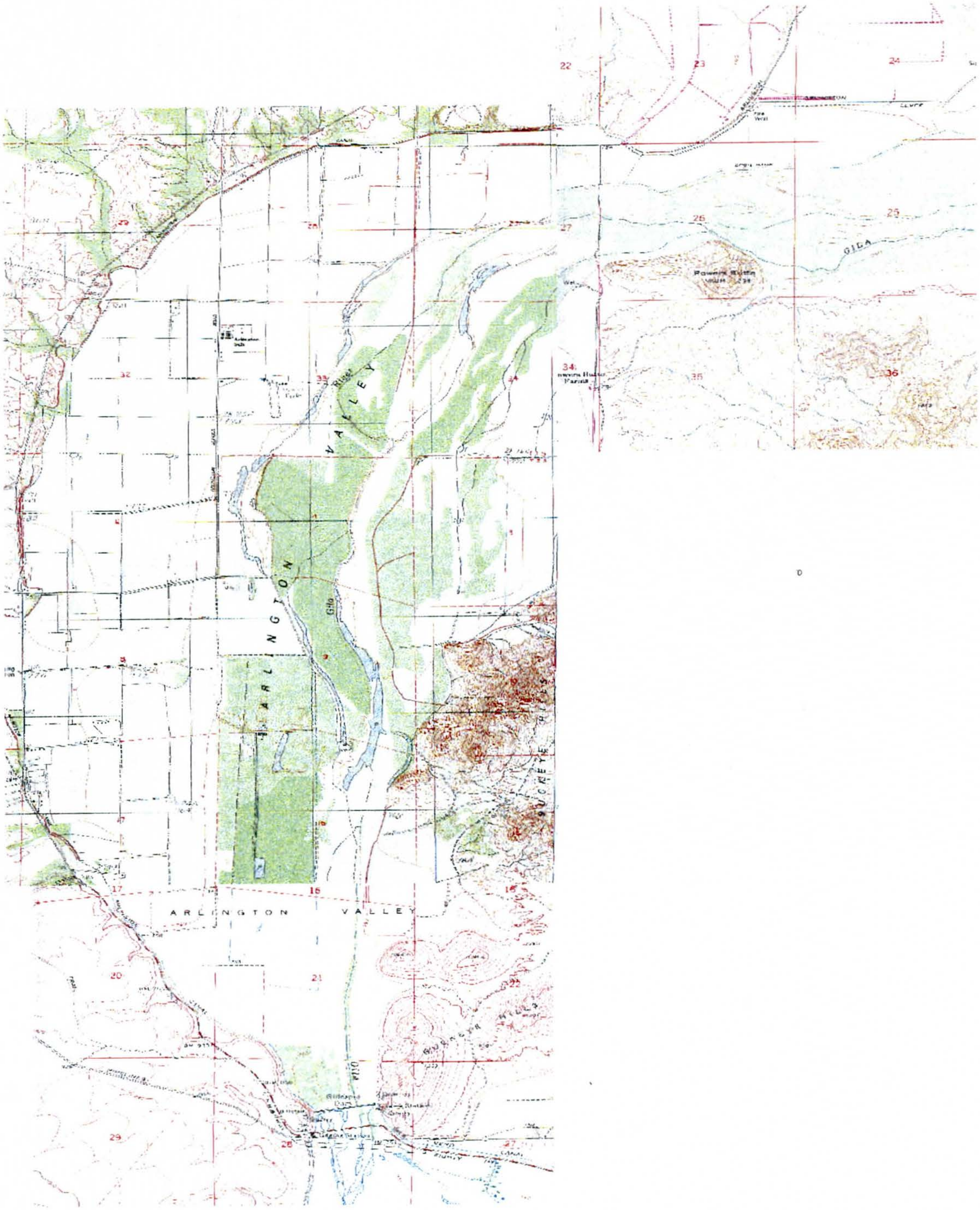


Figure 10. The 1973/1984 US Geological Survey topographic mapping of the Gila River valley from Powers Butte to Gillespie Dam.

MATHEMATICAL MODELS

Three mathematical models were employed to achieve the purposes outlined for this study.

1. With the one-dimensional model of the reach of Gila River from the Salt River confluence to the Gillespie Dam, an estimate was made of the flood-wave attenuation of the January 1993 flood peak. Did the flood peak decrease significantly as it moved downstream on 8 and 9 January 1993?

2. With the Seven-Mile two-dimensional model, the movement of the flood peak from Powers Butte to Gillespie was simulated under different configurations of channels and floodplain. One was the configuration of the channels, trees and floodplain as they existed at the time of the 1993 flood. Another was the configuration as it would have been if no trees had been removed in this area.

3. With the One-Mile two-dimensional model, refinements were made of the results obtained with the Seven-Mile model.

The one-dimensional model used was CanalCad (Appendix B), a proprietary model developed at the Civil Engineering Department at the University of Iowa, Iowa City, IA.

This model is a numerical solution of the one-dimensional full dynamic wave equation. It is appropriate as a first assessment the flood-wave attenuation. It is not appropriate for moving water from the river channels onto the floodplain nor from the floodplain to the channels in a river flooding like the Gila did in 1993.

The two-dimensional model is that marketed as RMA2 by Boss International, Madison, WI (Appendix C). This model can move water between the river channels and its floodplain in a realistic manner.

Information needed to build the models was obtained from US Geological Survey topographic maps, Digital Terrain Mapping done for the FCD, and aerial the photographs described previously.

MAPPING

Digital Terrain Mapping. The digital terrain mapping (hereinafter "DTM"), identified as Maricopa County Phase I, ARCINFO ASCII DTM Files, pre-flood, was used to define the channel and valley topography between the Gillespie Dam and Powers Butte.

The mapping is the x, y (horizontal), and z (vertical) coordinates of a vast array of points on the ground. These coordinates were created by digital photogrammetric methods using aerial photographs dated 14 December 1991.

The mapping was performed by Michael Baker Jr., Inc. under Service Order Number 18588-%%-ARP for the Flood Control District of Maricopa County, Salt-Gila Watercourse Project.

Horizontal Control. Three points on the US Geological Survey's 1:24,000 scale topographic maps were used for the horizontal control of the two-dimensional models. The points are Powers Butte, the west abutment of Gillespie Dam, and the County Road intersection on the west valley edge between Sections 5 and 6, T2S, R5W, about one and a half miles southwest of the Arlington School (Figure 10).

The horizontal coordinate system for the DTM was not the same as that on the US Geological Survey's topographic maps. The difference was determined by matching the two coordinate systems at the Gillespie Dam. The topographic map coordinates were adjusted by adding 200,000 feet to the East coordinate to agree with the DTM.

Vertical Control. Likewise, as best that we could determine, the vertical control for the DTM was slightly different than that used by others. For example, HEC-2 files for FEMA mapping set the dam crest elevation at 753.5 feet (Cella Barr Associates 1994). From the DTM files, the indication is that the dam is at elevation 755.3 feet. The latter number was employed for this mathematical modeling.

XYZ File. The coordinates used for topography in the two-dimensional mapping are those of the DTM. They are contained in an abbreviated file for ease of transfer among computer programs. The dam crest is taken level at elevation 755.3 feet.

FLOOD-WAVE ATTENUATION

As the flood moved down the Gila River from the confluence with the Salt River to Painted Rock Reservoir on the 8th, 9th, and 10th January 1993, the peak of the flood was attenuated because of the mechanisms by which the water moves. As the flood moves downstream, some is stored temporarily on the floodplain, and some in the channel cross section. The purpose of the one-dimensional model is to estimate the amount that the flood peak decreased in moving along the river.

Input. The distance along the Gila River from the Salt River confluence to Gillespie Dam is 32 miles. In this reach, the following average conditions (Table 4) were used to build the model:

The valley width and vegetation were taken from the US Geological Survey's 1:24,000 scale topographic maps. The riverbed profile was estimated from HEC-2 files created for the FCD from mapping done from aerial photographs taken in 1984 and 1985. The determination of the Manning's roughness coefficients is described in Appendix E.

The inflow hydrograph was that described in the 1993 Flood section of this report (Figure 7). It had an inflow peak of 175,000 ft^3/s.

Table 4. Features of the Gila River used in the one-dimensional mathematical model.

Feature	Dimension
Valley floor area	44.2 square miles
Valley width	7,300 feet
Width vegetated	3,400 feet
Bare floodplain width (fields or otherwise)	3,600 feet
Width of channels	300 feet
Riverbed slope	
Lower 4 miles	2.25 feet/mile
Upper 28 miles	5.60 feet/mile
Manning's roughness coefficient	
Channels	0.025
Bare floodplain	0.028
Trees	0.170

Results. The model moved the flood peak over the 32 miles of Gila River in 7.5 hours, the peak lowering 9,700 ft^3/s in this distance. The decrease was 5.5 percent, making the rate of decrease 0.17 percent per mile. The maximum amount of water in this reach during the passage was approximately 9.5 billion cubic feet. This corresponds to an average depth of 7.7 feet over the entire valley floor.

The Seven-Mile Model covers the seven miles of valley from Powers Butte to Gillespie Dam. In this reach the flood peak is expected to decrease 0.17 (7) = 1.2 percent. This is not a significant amount and flood-wave attenuation can be safely ignored in the two-dimensional models.

Because the flood-wave attenuation is small and the estimate of 175,000 ft^3/s for the 1993 flood peak is tenuous, all two-dimensional models were run at a steady-state (constant) flow of 178,000 ft^3/s. This was the peak discharge of the 1980 flood. The unit discharge for this flow would be 178,000/1,657 = 107 ft^3/s per foot width of dam.

SEVEN-MILE MODELS

The Seven-Mile Model covers the valley floor from Powers Butte to Gillespie Dam, a distance of seven miles. The purpose of this two-dimensional mathematical model is to get a good approximation of the flow distribution (depth and velocity) approaching the dam about a mile upstream from the dam. These approach conditions were then used in the more refined One-Mile Model to best estimate the focusing of the flow at Gillespie Dam.

In 1993, FCD's 1,000-foot wide corridor had a major influence of the focusing of the flow at the Gillespie Dam. Therefore, an estimate was made of the focusing if the corridor project had not been undertaken; that is, the trees had not been removed. This was the condition shown in the January 1981 aerial photograph, before any trees were removed. Next, the flow field has been estimated for the condition that all trees are removed from the valley floor. Finally, the conditions for the 1980 flood were simulated. Therefore, there are four Seven–Mile Models, identified as the Corridor Model, Trees Model, Bare Model and 1980 Model. The same DTM was used for all four models.

At Powers Butte the valley is only approximately 3,000 feet wide and the river flow is directly to the west. The valley widens out quickly to 15,000 feet as it turns to the south and then funnels into the Gillespie Dam. Powers Butte is an excellent place to set the upstream boundary of the two-dimensional models.

In the four Seven-Mile Models (Figure 11) there are one or more channels and the floodplain. The floodplain is partitioned according to what was growing on it. These conditions and the roughness assigned to them are given in Table 5. Details are in Appendices D and E.

Table 5. Manning's roughness coefficient for channels and floodplain.

Condition	Manning's Roughness Coefficient	Map Color
Channel	0.025	Blue
Bare Floodplain	0.028	Light Brown
Sparse Trees	0.060	Yellow-Green
Light Trees	0.080	Brown-Green
Heavy Trees	0.170	Dark Green

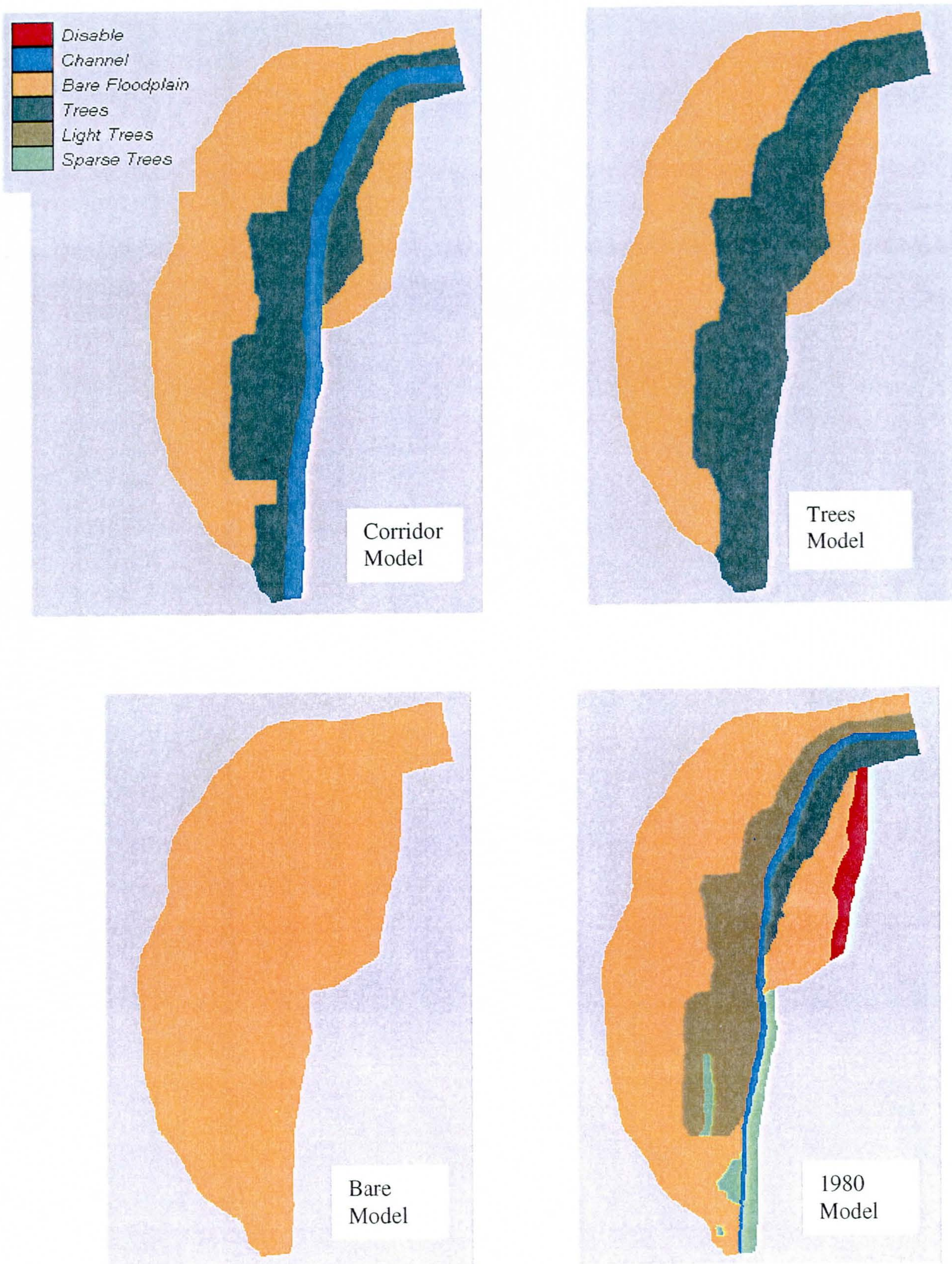


Figure 11. Maps of the four Seven-Mile Models.

As the flood flow moves down the valley from Powers Butte, it first expands to cover most of the very wide floodplain, but thereafter it is funneled into the narrowest section where the Gillespie Dam was constructed. That is, first expansion, then contraction. As such, when the flow approaches the dam, the unit discharge has been high along the west side where the contraction is.

The One-Mile Model extends upstream from the Gillespie Dam approximately 4,700 feet. Here the flood flow along the east side of the valley is from the north to the south. However, on the west side the flow approaches from the northwest. The upstream boundaries of the One-Mile Models have been set normal to the approach velocities.

The distribution of the unit discharge at the upstream boundaries to the One-Mile Models (Figure 12) varies according to the distribution of the trees. The Corridor Model has the most water and the highest unit discharge on the east side, where the 1,000-foot wide corridor was blazed. The Trees Model has the least amount of water on the east and the most on the west side. The 1980 Model had the strongest flow on the west side.

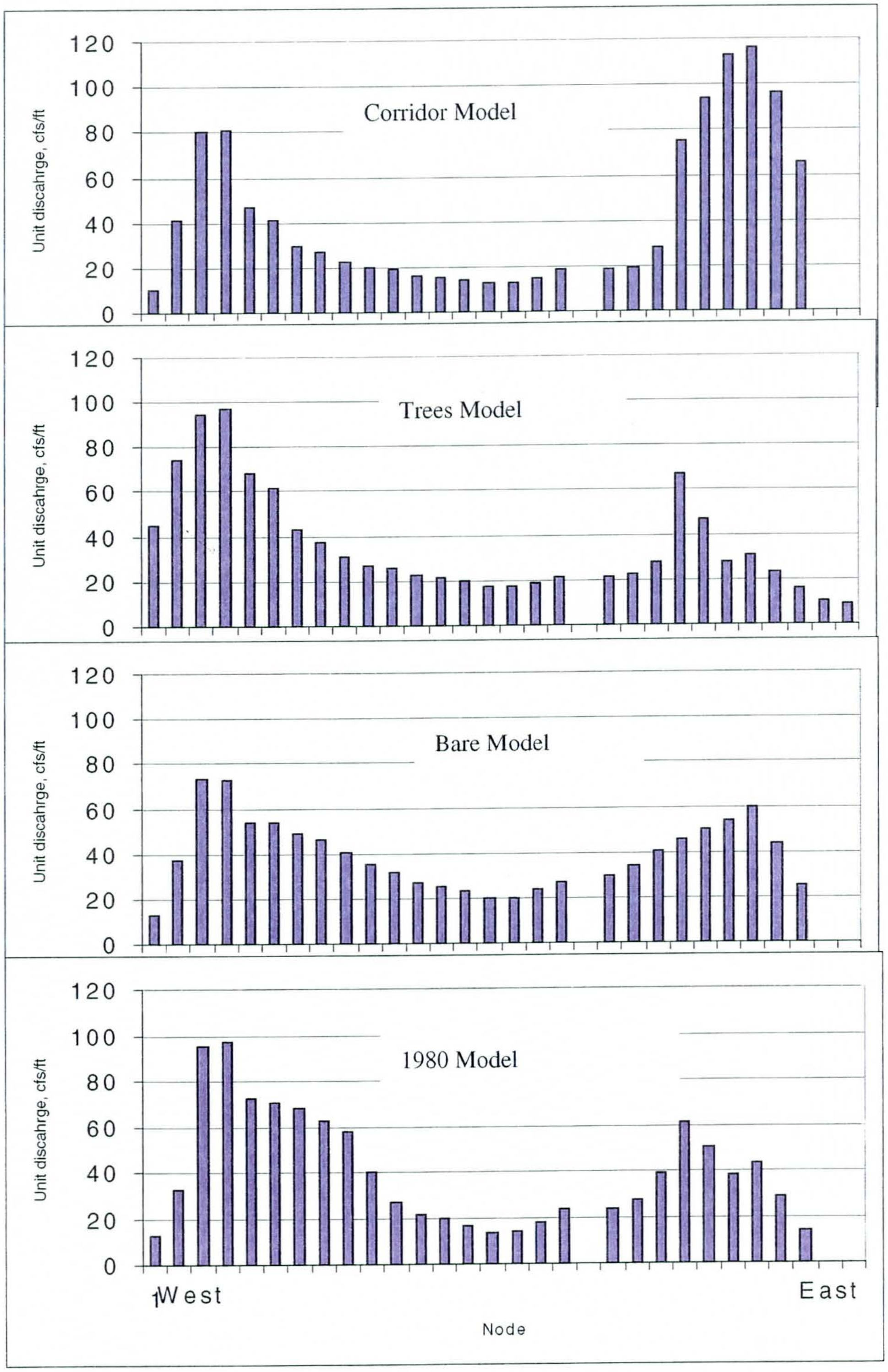


Figure 12. Unit discharges at the nodes across the upstream boundary of the One-Mile Models. The break is the corner between the northwest and north boundaries.

ONE-MILE MODELS

The One-Mile Model extends from the Gillespie Dam to the north a distance of some 4,700 feet. The number of elements defining the surface of the channels and floodplain was increased to 6,459, some 85 percent more elements than for the Seven-Mile Models, but with each element covering much less area. With more elements come greater refinements in topography and in conditions on the floodplain. With the refinements and good approximations of the upstream boundary from the Seven-Mile Models, better estimates of the distribution of flow along the crest of the Gillespie Dam are achieved. The One-Mile Models were developed for the same four conditions as the Seven-Mile Model (Corridor, Trees, Bare, 1980), plus a 1981 Model. The 1981 Model represented the conditions existing before clearing of the 1,000-foot wide corridor. Additional detail on the One-Mile Models is presented in Appendix G.

Corridor Model. The boundaries of the channels and floodplain and its vegetation (Figure 13) were obtained from the 9 January 1993 aerial photograph. The single channel of the Gila River coming down from the north became divided as it approached the dam. The west side channel occupied what was the main channel in 1980. The east main channel took a more direct path to the dam, staying within the 1,000-foot wide corridor, shown as bare floodplain in Figure 13. To the west, the dominant feature was the trees. The west boundary is along the Arlington Canal. The west floodplain flows had kept this and another small channel open.

The hydraulic roughness coefficients (Table 6) are those estimated by Thomsen and Hjalmarson (1991) for the FCD and by the Soil Conservation service (See Appendix E) and are the same as for the Seven-Mile Models.

Table 6. Manning's roughness coefficients.

Condition	Manning's Roughness Coefficient	Map Color
Channel	0.025	Blue
Bare Floodplain	0.028	Brown
50-Foot Channel	0.035	Orange
25-Foot Channel	0.047	Purple
Sparse Trees	0.060	Yellow
Light Trees	0.080	Light Green
Heavy Trees	0.170	Dark Green

The topography (Figure 14) is from the 1991 Digital Terrain Mapping. Based on a detailed digital map (Gila River Crossing at Gillespie Dam, Aero-Graphics, Inc.), the crest of Gillespie Dam is at El 755.0 to El 755.3 feet in all One-Mile Models. The main channel heading directly to the dam was much deeper than the side channel veering to the west. There was a higher area to the north in the center of the valley, the highest point being 9.6 feet above the crest of the dam. The small channel along the Arlington Canal was the deepest of the waterways. Its lowest point was 3.2 feet below the dam crest.

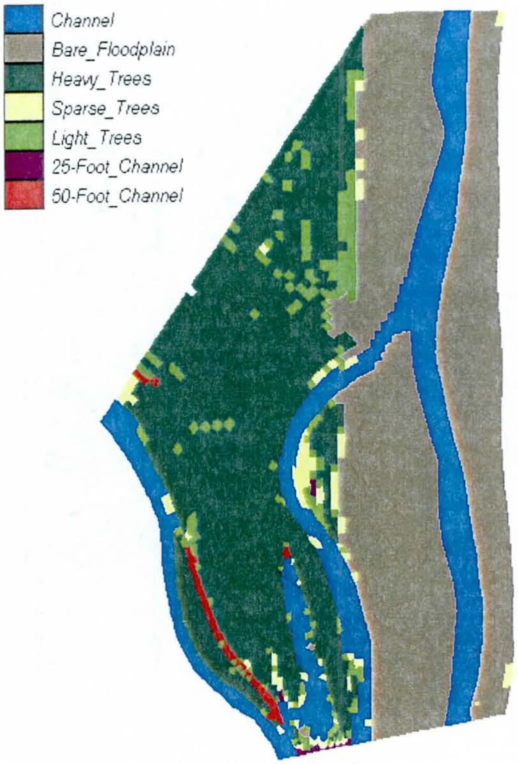


Figure 13. Map of the channels and floodplain for the One-Mile Corridor Model as taken from the 9 January 1993 aerial photograph.

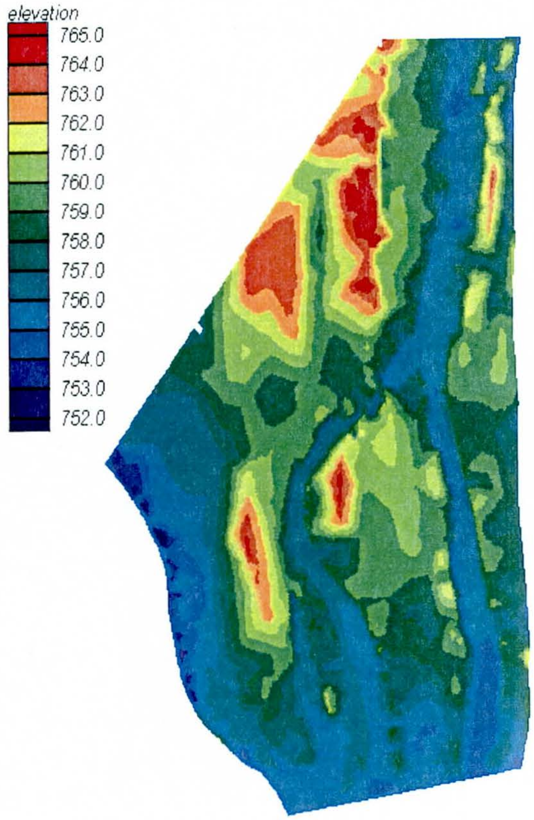


Figure 14. Contour map of the One-Mile Corridor Model derived from 1991 DTM.

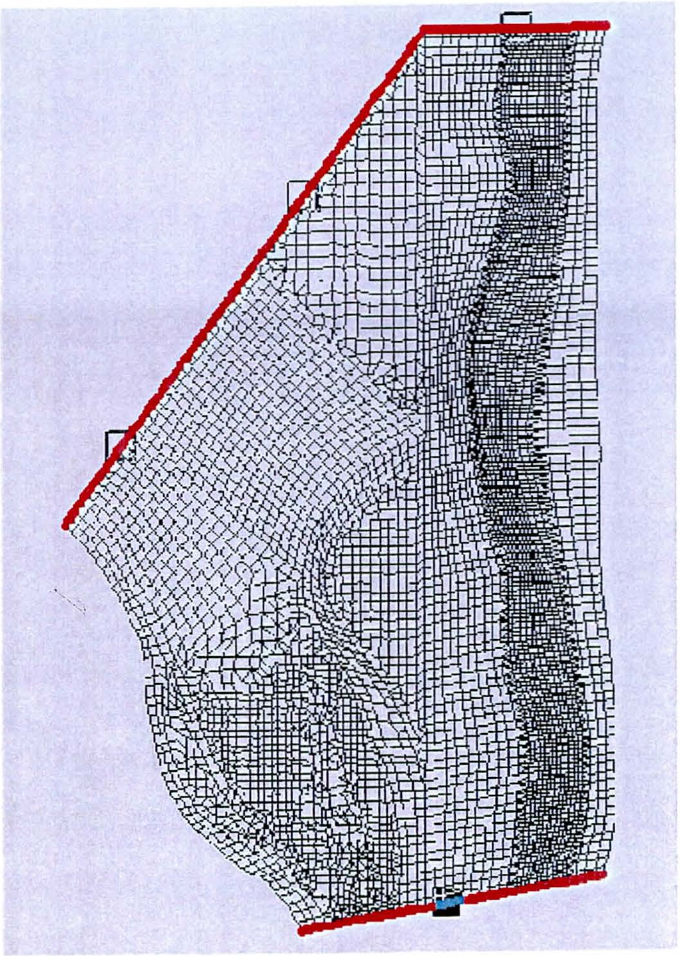


Figure 15. Map of the mesh for the One-Mile Corridor Model. The line at the bottom of the figure represents Gillespie Dam. The line at the top is the north upstream boundary. The other upstream boundary is the line along the northwest.

There is a total of 6,459 elements and 18,808 nodes in the two-dimensional mathematical model of the One-Mile Corridor Model (Figure 15). Eight hundred fifty-one elements are triangles; the rest are quadrangles. The line on the bottom representing Gillespie Dam is 1,657 + 35 = 1,692 feet long. The 1,657 feet is the length of the dam crest between abutments. The 35 feet represents the width of the sluice which was spilling 4,700 cubic ft^3/s at the time of the January 1993 flood peak (Loomis 1997, p.A9).

The north upstream boundary (top of Figure 15) is 999 feet wide and presents the width of the 1,000-foot wide corridor. The northwest upstream boundary is 3,376 feet long, made up of a 1,078-foot long lower section and a 2,298-foot long upper section.

A flood-peak flow of 178,000 ft^3/s enters the upstream boundaries of the One-Mile Corridor Model, divided among the sections of the upstream boundary in accordance with the results of the corresponding Seven-Mile Corridor Model (see Appendix G).

The resulting computed flow at the dam is concentrated in the main channel within the 1,000-foot wide corridor (Figure 16). The highest unit discharge, 147 ft^2/s, is at the section where the dam was breached. This unit discharge is approximately 37 percent greater than what would have been achieved if the flow were entirely uniform at 107 ft^2/s across the length of the dam.

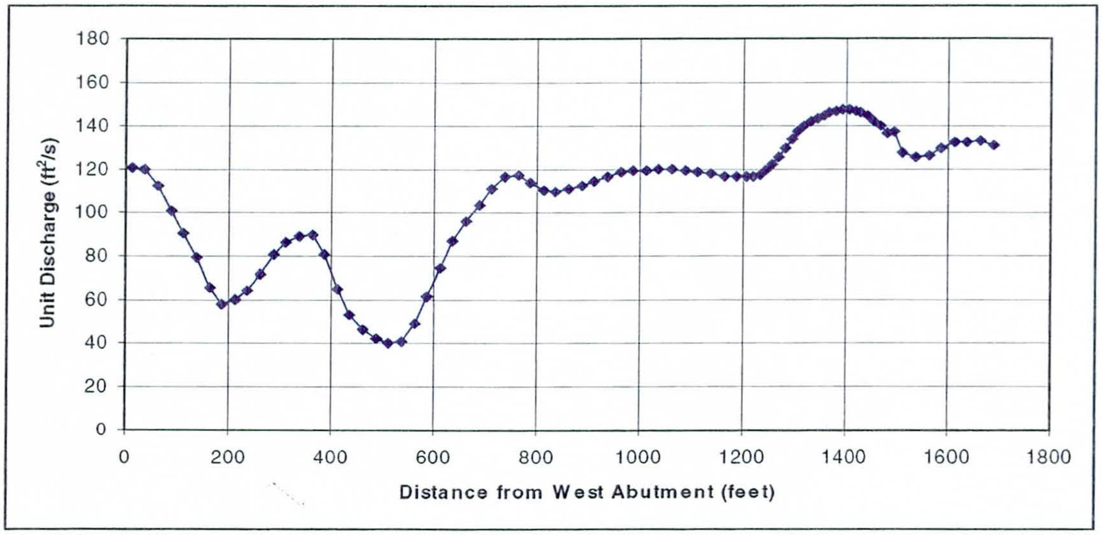


Figure 16. Distribution of the unit discharge in the 1993 Model from the west abutment (Distance Zero) along the length of Gillespie Dam for a flood peak of 178,000 ft^3/s.

Flow from the 1,000-foot wide corridor over the dam is everywhere higher than the uniform rate of 107 ft^2/s. The average unit discharge over Arch 12 through Arch 16 is 146 ft^2/s. The flow along the Arlington Canal to the west is also higher than the uniform flow rate.

Much of the model flow from the northwest upstream boundary travels southeastward to the edge of the 1,000-foot wide corridor and then turns south (Figure 17). The west side channel is not effective in capturing this southeast flow. This effect is also indicated on the 9 January 1993 aerial photograph. On the 5 May 1991 aerial photograph, there is an embankment across the inlet to this west side channel. That and the unfavorable direction of the approach flow kept this side channel ineffective during the passage of the peak. Its centerline unit discharge is only 75 ft^2/s at the dam (625 feet from the west abutment).

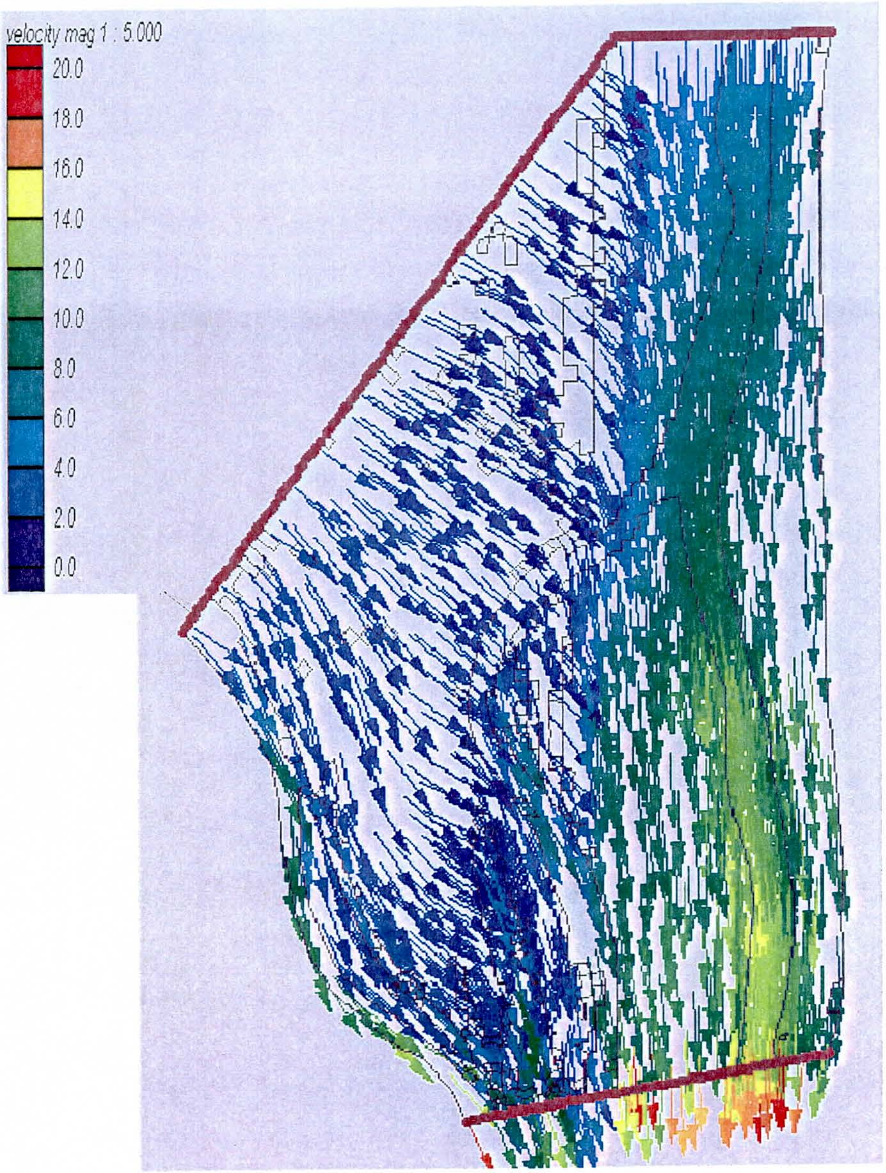


Figure 17. Velocity vectors (ft/s) for the One-Mile Corridor Model. Blue vectors have slow speeds; red vectors represent fastest moving water.

Trees Model. This One-Mile Model was conceived to estimate the flow distribution at Gillespie Dam if the entire approach area, shown in (Figure 13) were covered with trees. The topography is the same as for the Corridor Model, the assumption being that the trees would grow in the channels as well as elsewhere. The upstream boundary conditions (Appendix G) are for 178,000 ft^3/s and are taken from the Seven-Mile Trees Model.

Under such conditions Gillespie Dam, the unit discharges across the length of the dam become much more uniform (Figure 18). At the location of the breach, it is 111 ft^2/s, only a few cubic feet per second per foot of width higher than uniform. The greatest unit discharge is at the west abutment where the floodplain narrows. With trees everywhere there is much more water to the west than in the 1993 model.

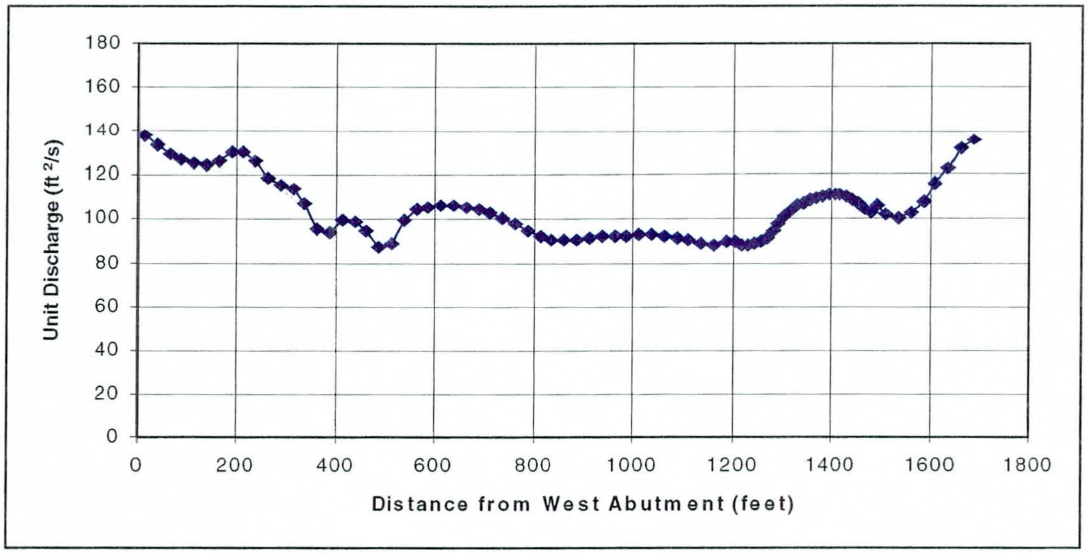


Figure 18. Distribution of the unit discharge from the west abutment (Distance Zero) along the length of Gillespie Dam for a flood peak of 178,000 ft^3/s in the Trees Model.

Bare Model. Free of all trees, this One-Mile model was conceived to compare the flow distribution at the Gillespie Dam with other conditions. The map for the Bare model is the same as for Trees but the entire area is bare floodplain with a Manning's roughness coefficient of 0.028.

The results (Figure 19) are even more uniform flow along the length of the dam with a bare approach are than for the all-trees condition. The unit discharge is slightly elevated where the main channel is; it is also the location of the breached arch.

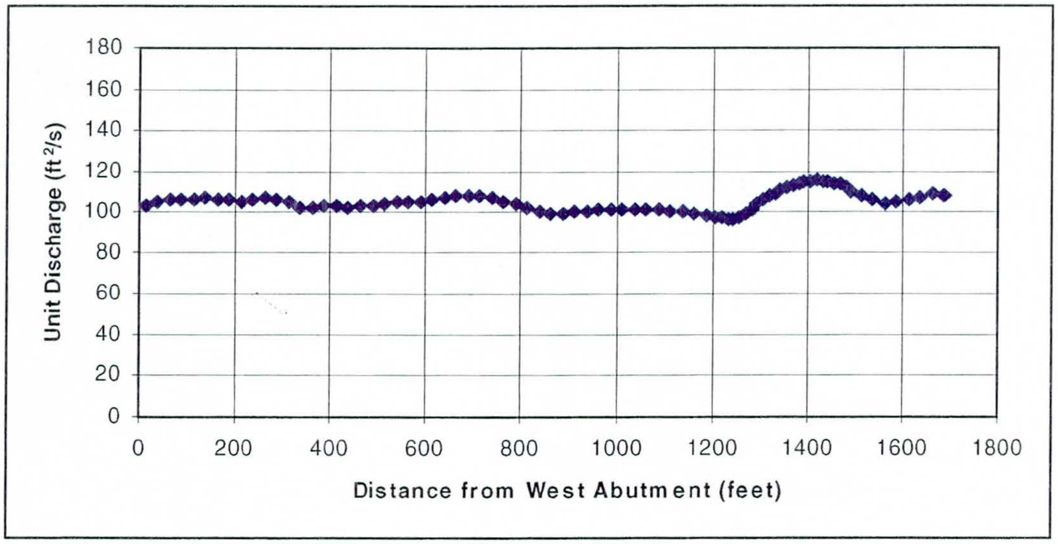


Figure 19. Distribution of the unit discharge from the west abutment (Distance Zero) along the length of Gillespie Dam for a flood peak of 178,000 ft^3/s in the Bare Model.

1980 Model. Shown in Figure 20, the 1980 model was configured principally from information on the 1979 aerial photograph with supplementary information from the 1980 aerial photograph. The 1980 flood approached the One-Mile Model area much differently than that of the previous models. There was more flow on the west side and more curvature of the flow on the west floodplain (see 16 Feb 1980 photograph in Appendix A).

This motion captured on the photograph is reflected in the output of the model. The velocity vectors are more pronounced approaching the dam from the west than from the north and east side (Figure 21)

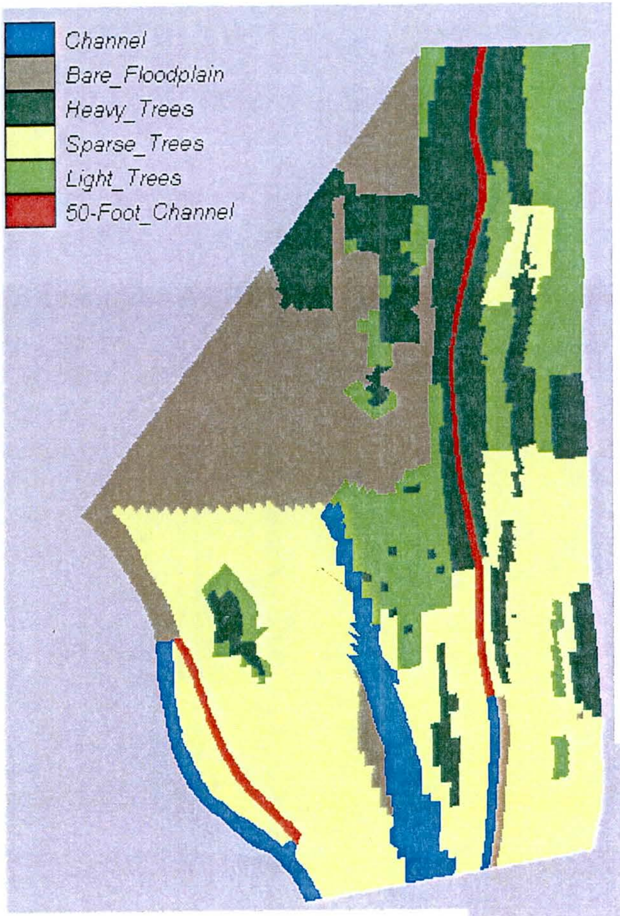


Figure 20. Map of the channels and floodplain of the 1980 Model

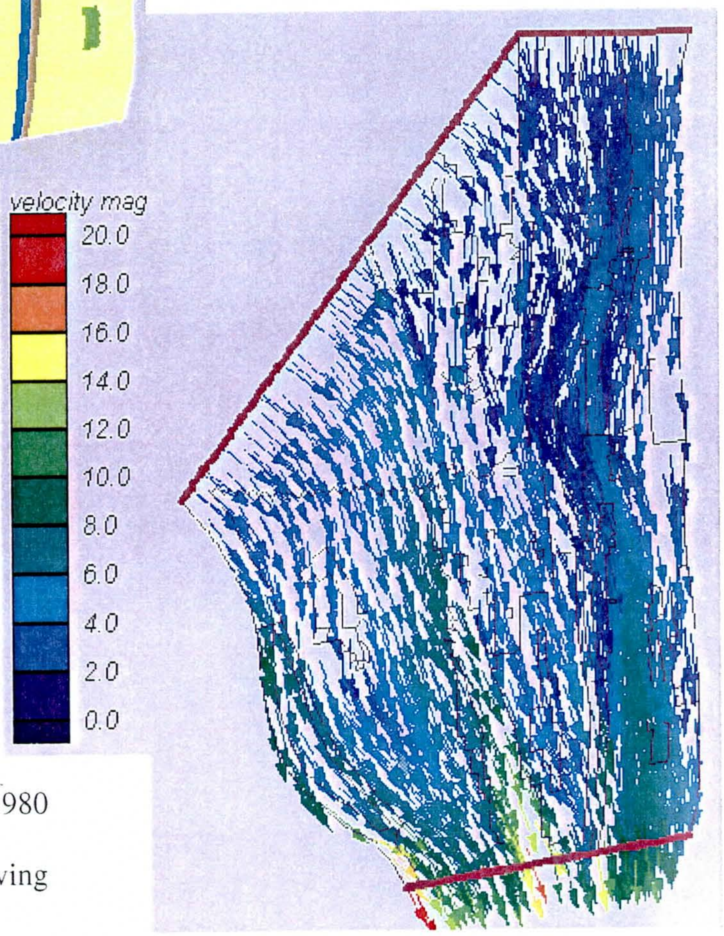


Figure 21. Velocity vectors for the 1980 Model. Blue vectors represent slow speeds; red vectors represent fast moving water.

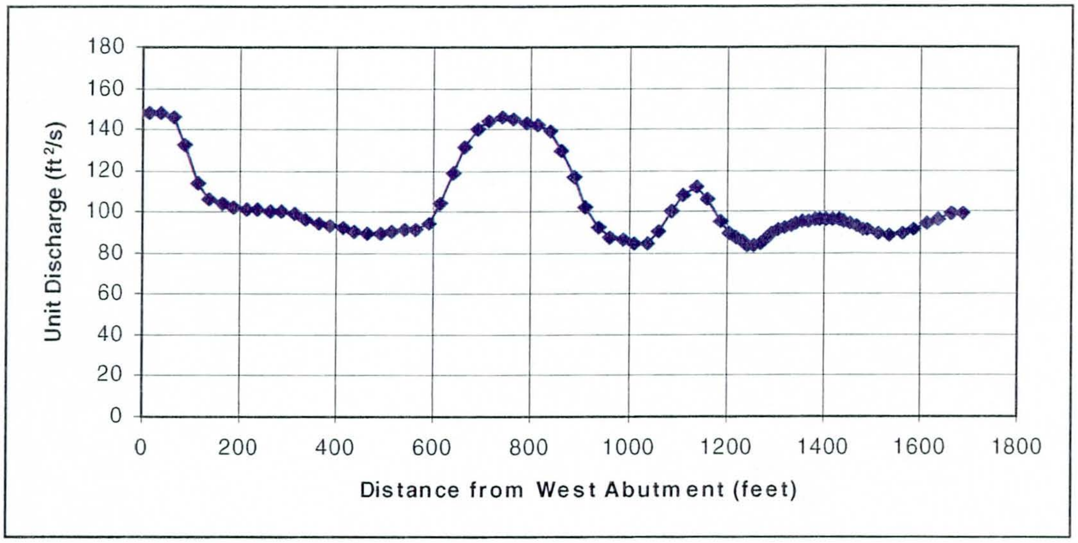


Figure 22. Distribution of the unit discharge from the west abutment (Distance Zero) along the length of Gillespie Dam for a flood peak of 178,000 ft^3/s in the 1980 Model.

As shown in Figure 22, the unit discharge at the dam is highest, 148 ft^2/s, at the west abutment and just slightly lower at the main channel near the center of the dam. At the arch where the dam was breached 13 years later, the unit discharge was only 97 ft^2/s, less than the uniform distributed value of 107 ft^2/s.

1981 Model. Crafted from information on the 2 Dec 1981 aerial photographs, the 1981 One-Mile Model is mostly trees (Figure 23). What was the main channel in 1980 had become cutoff from its former source of water and was reduced to a bare low area. On the east, the vegetation was linear following the direction of former channels. The new low-flow channel was poorly defined as it approached the dam. The upstream boundary of this model is almost entirely trees. Therefore, the upstream boundary conditions were taken from the Seven-Mile Trees Model.

The unit discharge was still highest, 166 ft^2/s, in the remnant of the 1980 main channel near the center of the dam (Figure 25). The remnant collected the water from the surrounding trees and delivered it to the dam (Figure 24). On the east side, the flow in the poorly defined channel delivered a peak of 129 ft^2/s to the dam near the point where the dam was breach 12 years later.

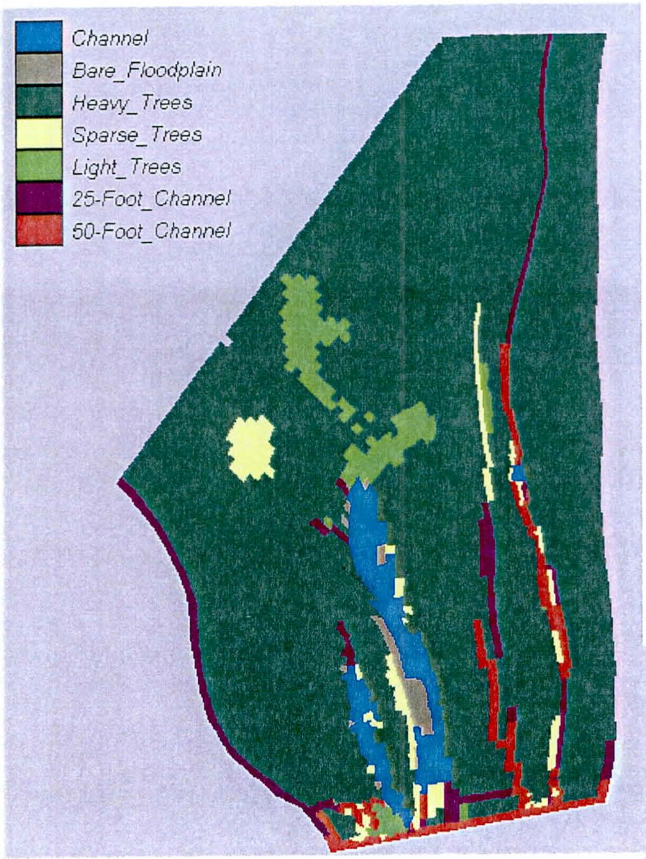


Figure 23. Map of the 1981 One-Mile Model. Most of the area was trees with the Gila River only a sliver of a channel.

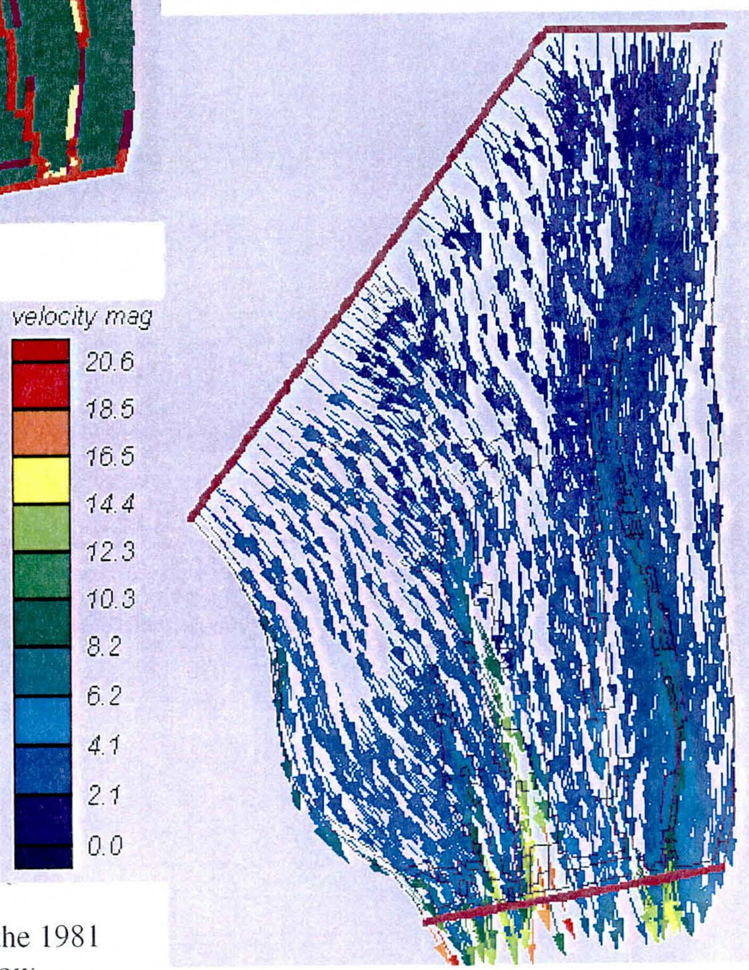


Figure 24. Velocity vectors for the 1981 Model. Blue vectors represent slow speeds; red vectors represent fast moving water.

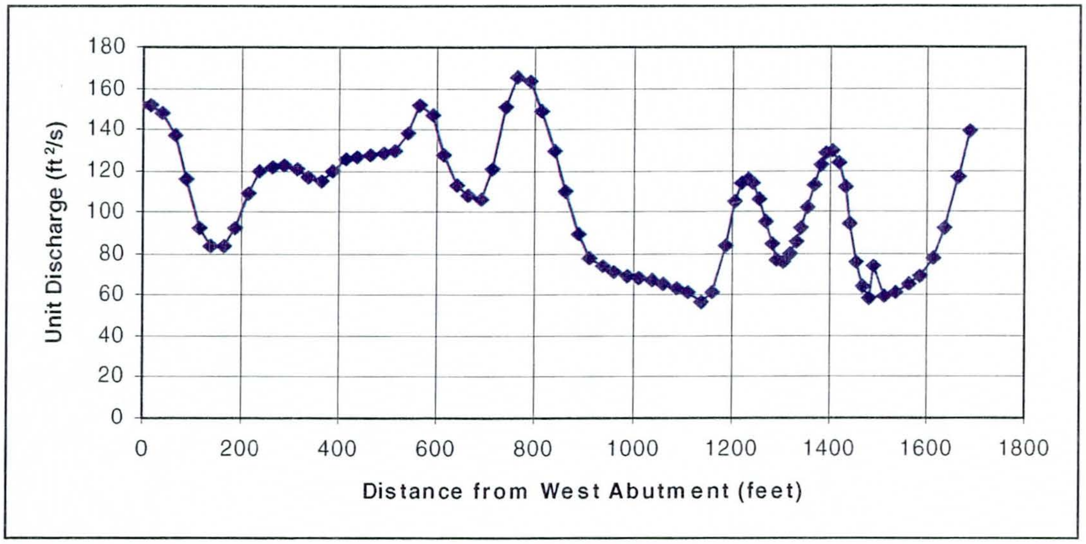


Figure 25. Distribution of the unit discharge from the west abutment (Distance Zero) along the length of Gillespie Dam for a flood peak of 178,000 ft^3/s in the 1981 Model.

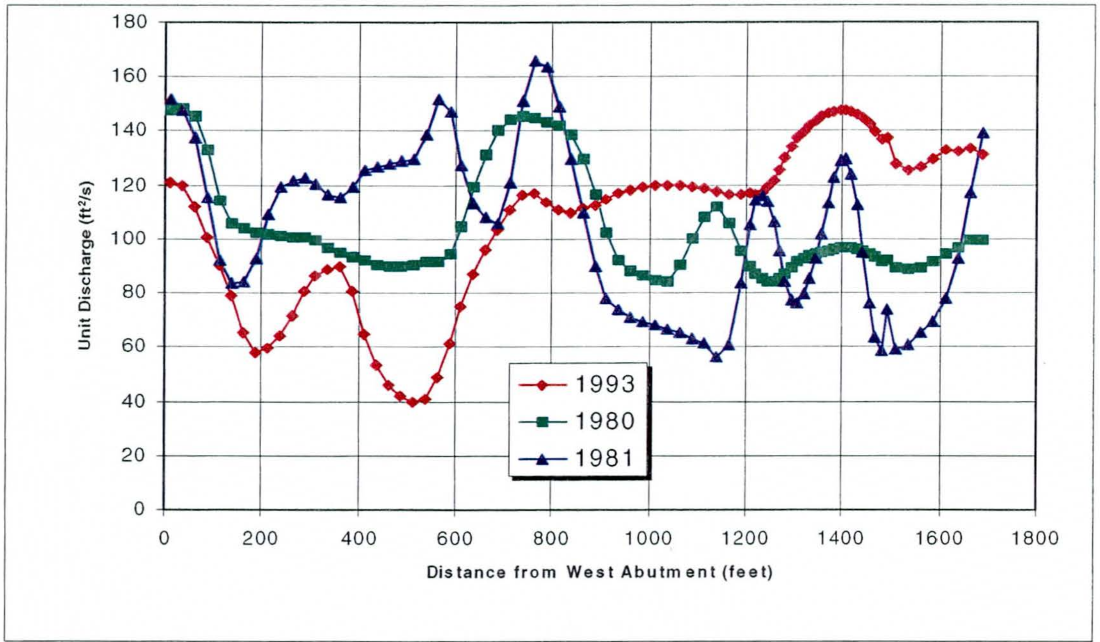


Figure 26. Comparison of unit discharges along the Gillespie Dam for a flood flow of 178,000 ft^3/s.

Table 7. Summary of two-dimensional mathematical modeling of a flow of 178,000 ft^3/s over the Gillespie Dam. Values are the unit discharge at the crest of the dam, in ft^2/s. Completely uniform flow at the dam has a unit discharge of 107 ft^2/s.

Condition	At the Breached Arch	Maximum Near Breached Arch	Average of Arches 12-16	Entire Dam Maximum	Entire Dam Minimum
1993 (FCD Corridor)	147	147	146	147	40
All trees	111	111	109	138	87
All bare	115	115	113	115	97
1980	97	97	96	148	84
1981	127	129	112	166	56

FINDINGS

The results of the mathematical modeling for a flood peak such as occurred in 1980 and 1993 are quite clear (Table 7):

1. The flow across the Gillespie Dam crest is most uniform when the floodplain is bare of trees.
2. With trees everywhere, there is a focusing of the flow at both abutments, but across the main portion of the crest, it is fairly uniform.
3. With the 1,000-foot wide corridor as it was in 1993, flow was non-uniform across the length of the Gillespie Dam and was focused at the arch where the dam was breached.
4. The 1980 flood peak was also highly focused but at a different point of the dam.
5. With the treed conditions in 1981, just prior to the clearing of the 1,000-foot wide corridor near the dam, the flood flow would have approximately 14 percent less at the breach arch.
6. Without the clearing of the 1,000-foot wide corridor, it is likely that the approach to the Gillespie Dam would have been predominantly trees in 1993. Then, the major focusing of the flow would have not been at the breached arch but elsewhere near the center of the dam (Figure 26).
7. Of the three models of actual conditions in the field (Table 7 and Figure 26), the 1993 condition produced the highest unit discharge at the breach arch location.
8. By using the same topography in all models, it has been shown that changing the type and distribution of vegetation in the floodplain by itself can significantly alter the flow distribution at the dam and focus the flow at different points on the dam.

OPINIONS

1. The Flood Control District of Maricopa County should have changed the 1,000-foot wide corridor to the entire width of the river in the vicinity of the Gillespie Dam to prevent the focusing of flow at the dam.
2. The least focusing of the flow occurs at the Gillespie Dam if there are no trees in the area upstream from the dam.
3. There is slightly more focusing if the area is all trees.
4. There is a combination of trees, bare floodplain, and channel that gives the greatest amount of focusing.
5. Focused flow increases the potential for scour at the end sill of the dam.
6. Focused flow increases the forces of water on the dam, its apron, deflecting wall, and end sill.
7. Focusing the flow increases the impact of any floating debris on the structure.
8. The reason that Gillespie Dam did not fail during the 1980 flood and did fail during the 1993 flood was probably due to the location of the focused flow.

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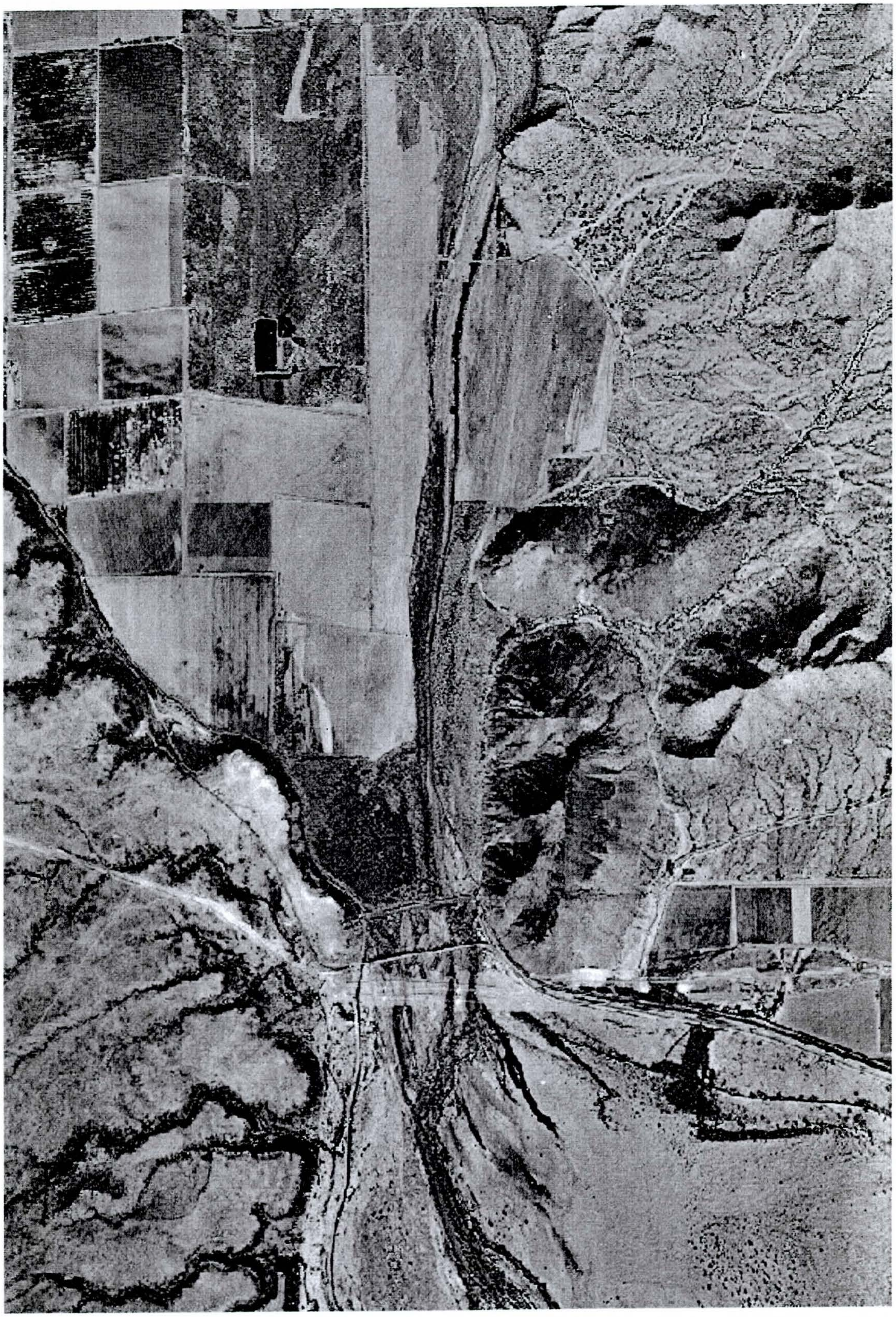
LIST OF APPENDICES

APPENDIX A – AERIAL PHOTOGRAPHS

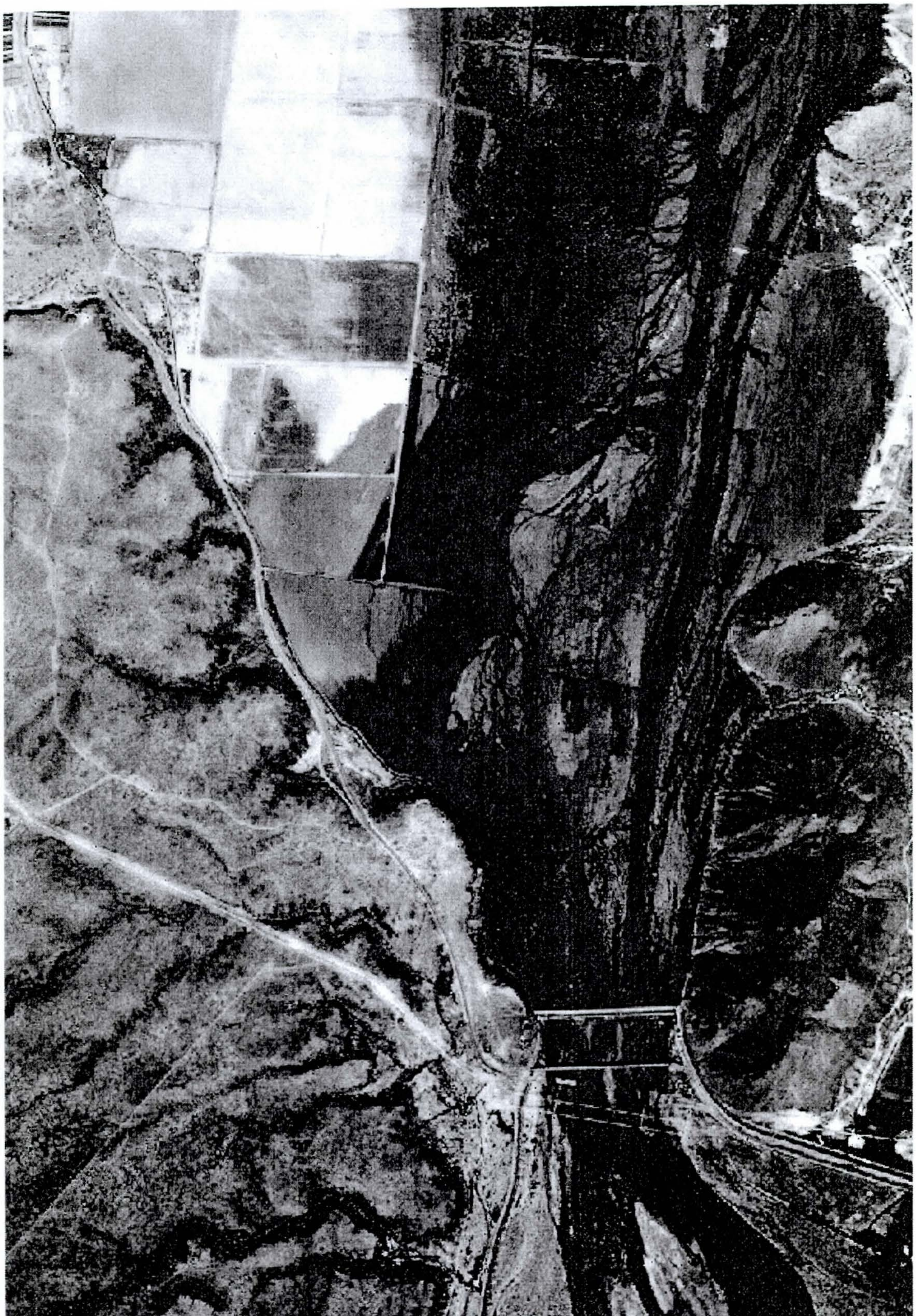
An assemblage of photographs has been studied to assess what has gone on in the last few miles above Gillespie Dam in the years from 1975 to 1993. Copies of these photographs are presented in this appendix.

Sequence of aerial photographs along with significant flood peaks.

Photograph Date	Source	Approximate Scale	Flood peaks in interval ft^3/s	
15 Dec 1975	ADOT	1" = 2,500 ft	3 Mar 78	92,900
			20 Dec 78	125,000
			19 Jan 79	86,600
15 Feb 1979	FCD	1" = 2,000 ft	30 Mar 79	59,900
			16 Feb 80	178,000
16 Feb 1980	FCD	1" = 1,000 ft	20 Feb 80	126,000
			22 Feb 80	117,000
26 Jan 1981	FCD	1" = 3,000 ft		
2 Dec 1981	ADOT	1" = 1,000 ft		
5 Dec 1982	Landiscor	1" = 3,000 ft	5 Oct 83	95,200
5 Mar 1985	Landiscor	1' = 3,000 ft		
8 Nov 1986	Landiscor	1" = 3,000 ft		
30 Jun 1989		1" = 800 ft		
5 May 1991	ADOT	1" = 4,000 ft		
9 Jan 1993	ADOT	1" = 800 ft	9 Jan 93	175,000
7 Feb 1993		1" = 1,600 ft		

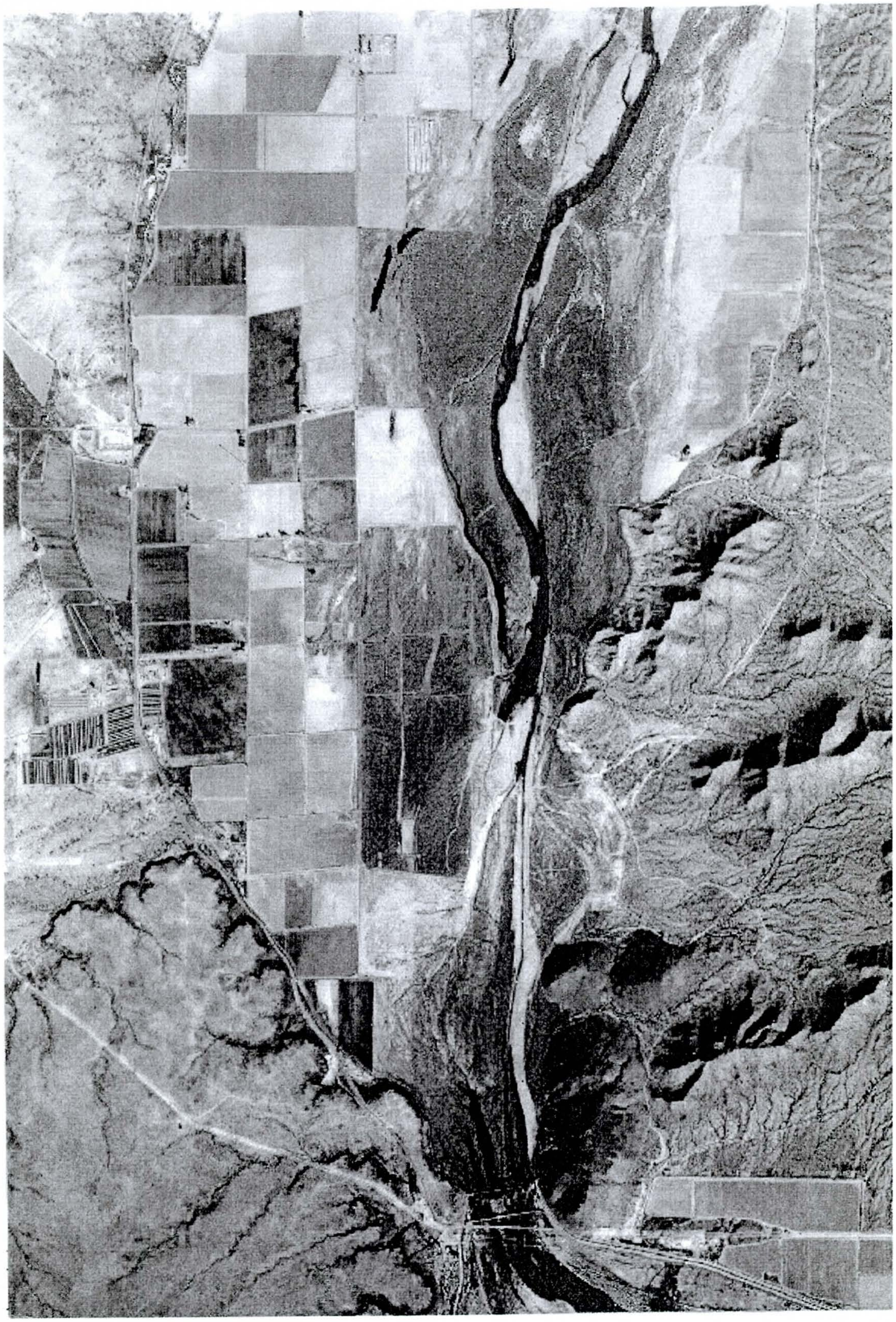


15 Dec 1975

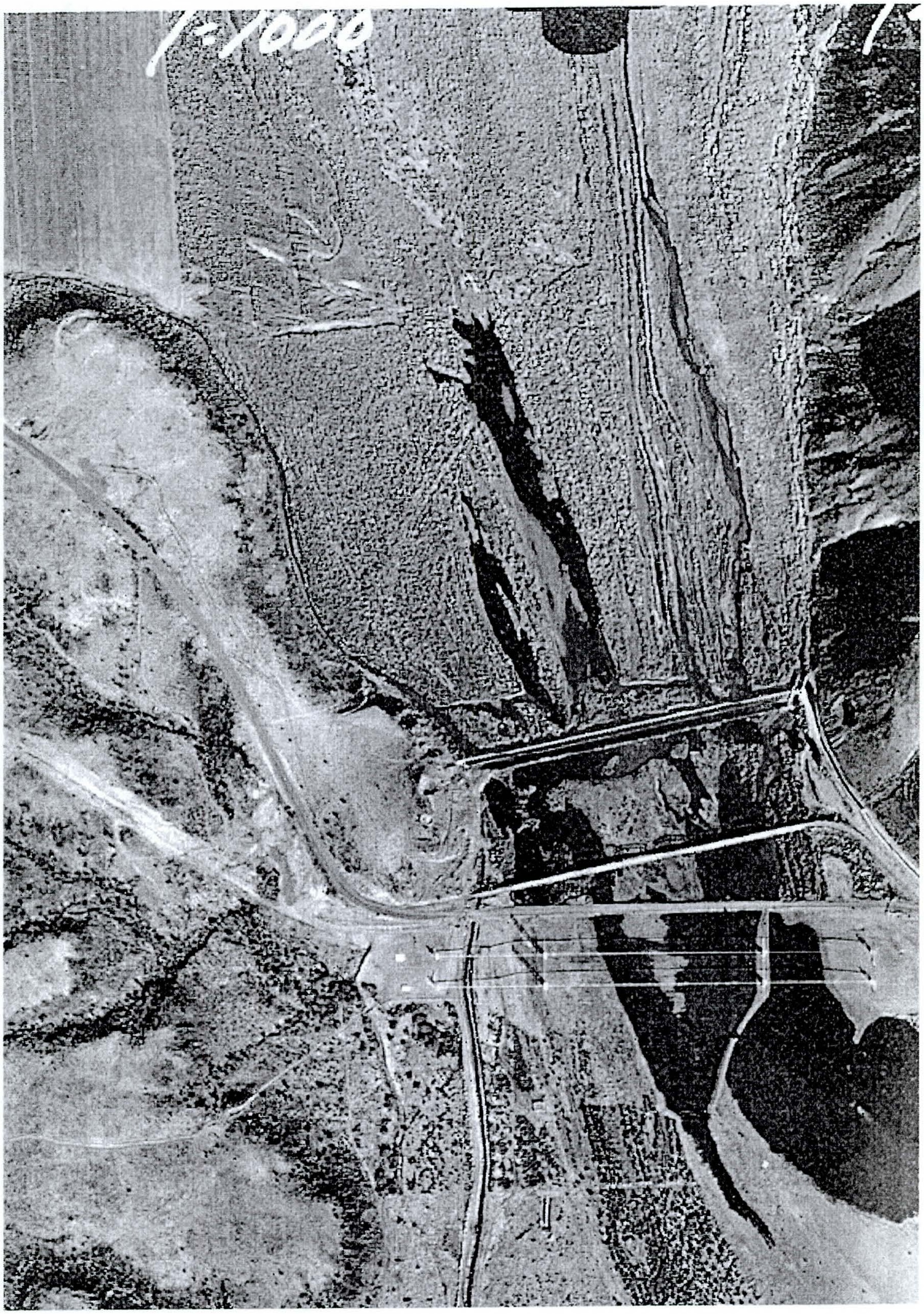


15 Feb 1979

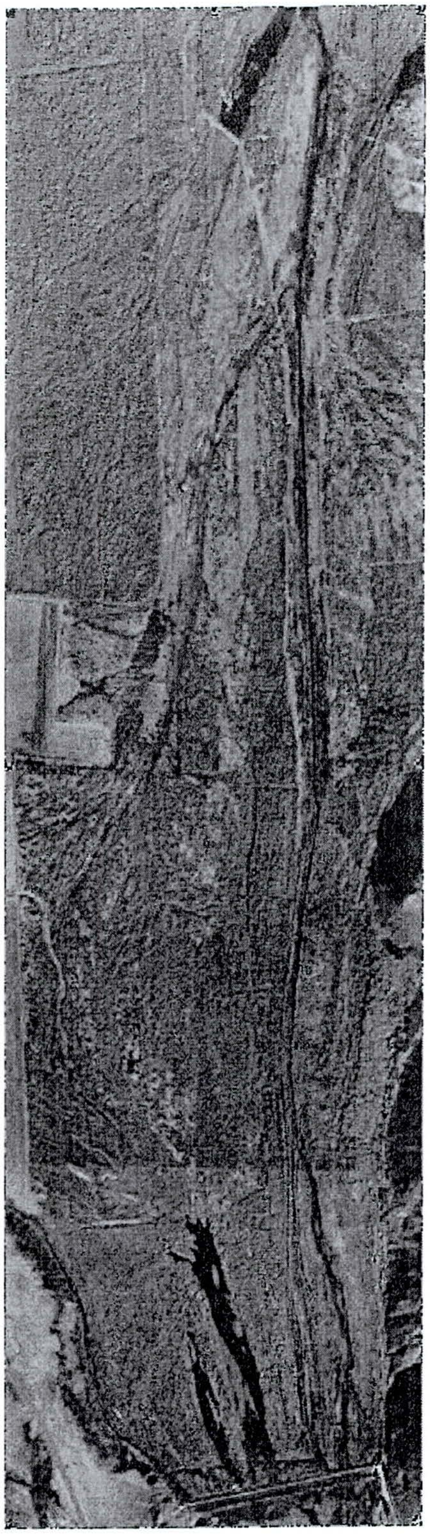
16 Feb 1980



26 Jan 1981

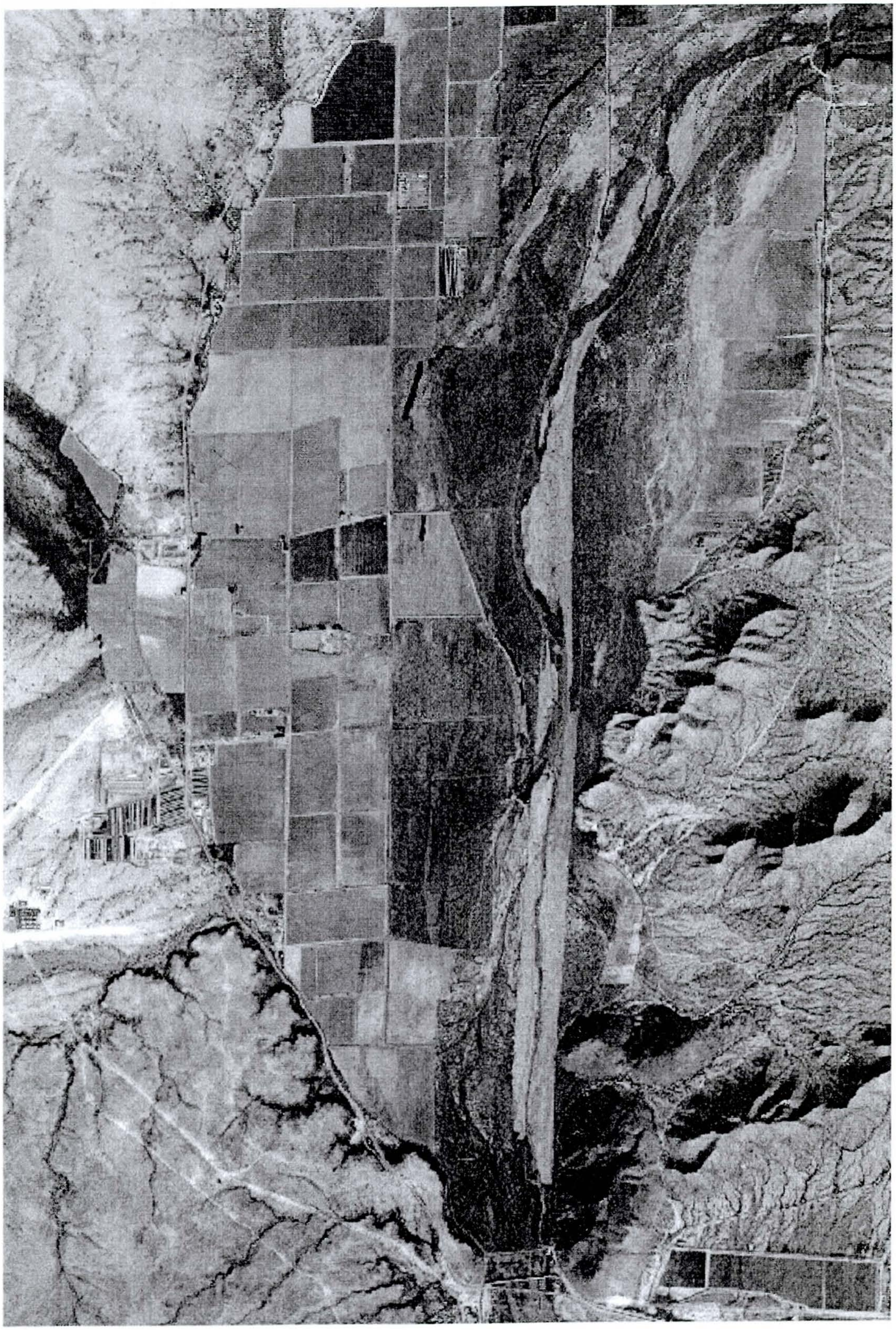


2 Dec 1981 (Photograph 1)

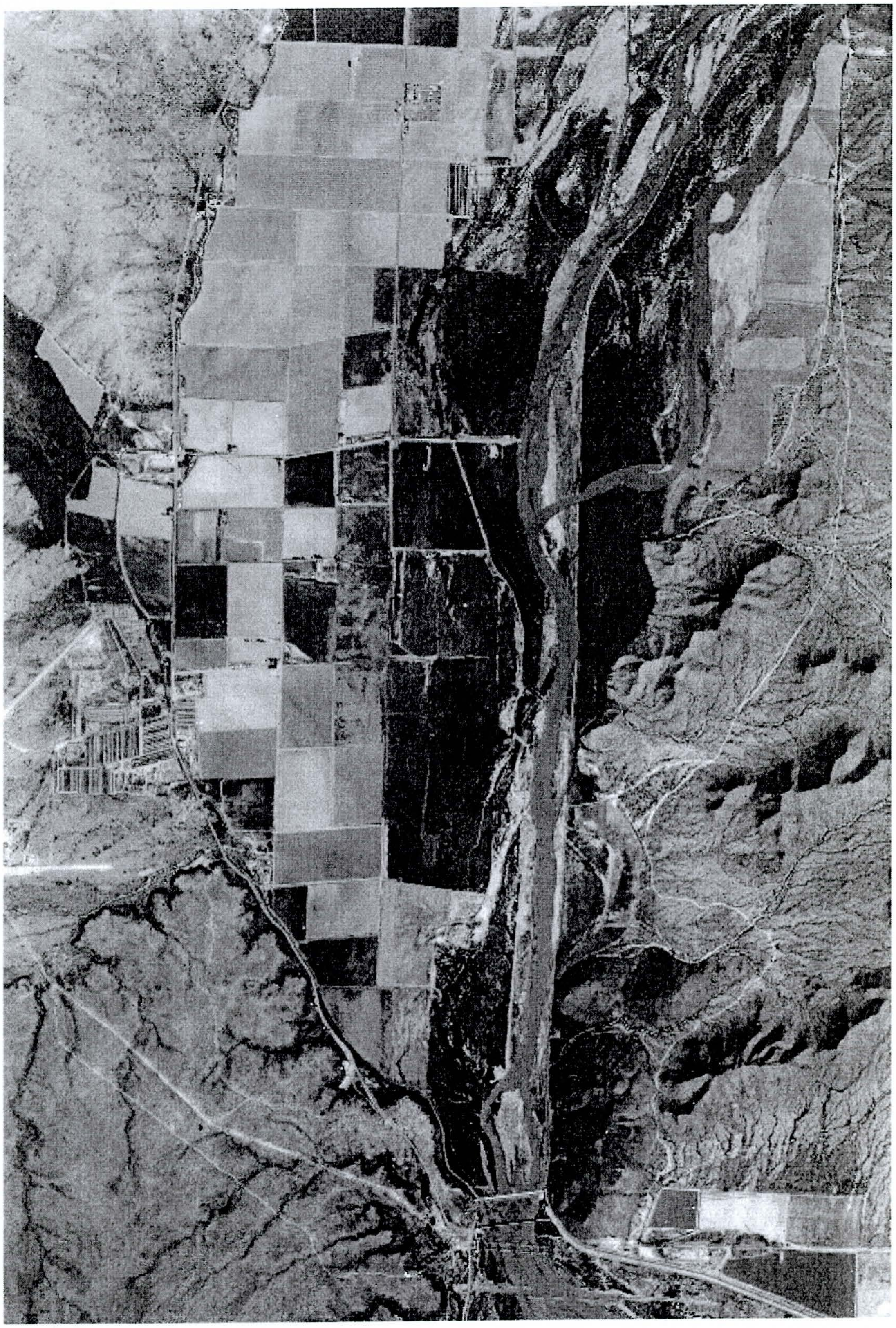


2 Dec 1981 (Photograph 2)

2 Dec 1981 (Photograph 3)



5 Dec 1982



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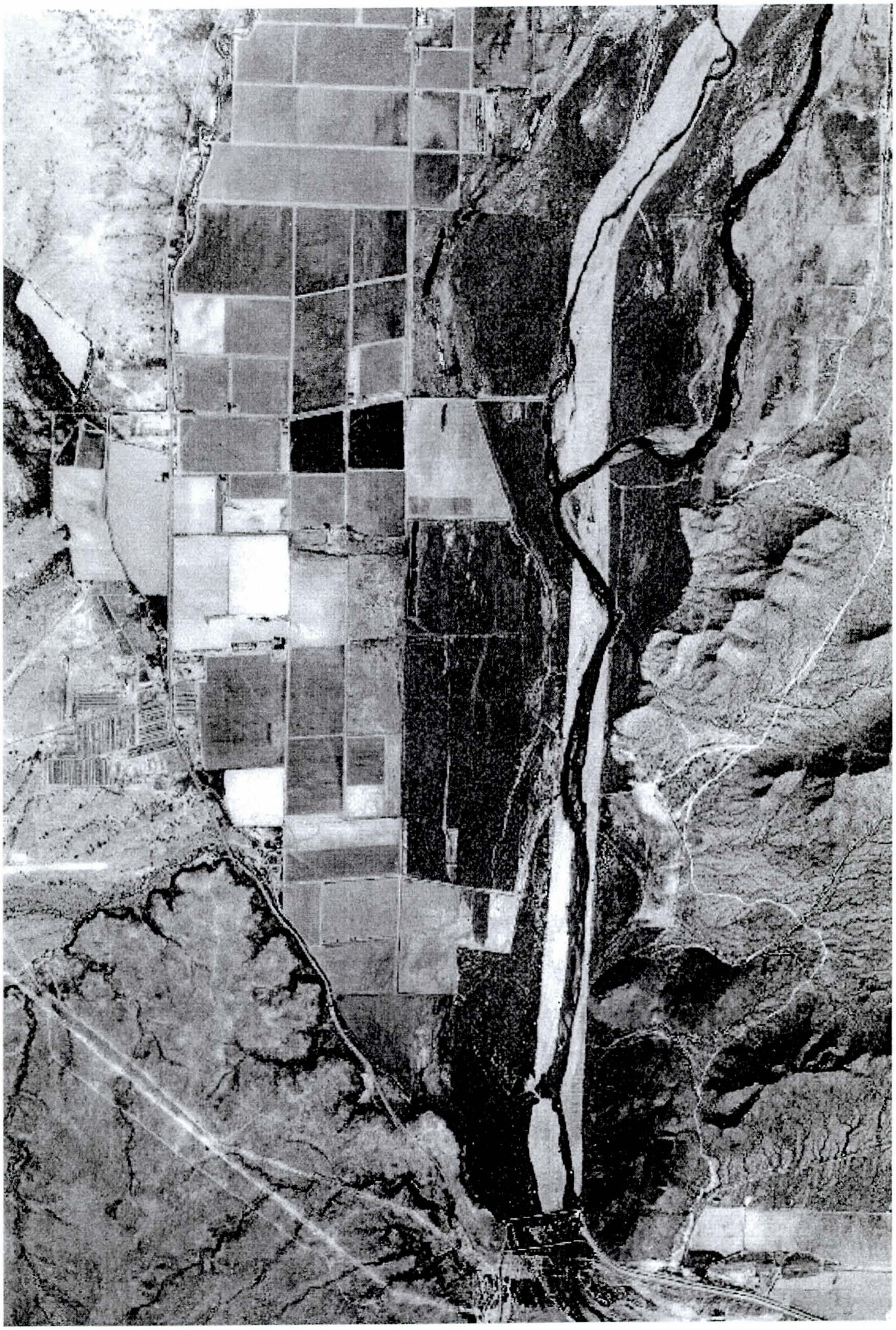
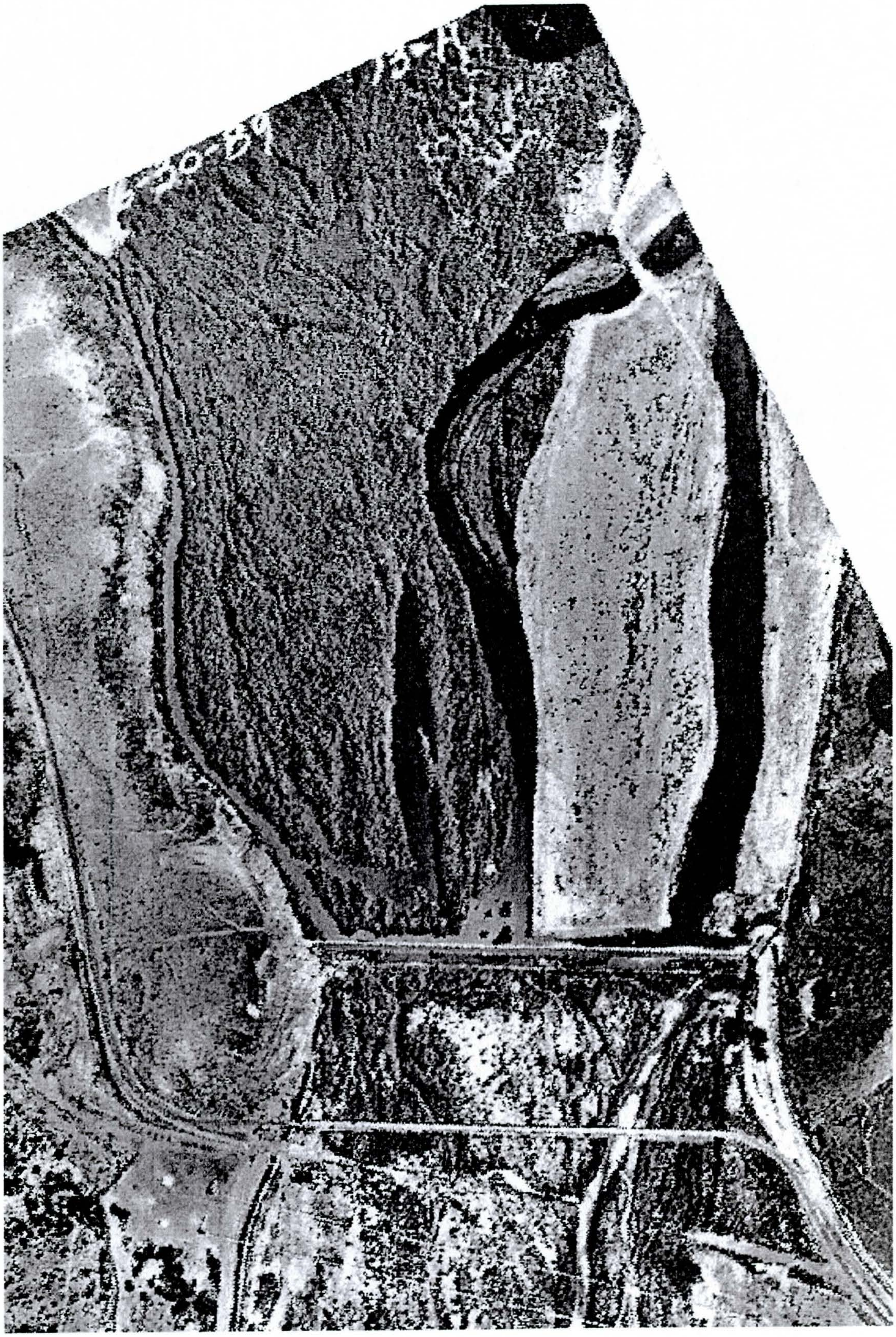


8 Nov 1986



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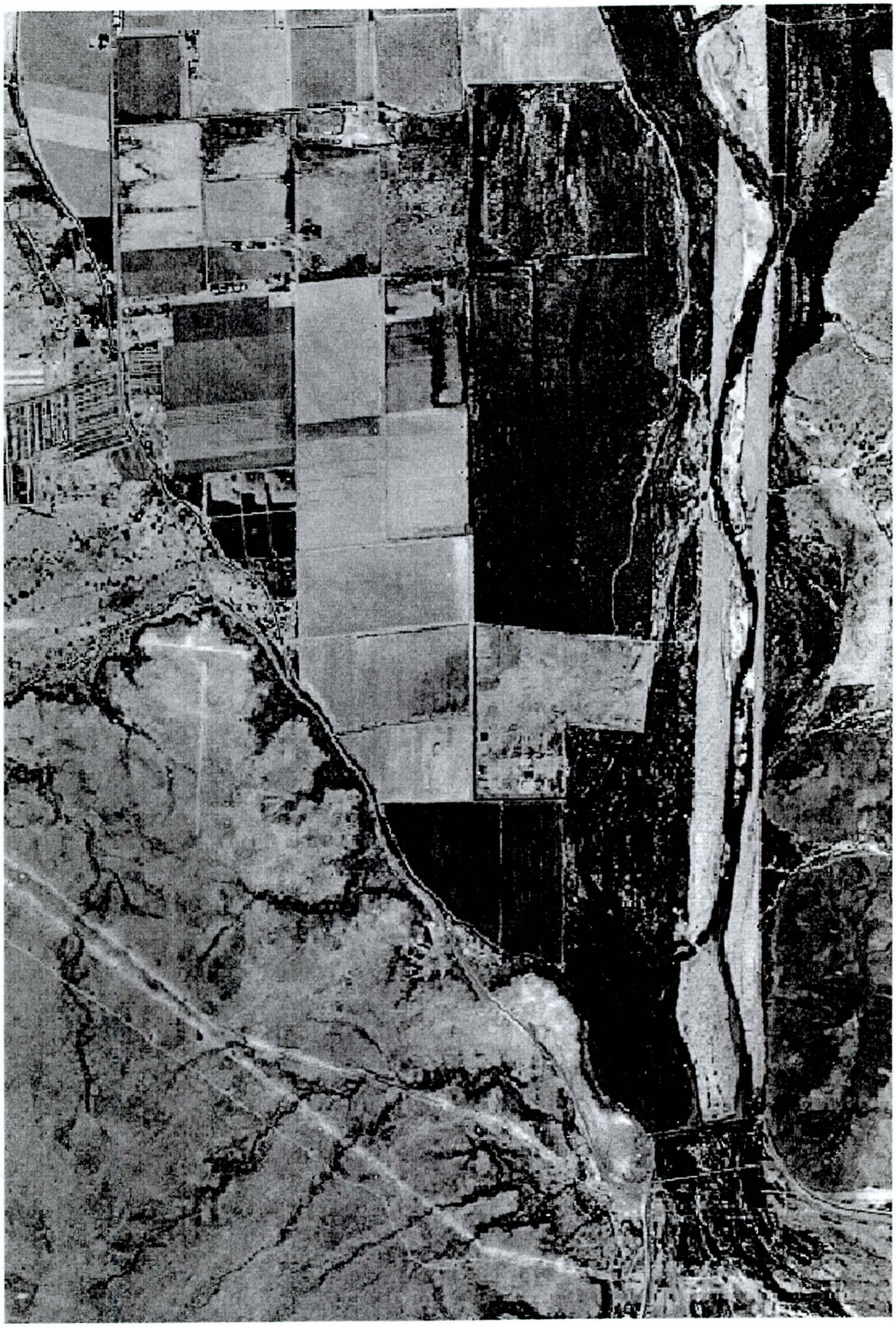

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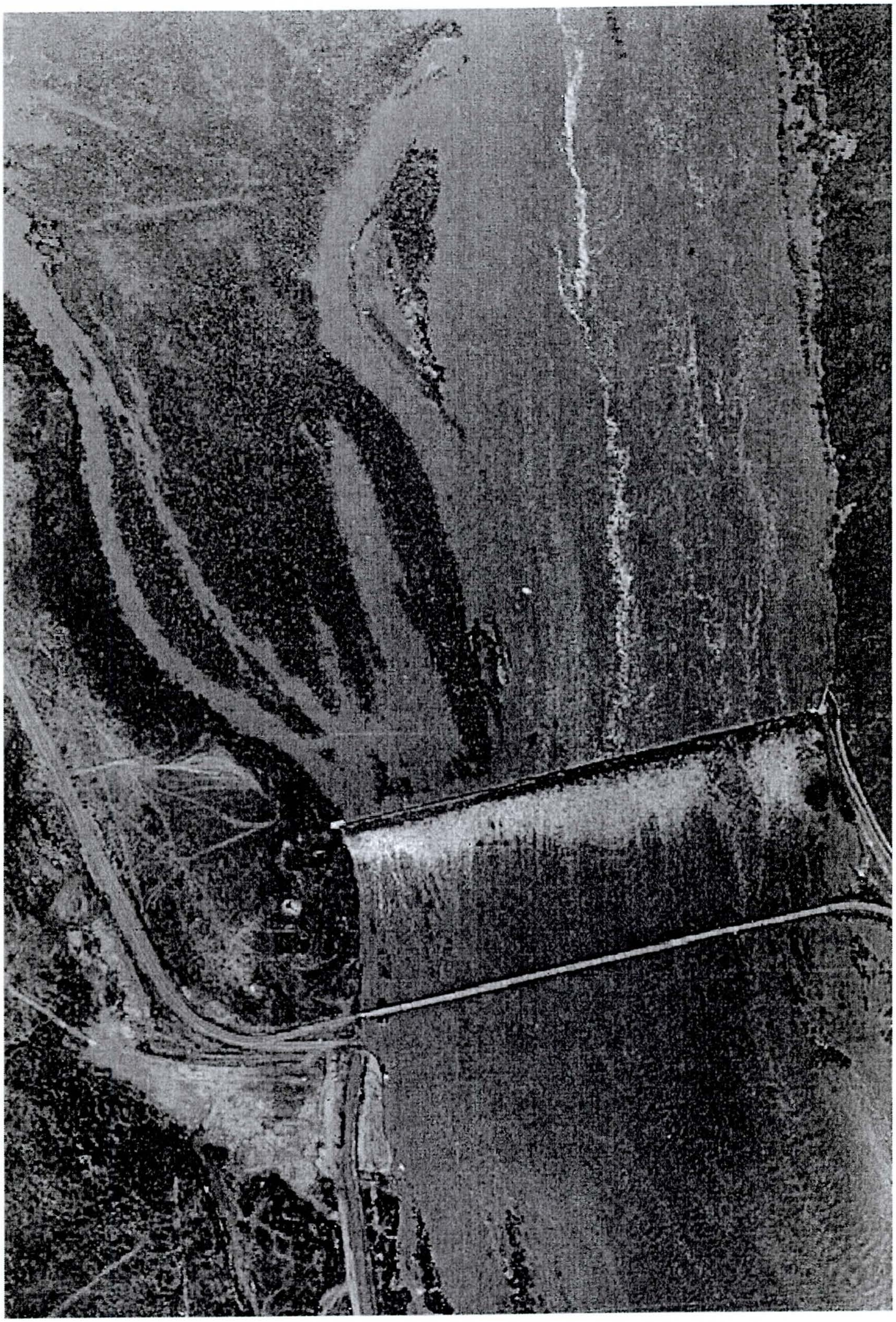
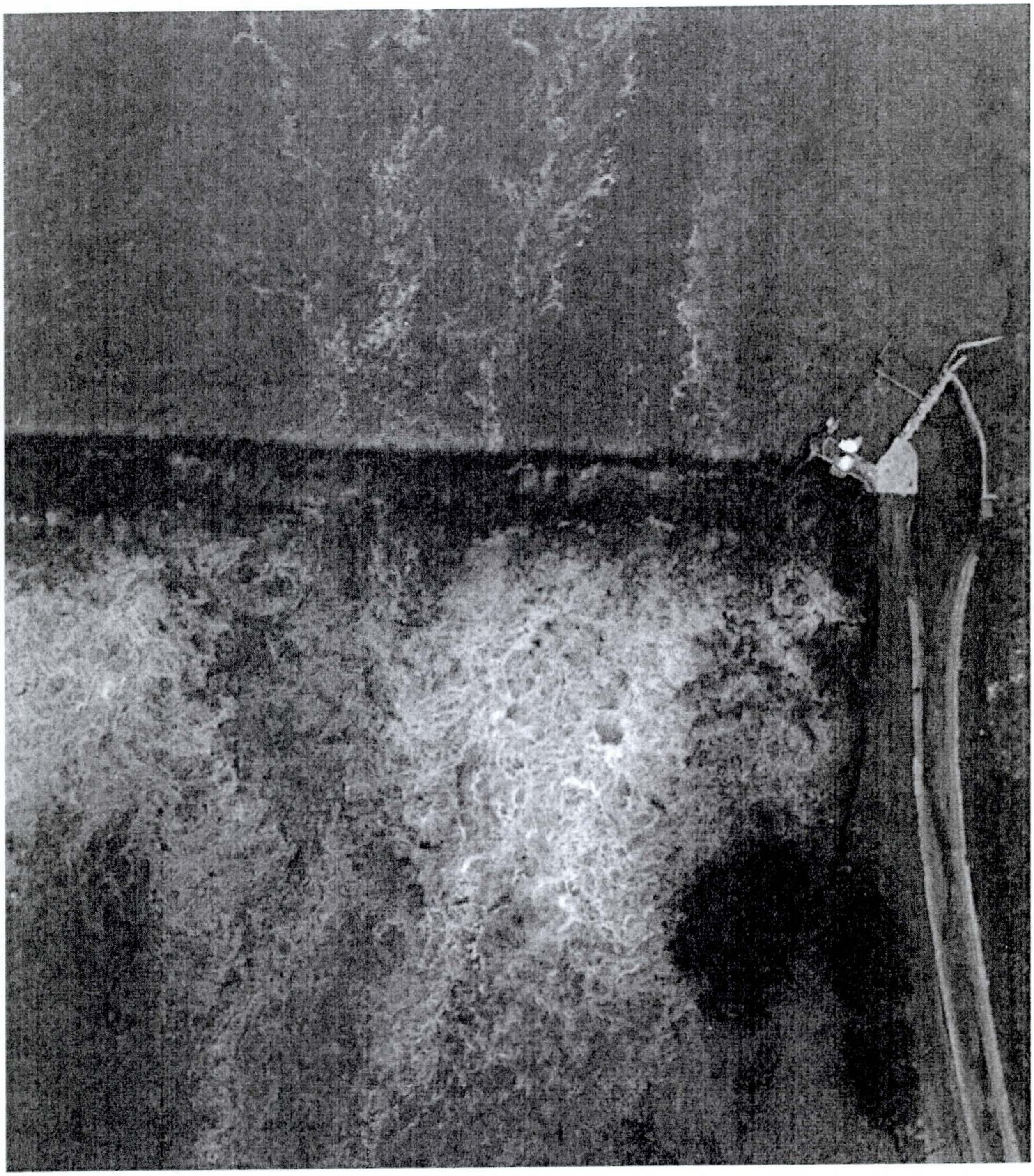


9 Jan 1993 (Photograph 1)



9 Jan 1993 (Photograph 2)

7 Feb 1993

APPENDIX B - CANALCAD

The Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa City developed CanalCAD under the direction of Forrest M. Holly Jr.

The CanalCAD system of programs (1992) simulates unsteady flow in irrigation canal systems with automatic gates. CanalCAD comprises the synthesis of a mature, reliable dynamic-equation solver; a menu-driven interface for canal definition and results processing; and user-customized access to gate-control algorithms.

CanalCAD is designed for use on IBM-compatible PCs in the design, analysis, and operation of irritation canals comprising subcritical flow in a single in-line system of pools and appurtenant structures including weirs, check structures, and storage reservoirs. The system provides a high degree of user guidance in canal description and simulation diagnosis.

CanalCAD produces a solution to the unsteady one-dimensional equations of motion for water. The program treats the water movement as a full-dynamic wave, including all the forces and acceleration in one-dimensional flow.

CanalCAD is quite suitable for estimating the flood-wave attenuation in a reach of the Gila River as the data requirements are judiciously limited and the output is readily diagnosed.

REFERENCE

Holly, F.M. and Parrish, J.B., 1992. *CanalCad – Dynamic Flow Simulation in Irrigation Canals with Automatic Gate Control.* Prepared for Imperial Irrigation District, Imperial, CA., by Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA.

APPENDIX C – RMA2

RMA2 is a part of the BOSS SMS group of programs for Microsoft operating systems for PCs that deal with the two-dimensional modeling of water and sediment motion. Brigham Young University Engineering Computer Graphics Laboratory developed part of the group. SMS stands for Surface-Water Modeling System (BOSS SMS Users Manual, 1994).

The RMA2 component is a hydrodynamic modeling code that supports subcritical flow analysis, including wetting and drying models. It is part of the TABS analysis package supported by the US Army Corps of Engineers Waterways Experiment Station (1996).

RMA2 is a two-dimensional depth averaged finite element hydrodynamic numerical model. It computes water surface elevation and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields.

RMA2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's or Chezy equations, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state problems can be analyzed.

Some of the assumptions of two-dimensional depth averaged models, including RMA2, are:

- Vertical accelerations are negligible.
- Pressure is hydrostatic in the vertical.
- Velocity vectors point in the same direction over the entire depth of the water column at any time.
- The water is homogeneous with a free surface.
- The channel bed and floodplain and vegetation are fixed, there is no scouring or deposition of sediment.

In actuality, large flows can cause many changes in the Gila River near Gillespie Dam. Channels are enlarged and filled; new channels are created and old ones lost; the floodplain is scoured or inundated with new sediment; trees can be scoured and become debris to be deposited elsewhere.

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APPENDIX D - SEVEN-MILE MODELS

The Seven-Mile Model covers the valley floor from Powers Butte to Gillespie Dam, a distance of seven miles. The purpose of this two-dimensional mathematical model is to get a good approximation of the flow (depth and velocity) approaching the dam about a mile upstream from the dam. These conditions were then used in the more refined One-Mile Model to best estimate the focusing of the flow at Gillespie Dam during the peak of the 1993 flood.

In 1993, FCD's 1,000-foot wide corridor had a major influence of the focusing of the flow. Therefore an estimate was made of the focusing if the corridor project had not been undertaken; that is, the trees would be allowed to grow. This condition was estimated from the January 1981 aerial photographs. Finally, the flow field has been estimated for the conditions that all trees are removed from the valley floor. Therefore, there are four Seven–Mile models identified as the Corridor Model, Trees Model, Bare Model and 1980 Model. The same XYZ topography was used for all four.

At Powers Butte the valley is only approximately 3,000 ft wide and the river flow is directly to the west. The valley widens out quickly to 15,000 ft as it turns to the south and then funnels into the Gillespie Dam. Powers Butte is an excellent place to have the upstream boundary of the two-dimensional models.

Because of the large size of the triangular elements in the Seven-Mile Models (and limitations of RMA2), there are features missing in the model that affect the flow locally. These include small embankments, linear levees and vegetation, dikes, and local roads. These features are either not present or can be handled to some extent in the One-Mile Models because the elements are closer to the size of the features. For example, one cannot define a 60-foot wide road with triangles that are 200 ft on a side. But with triangles 25 ft on a side, the road can be modeled.

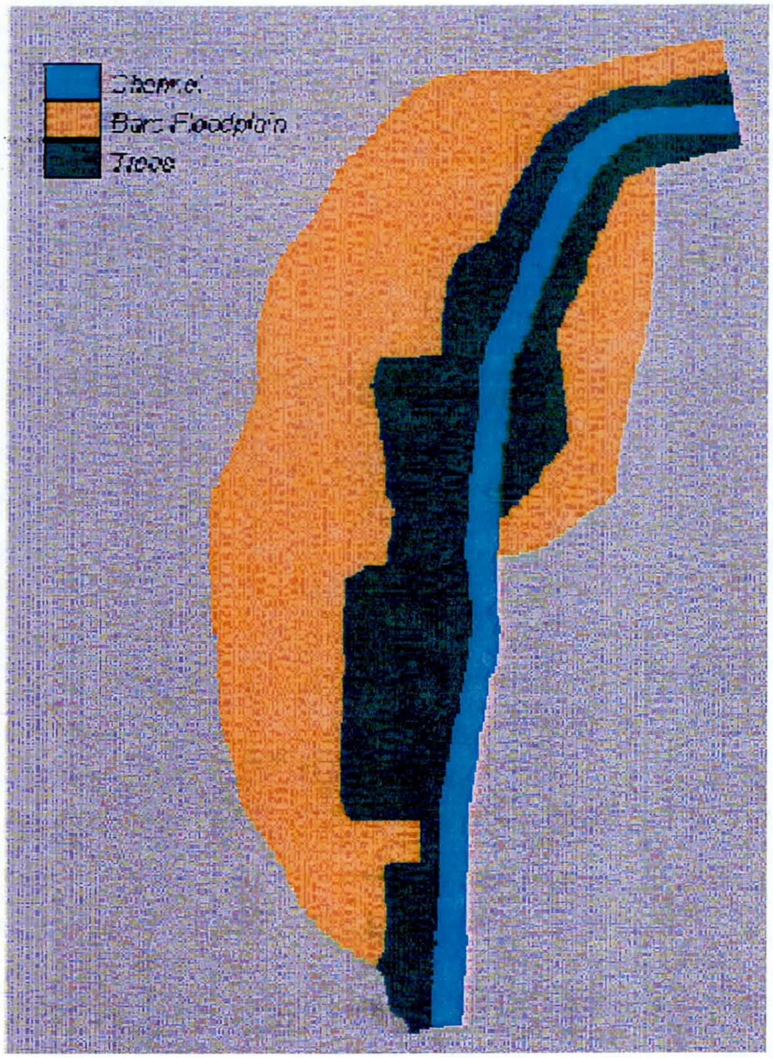

Figure 1-D. Map of the Corridor Model showing the 1,000-foot wide corridor, bare floodplain, and trees.

CORRIDOR MODEL

Shown in Figure 1-D, the prominent feature of the Corridor model is the FCD's 1,000-foot wide strip of cleared area near the east valley wall. Trees bordered the 1,000-foot wide corridor on the west and on the upper east side. The corridor abuts the east valley wall near the dam. The small coves in the east valley wall were not modeled. Most of the rest of the valley floor was farmers' fields.

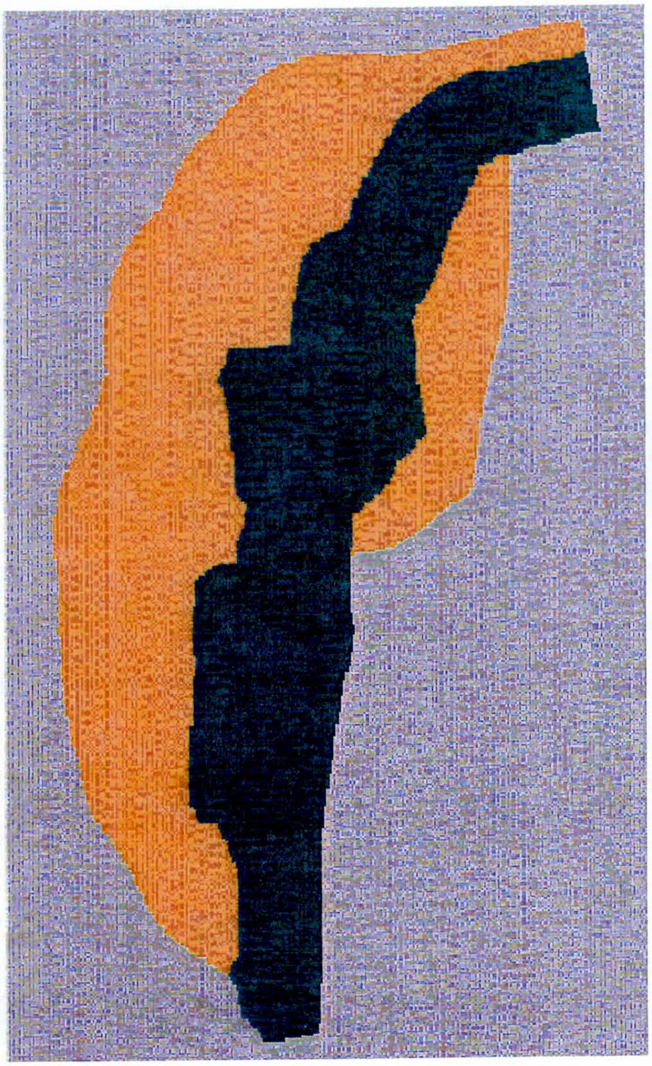

Figure 2-D. Map of the Trees Model showing the trees and the bare floodplain.

TREES MODEL

The Trees Model is a hypothetical case. The model (Figure 2-D) the same as the Corridor Model except that the 1,000-foot wide corridor is covered with trees. Also, the farmer's field that extends into the trees on the west side of the corridor about one mile upstream from the dam has been made trees.

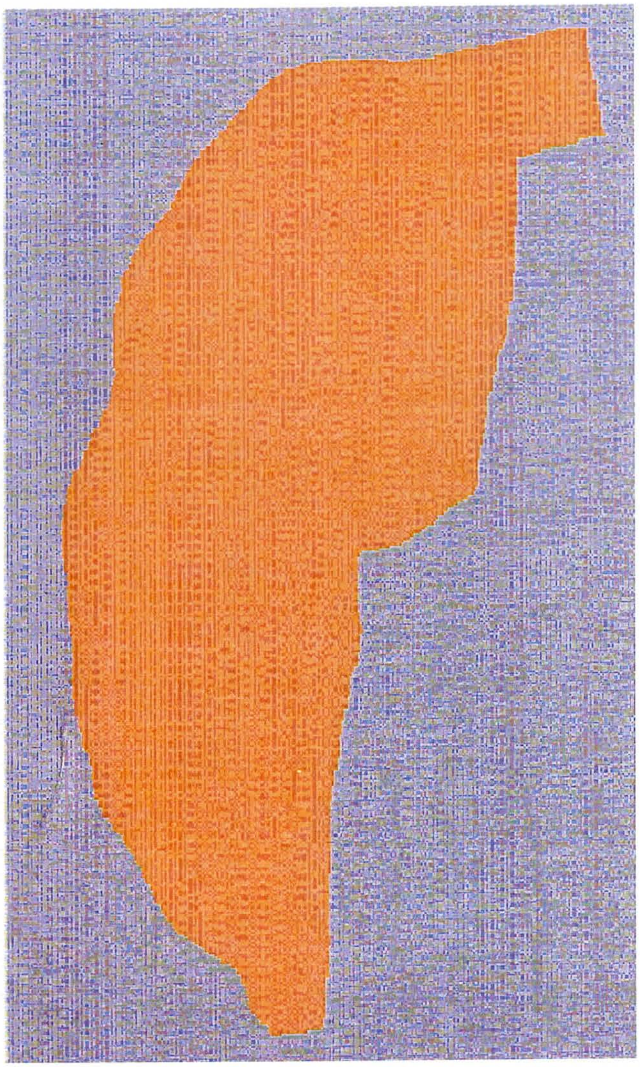

Figure 3-D. Map of Bare Model with only bare floodplain

BARE MODEL

The Bare Model is another hypothetical case. The model is the same as the Trees Model but with all trees removed from the entire valley floor.

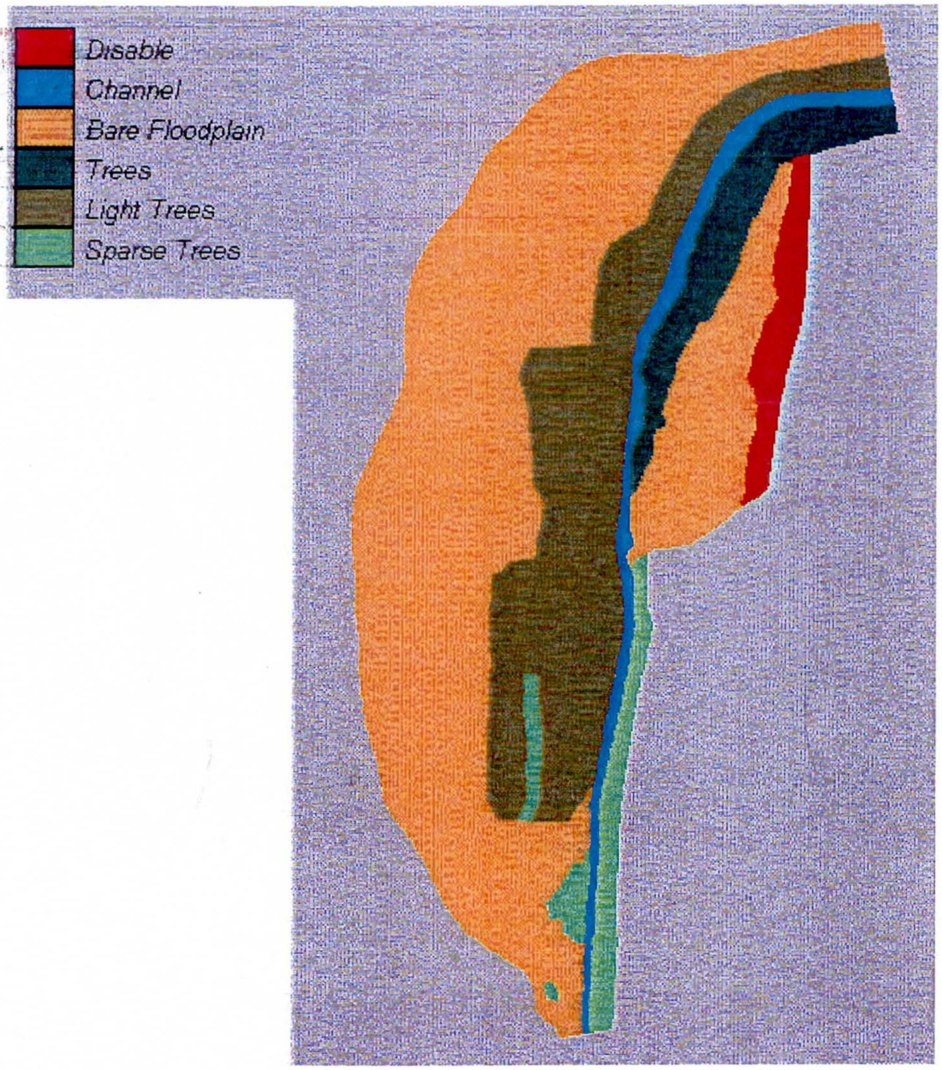

Figure 4-D. Map of the 1980 model showing young and older trees, the bare floodplain, and a 200-foot wide channel.

1980 MODEL

The aerial photographs of 1979 and 1980 give an indication that the trees were being established after a thorough scouring of the valley during the 1978 and 1979 floods. An estimate of the channel location and floodplain vegetation (Figure 4-D) were made to simulate the 1980 flood peak.

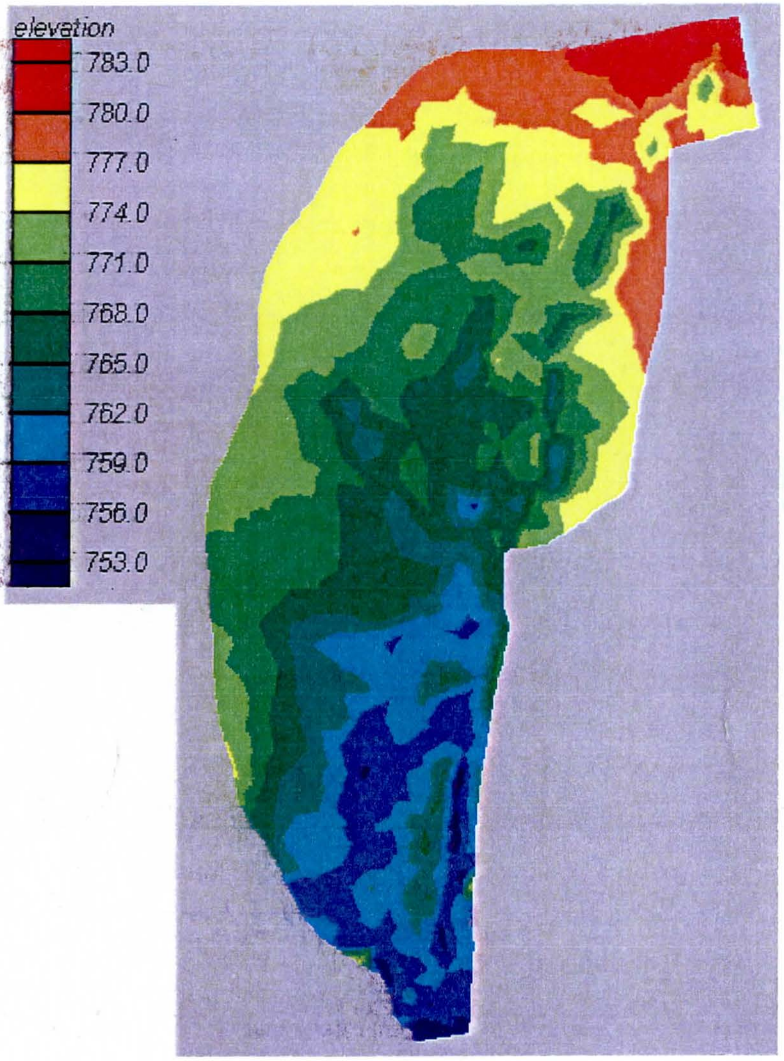

Figure 5-D. Contours of ground elevations for all Seven-Mile Models.

CONTOURS

The horizontal position and elevations of points on the valley floor, including the channels, were obtained from the DTM. In Figure 5-D, the red on the north of the valley at Powers Butte is the highest ground with the elevation being 780 ft and higher. The crest of the Gillespie Dam, El. 755.3, is 25 ft lower.

The valley floor slopes steeply out of the narrows at Powers Butte and then flattens. The green area on the map is between El. 762 and El. 774.

There is a green hill with lower blue areas to the west and east in the lower part of the model. The hill, as well as the trees, influences the approach of floodwater to the dam.

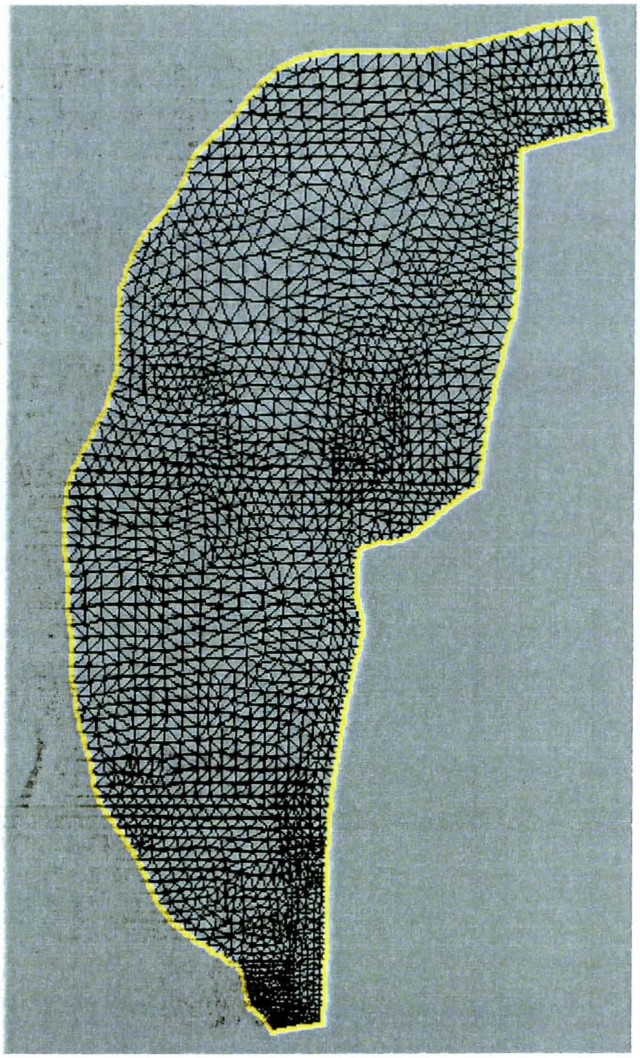

Figure 6-D. Map of the triangular mesh for Seven-Mile Models.

MATHEMATICAL STRUCTURE

In the two-dimensional model, the entire area was divided into triangles (Figure 6-D); in this case a total of 3,486 triangles were defined. The elevations and horizontal positions of the triangle apexes were determined internally by the model from the DTM. Each triangle is given a surface in accordance with the 1993 aerial photograph. There are three choices: channel, bare floodplain, and trees. The hydraulic roughness of these surfaces is taken to be 0.025, 0.028, and 0.170 (Appendix E).

The corners of the triangles are called nodes. In addition to these three nodes, the program assigns nodes at the mid-point of each side. These additional nodes are also given XYZ coordinated from the DTM.

The mathematical model uses these triangles, their nodes, their surface properties, and Newton's Second Law of Motion to calculate the depth and velocity vector at each node.

BOUNDARY CONDITIONS

The steady discharge for all Seven-Mile Models is that taken 178,000 ft^3/s, the nominal reconstructed peak of the January 1993 flood. This flow is entered uniformly across the valley at Powers Butte. Immediately, the model spreads the flow amongst the channel, trees, and bare floodplain, so by the bend in the valley, there are appropriate amounts on each surface.

At the dam, the water surface level was set at Elevation 763.3 ft, 8.0 ft above the crest level. The description of the determination of this value is given in Appendix F.

RESULTS

Corridor Model. There is confirmation that the two-dimensional mathematical model was very successful in reproducing the essence of the flow in the Gila River during the peak of the 1993 flood that breached Gillespie Dam. Figure 7-D is a representation of the flow directions in the field surrounded on three sides by trees. The flow is bending quickly towards the 1,000-foot wide corridor to the east (right). The field is approximately one mile upstream from the dam.

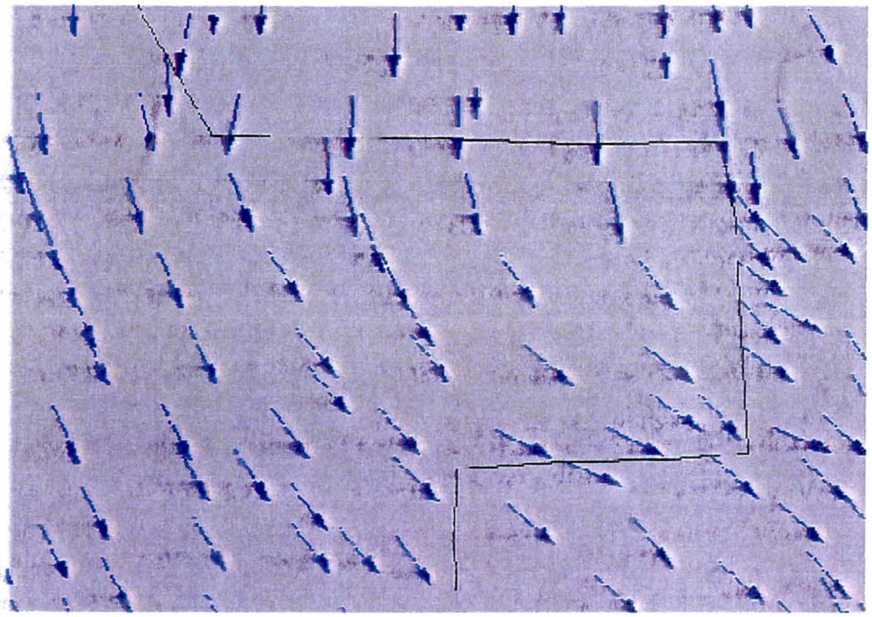

Figure 7-D. Model velocity vectors in the field.

Figure 8-D is the same area on the 1993 flood-peak photograph. The shadowed streamlines in the real flow were bending in the same manner, towards the corridor to the east.

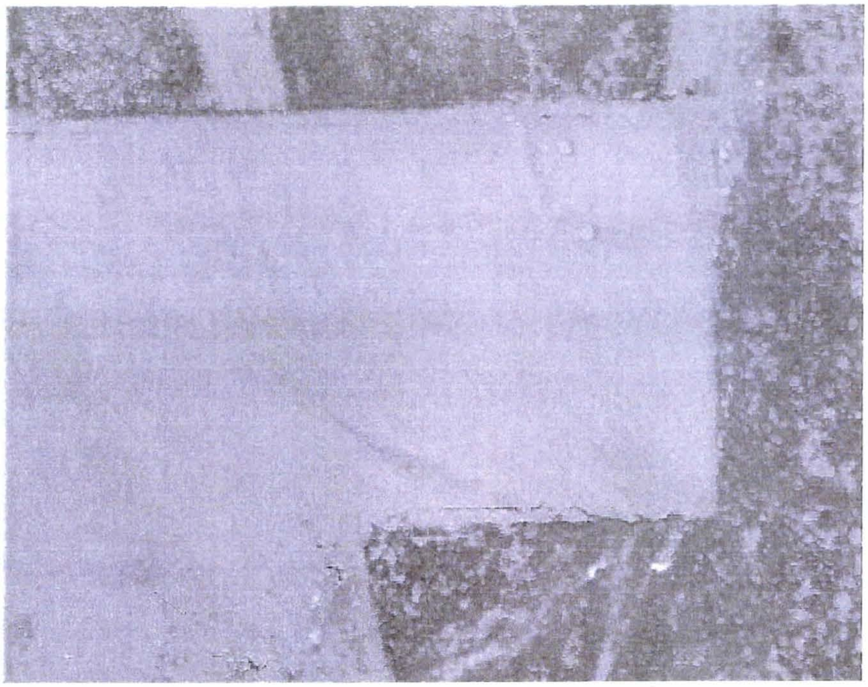

Figure 8-D. The 1993 flood-peak aerial photograph of the same field surrounded on three sides by trees. The streamlines for the flow are shadows on the photograph.

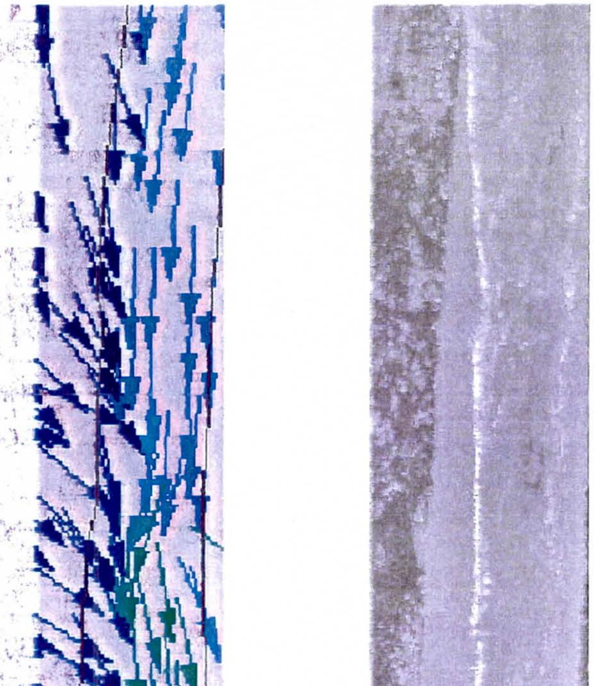

Figure 9-D. The mathematical model (left) shows the flow coming out the trees into the 1,000-foot wide corridor and then turning south with the flow in the corridor. The 1993 flood photograph shows the same thing. The strong white line indicates the division between the water that came from the trees and the water coming down the corridor from above.

The 1,000-foot wide corridor was carrying a large part of the flood in 1993. In addition to conveying the flow from the upstream part of the corridor, it was attracting flow from the floodplain to the west. Water that had been spilled to the west floodplain farther upstream was returning to the corridor in the last mile upstream from the dam.

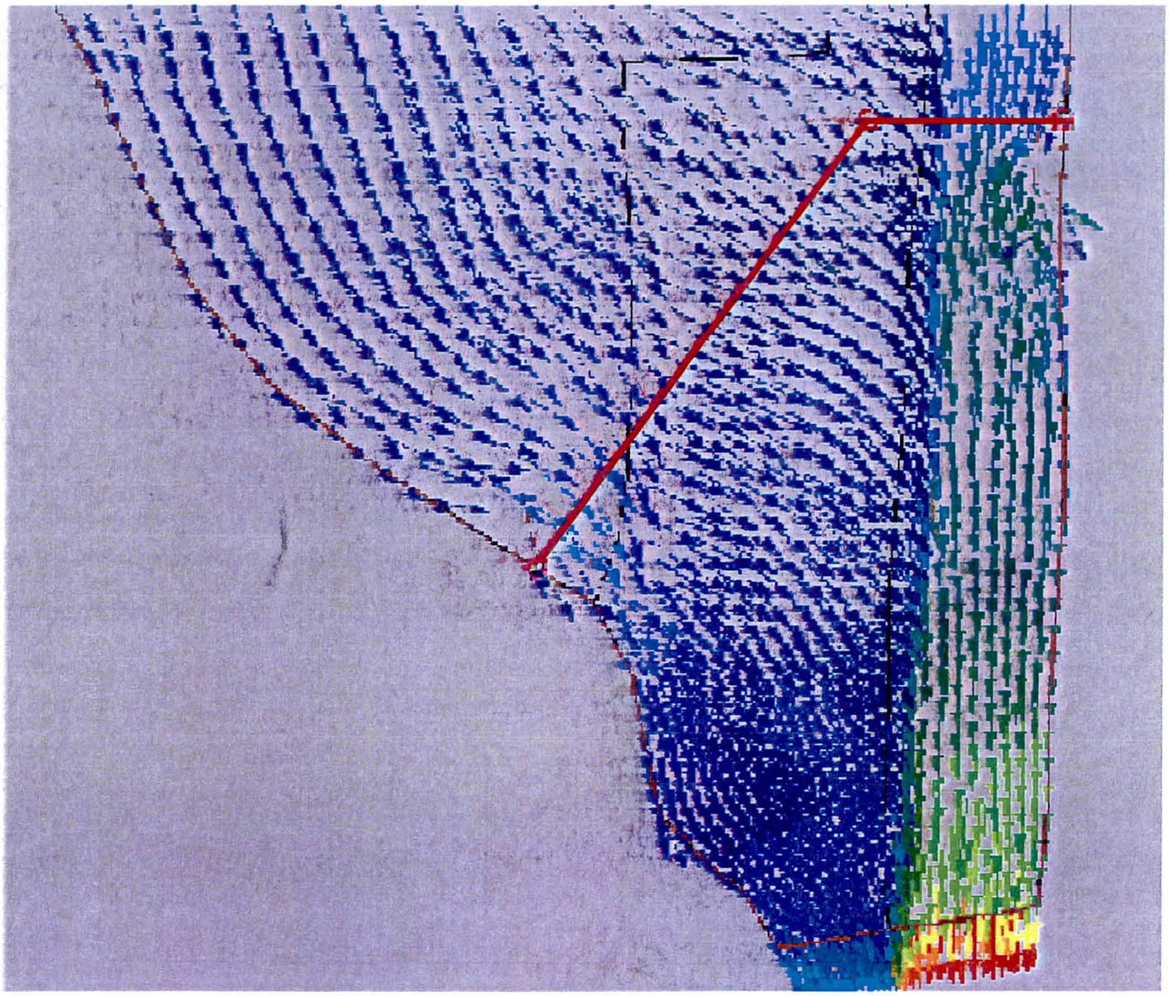

Figure 10-D. Velocity vectors in the last mile upstream from Gillespie Dam. The dark blue ones are low speeds, and red are the fastest. The red markers and lines define the upstream limit of the One-Mile Models.

In the last mile upstream from the dam, the flow returned quickly from the west floodplain; some to the 1,000-foot wide corridor, the rest funneling to the west side of the dam. The flow was fairly well straightened, going over the crest of the dam. In the corridor, the flow accelerated in the last mile reaching peak speed at the dam.

The boundary points for the One-Mile Model were chosen from the study of information in Figure 10-D. The north part is across the 1,000-foot wide corridor. The northwest boundary is through the trees normal to the direction of flow.

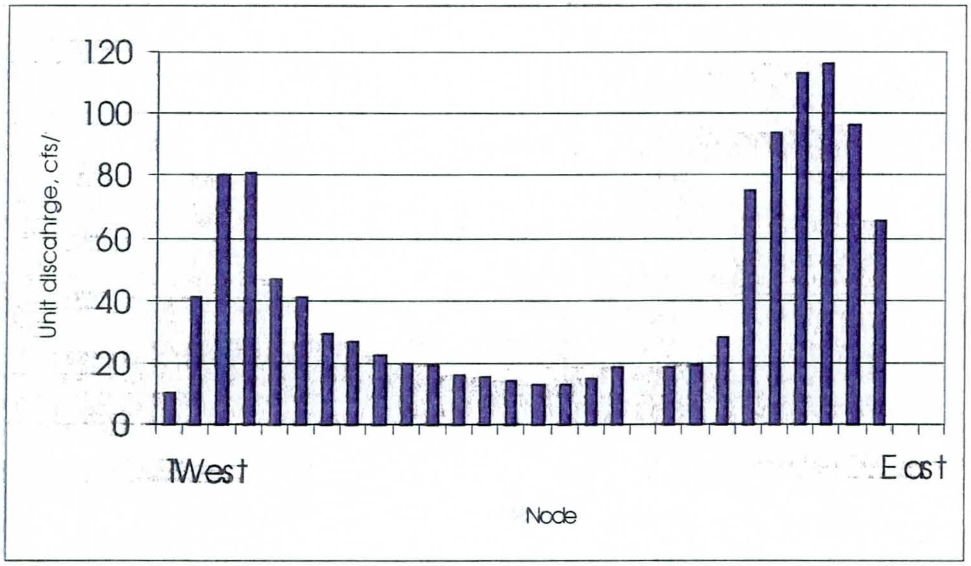

Figure 11-D. Unit discharge at nodes across the upstream boundary of the One-Mile Corridor Model. The break is the corner between the northwest and north boundaries.

The unit discharge was high near the west side as the flow converged to the narrow part of the valley where the dam was constructed. In the middle where the trees have the most influence, the unit discharge dropped to a value near 20 ft^2/s. In the center of the 1,000-foot wide corridor, the unit discharge reached almost 120 ft^2/s.

Information on values of important variables in the entire valley floor from Powers Butte to Gillespie Dam is listed below.

Table 1-D. Summary of information for the entire Seven-Mile Corridor Model area.

Variable	Maximum	Minimum	Mean
Water level, ft	794.0	763.4	777.1
Depth, ft	21.6	0.0	10.0
Velocity, ft/s	21.4	0.0	2.8
Unit discharge, ft^2/s	183.8	0.6	27.4

The water surface level fell 794.0 – 763.3 = 30.6 ft from Powers Butte to Gillespie Dam. In one spot the water was 21.6 ft deep and at another, the velocity was a maximum at 21.4 ft/s. The Seven-Mile Corridor Model gives a unit discharge of 164 ft^2/s at the dam arch where the breach occurred. The One-Mile Model discussed farther on gives a more refined estimate of this number.

Trees Model. In January 1981 trees were prolific along the channels of the Gila River near Gillespie Dam. The Trees Model is a representation of what could have happened if the trees were not cleared from the 1,000-foot wide corridor and from the areas of two fields on the west floodplain.

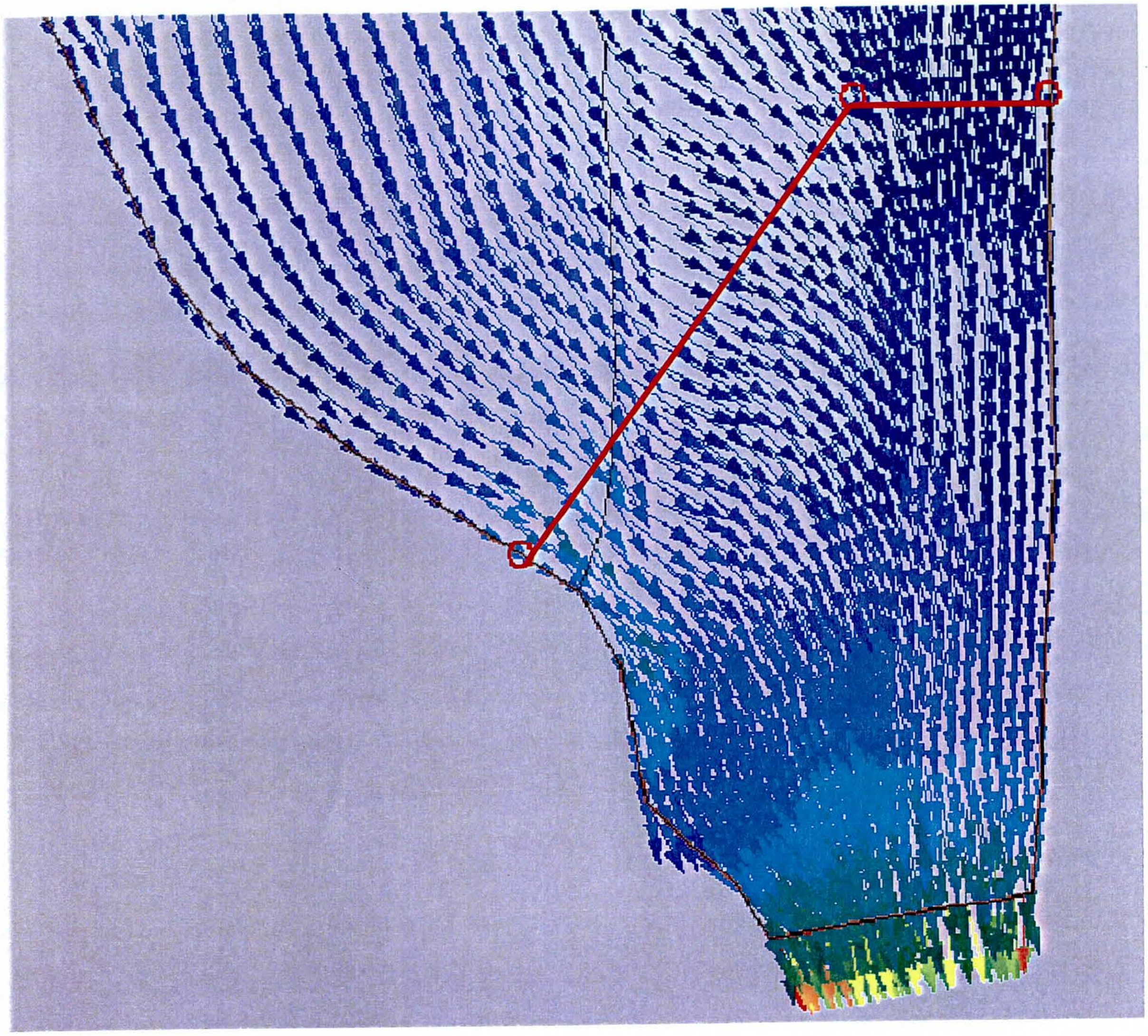

Figure 12-D. Trees Model velocity vectors in the last mile upstream from Gillespie Dam. The dark blue ones are the lowest speeds, and the red are the fastest. The red markers and lines define the upstream limit of the One-Mile Models.

The velocity vectors (Figure 12-D) are straight down the east side of the valley to the dam. The flow from the bare fields to the west into the trees has a strong component to the east and bends in with the current along the east valley wall. The model flow accelerates in the last mile and approaches the dam very uniformly.

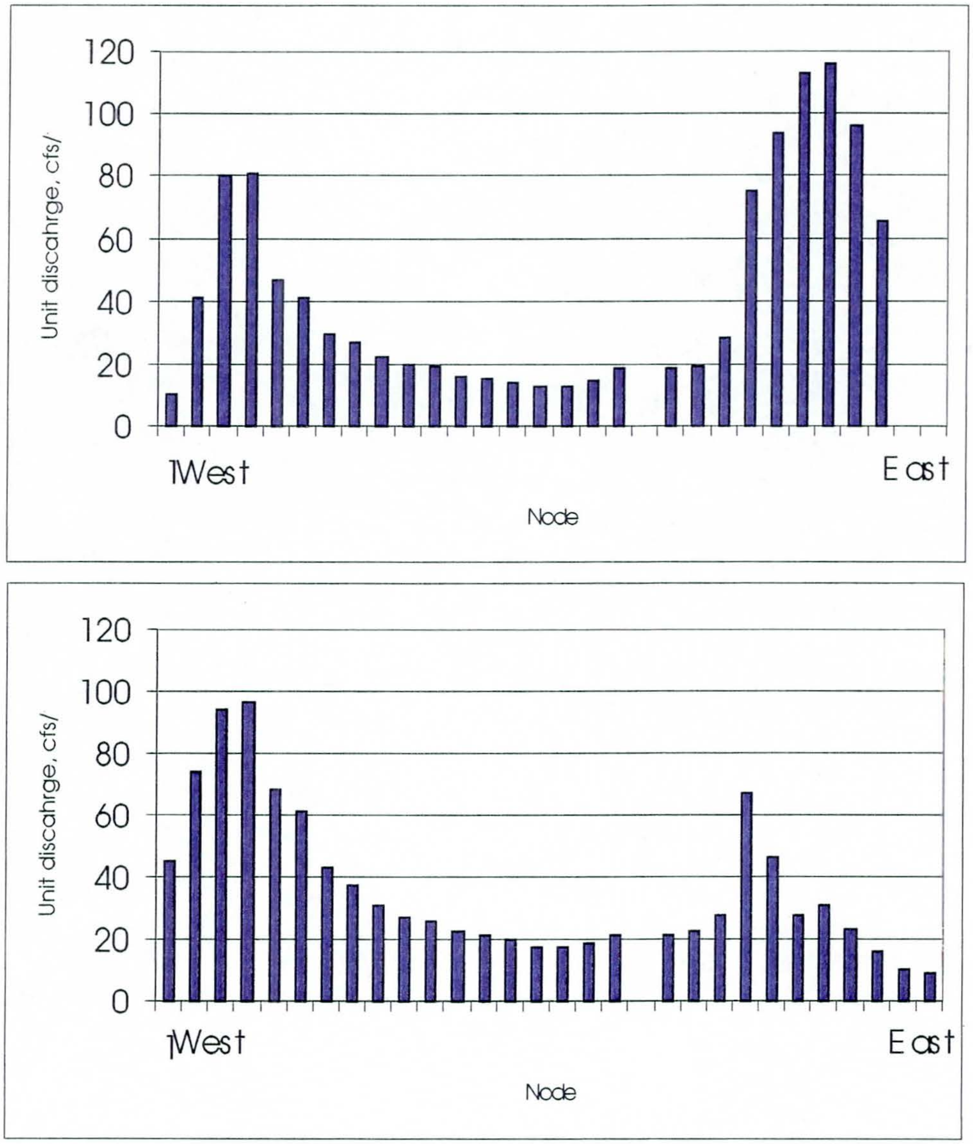

Figure 13-D. The two graphs are representations of unit discharges at the upstream limit of the One-Mile Models. The lower one is for all trees (Trees Model) and the top one is for the Corridor Model.

With all trees (lower graph), the unit discharge on the east is much lower than when the east side is cleared for the 1,000-foot wide corridor (upper graph). Trees force more water to the west and the corridor collects and conveys more water on the east.

Table 2-D. Summary of information for the entire Seven-Mile Trees Model area.

Variable	Maximum	Minimum	Mean
Water level, ft	797.3	764.2	782.7
Depth, ft	28.8	4.7	15.5
Velocity, ft/s	15.6	0.2	1.9
Unit discharge, ft^2/s	166.6	2.0	27.4

Information on variables for the Trees Model (Table 2-D) is much different than for the Corridor Model. The water levels are everywhere higher; the maximum at Powers Butte being 797.4 – 794.0 = 3.4 ft higher; and the mean 782.7 – 777.1 = 5.6 ft higher. The velocities in the trees are also much less the mean being 1.9/2.8 = 0.67 or two-thirds what it was for the Corridor Model.

The completely uniform unit discharge over the dam is 178,000/1,657 = 107 ft^2/s. With trees, the flow approaches the dam almost uniformly, being 96 ft^2/s at the breach point, and only about 10 percent from entirely uniform.

Bare Model. With all the trees taken out of the seven miles of valley from Powers Butte to the Dam, the flood waters can course with only topographic impediment to the dam. As a result the flow at the dam is more uniform than for any other situation. Still one mile upstream, there is more water on the west of the valley than on the east (Figure 14-D).

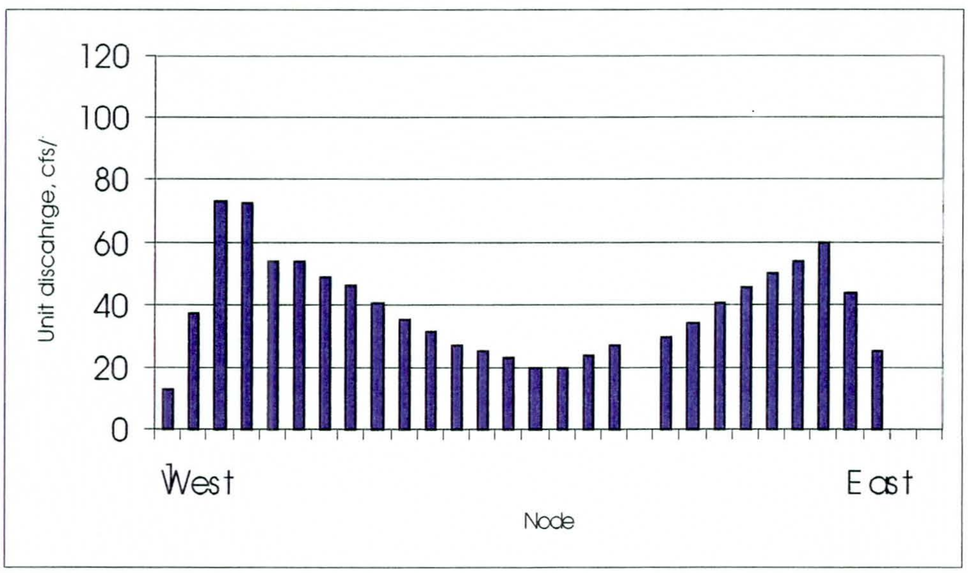

Figure 14-D. The Bare Model unit discharges at nodes across the upstream boundaries of the One-Mile Model. The break is the corner between the northwest and north boundaries.

Table 3-D. Summary of information for the entire Seven-Mile Bare Model area.

Variable	Maximum	Minimum	Mean
Water level, ft	763.37	791.89	776.74
Depth, ft	20.57	0.0	9.6
Velocity, ft/s	15.3	0.0	2.7
Unit discharge, ft^2/s	133.9	0.0	27.7

The intention was to use a Manning's roughness coefficient of 0.028 for all of the Bare Model, the same value as for the other models. This however results in lowering the water level near Powers Butte to the point were the mathematical model failed to run. In reality, if all the trees were cleared a flood would erode and change the topography of the valley until the waters established a new configuration of channels and floodplain that was more stable. For the purpose of this Seven-Mile Model, the roughness was increased everywhere to 0.056.

Because of the change in roughness, the information in Table 3-D is not directly comparable with that of other models.

1980 Model. The 1980 model configuration forces most of the flood water to the west, in agreement with the 15 February 1980 aerial photograph. The unit discharges for the upstream boundary of the One-Mile Model (Figure 15-D) indicates that clearly. The distribution is somewhat similar to that with no trees (Figure 14-D).

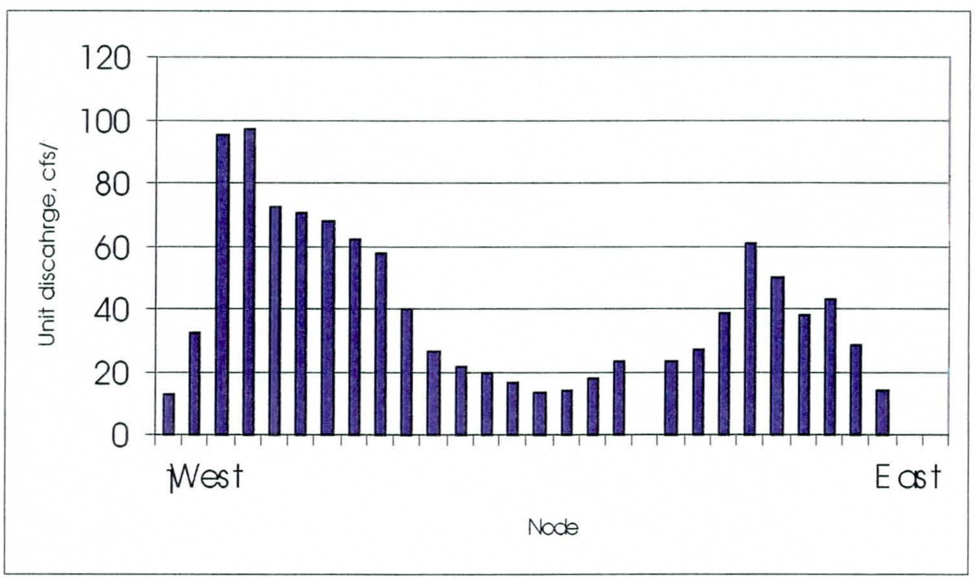

Figure 15-D. The 1980 Model unit discharges at nodes across the upstream boundaries of the One-Mile Model. The break is the corner between the northwest and north boundaries.

Table 4-D. Summary of information for the entire Seven-Mile 1980 Model area.

Variable	Maximum	Minimum	Mean
Water level, ft	795.2	763.4	775.33
Depth, ft	21.8	0.0	8.6
Velocity, ft/s	16.9	0.0	3.3
Unit discharge, ft^2/s	159.8	0.0	28.0

In information on variables (Table 4-D) indicates that overall, the water level, averaged over the entire area, in 1993 was higher than in 1980 due the strong growth of trees along the west side of the river. In this area, the trees were given a Manning's roughness coefficient of 0.08 in 1980 and 0.17 in 1993. For the same reason, the velocity is lower for 1993 than for 1980.

APPENDIX E - ROUGHNESS

Trees retard the velocity of the floodwater whereas channels and bare floodplain (farmers' fields and the like) allow its fast passage. In engineering, Manning's roughness coefficient is used to describe the retarding effect of all kinds of channels and floodplains. When the Manning's roughness coefficient n is large, the flow is slow and deep; where it is small the flow is fast and shallower.

Thomsen and Hjalmarson (1991) estimated Manning's roughness coefficients for the Flood Control District of Maricopa County in the spring and summer of 1989. In addition to many other places in the County, they estimated the roughness in the Gila River 500 feet upstream from the Gillespie Dam. From their Figure 6 (p.25). The following Manning's roughnesses were selected for use in this study.

Surface	Manning's n
Channel	0.025
Bare floodplain	0.028
Sparse trees	0.060
Light trees	0.080
Heavy trees	0.170

The 1993 flood occurred in January, the time of year when the vegetation is dormant. Burkham (1976) determined change of 0.008 in Manning's n between dormant and full foliage Gila River vegetation at the downstream end of Safford Valley. Full-foliage roughness is 0.008 larger. The value of 0.17 includes this effect.

The FCD (1885) used a Manning's n of 0.028 in the design of the Pilot Channel which is approximately 100 ft wide.

For a narrow channel with vegetated banks, larger roughness is in order. Using the Soil Conservation Service's guide, these were selected.

Width of Channel feet	Manning's n
20	0.050
40	0.038
60	0.032
80	0.027
100	0.025

The pre-failure 1992 Baker HEC-2 data set (in Loomis 1997) uses Manning's n of 0.15 for heavily vegetated areas upstream from the Gillespie Dam. Loomis (1997) decreased this to 0.04 and 0.08 for his report to Helm and Kyle. Both Baker and Loomis were employing one-dimensional modeling. We interpret that the Loomis values were global roughness, combining the effects of bare ground roughness with that of treed floodplain roughness.

The roughness used for FEMA regulatory flood studies in Maricopa County do not use the high values reported by Thomsen and Hjalmarson (1991). Instead, for the Gila River they use

Area	Manning's n
Channel	0.030 – 0.120
Floodplain	0.035 – 0.100

There is a wide range in the estimates of roughness employed for the Gila River channel and its floodplain. Those selected for this study are in accordance with the most authoritative work on the river and are in line with that determined elsewhere by the USGS (Arcement and Schneider 1989).

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Arcement, G.J., and Schneider, V.R., 1989. *Guide for selecting Manning's roughness coeficients for natural channels and flood plains.* U.S. Geological Survey Water-Supply Paper 2339, Washington, DC, 38 pp.

Burkham, D.E., 1976. *Hydraulic effects of changes in the bottom-land vegetation on three major floods, Gila River in southeastern Arizona.* U.S. Geological Survey Professional Paper 655-7, Washington, DC, 14 pp.

Cella Barr Associates, 1994. *HEC-2 Water Surface Profiles Run Date 5 May 1991, 11:30.* Phoenix, Az.

FEMA, 1995. *Flood insurance study, Maricopa County, Arizona and Incorporated areas.* Volume 1 of 12, Revised: September 30.

Loomis, T.R., 1997. *Hydraulics and flooding analysis of the 1993 flood on the gila river in regard to the breach of the Gillespie Dam.* Report prepared for Helm & Kyle, Ltd, Attorneys at Law, January.

Soil Conservation Service, 1963. *Guide for selecting roughness coefficient "n" values for channels.* Compiled by G.B. Fasken, U.S. Department of Agriculture, Lincoln, NE, December.

Thomsen, B.W. and Hjalmarson, H.W., 1991. *Estimated Manning's roughness coefficients for stream channels and flood plains in Maricopa County, Arizona.* Prepared by the U.S. Geological Survey for the Flood Control District of Maricopa County, April, 125 pp.

APPENDIX F – BRINK DEPTH

As the stream of water approaches, it senses the presence of the dam through its pressure field. Whereas, back from the dam, the flow is hydrostatic, the pressure on the ground being the weight of water above the ground, it is much less on the crest of the dam. This lower pressure at the crest means that the flow accelerates towards the dam before falling over the crest. The flow is three-dimensional and the pressure is decidedly non-hydrostatic. The depth at the lip of the dam is called the brink depth.

One-Dimensional Flow. In one-dimensional models the adjustment for three-dimensional effects is done in two ways.

1. Through an experimentally determine coefficient. The expression is

$$Q = CLH^{3/2}$$

and

$$H = y + \frac{V^2}{2g}$$

The meaning of the symbols is as follows:

Q = total discharge over the dam;

C = coefficient of discharge, experimentally determined;

L = length of the dam crest;

H = total head on the dam, referenced to the dam crest level;

y = depth of water referenced to the dam crest level; and

V = average approach velocity;

g = acceleration due to gravity.

For average conditions of the flood peak approaching Gillespie Dam, we have:

Q = 178,000 ft^3/s

C = 3.0 (US Bureau of Reclamation 1987, p.370 and Smith 1985, p.67)

L = 1,657 ft

Then by the equations above

H = 10.87 ft.

It follows that

y = 8.2 ft and

$V = 13.0$ ft/s

2. Through application of Newton's Second Law in one dimension. The flow must reach the minimum specific force, just before it reaches the dam. If it is assumed that the pressure at minimum force is hydrostatic, this flow has the critical depth, which is

$$y_c = \left[\frac{q^2}{g}\right]^{1/3}$$

Here q = discharge per unit length of dam = 178,000/1,657 = 107 ft^2/s. It follows that the critical depth is 7.1 ft.

Rating Curve. The US Geological Survey had maintained a water-level recorder on the abutment of the sluices for the Gila Bend Canal. The gage is visible in the photograph Figure 2-1 (Loomis 1997). The water level at this gage is related to the discharge by a rating curve given as Figure A-1 (ibid. p.A11). For a flow of 178,000 ft^3/s, the rating curve places the water level 8.7 feet ove the crest of the dam.

Two-Dimensional Flow. In the RMA2 model, it is assumed that the flow is hydrostatic everywhere, including the approach to the dam. The flow at one point on the crest can be influenced by what is going on at another. It is not necessary that the water level be horizontal across the length of the crest. Yet, the flow approaches the dam nearly perpendicular to the crest axis.

Since two-dimensional flow is somewhere in the mathematical region between one-and three-dimensions, and we have no estimate of three-dimension flow at the dam, it seems prudent to select an unbiased water level at the dam. The most unbiased is the mean.

The mean of three water depths values determined above is (7.1 + 8.2 + 8.7)/3 = 8.0 ft. Then the water level above the crest of the dam was 8.0 + 755.3 = 763.3 ft for the peak of the flood. This is the value used in the Seven-Mile and One-Mile two-dimensional models.

APPENDIX G – ONE-MILE MODELS

Upstream Boundary

The upstream boundary of the One-Mile Model (Figure 1-G) consists of a north section, located across the 1,000-foot wide corridor, and a northwest section. Each is approximately normal to the velocity vectors of the flow crossing it. The northwest boundary is again divided into a lower and an upper part. For each One-Mile Model there are three flows assigned to the upstream boundary (Table 1-G). These are in accordance with the results of the Seven-Mile Models.

Table 1-G. Upstream boundary flows for a flood peak of 178,000 ft^3/s. Units are ft^3/s.

	Northwest Boundary		
Model	Lower	Upper	**North Boundary**
1993 Corridor	55,500	46,400	76,100
Trees	87,300	56,300	34,400
Bare	61,400	73,600	43,000
1980	104,600	35,400	38,000
1981	87,300	56,300	34,400

The RMA2 model distributes the boundary discharge 50 percent according to depth and 50 percent uniformly along the boundary. If this approximation is in error, the model, through iteration, redistributes the flow to the correct amounts in a very short distance downstream. It is necessary only that the boundary distribution of flow be approximately correct.

The distances along the upstream boundary are the same for all One-Mile Models (Table 2-G) except for the 1980 Model.

Table 2-G. Upstream boundary distances (see Figure 1-G). Units are ft.

	Northwest Boundary		North Boundary
Model	**Lower (A to B)**	**Upper (B to C)**	**(C to D)**
1993 Corridor	1,080	2,300	1,000
Trees	1,080	2,300	1,000
Bare	1,080	2,300	1,000
1980	1,690	1,690	1,000
1981	1,080	2,300	1,000

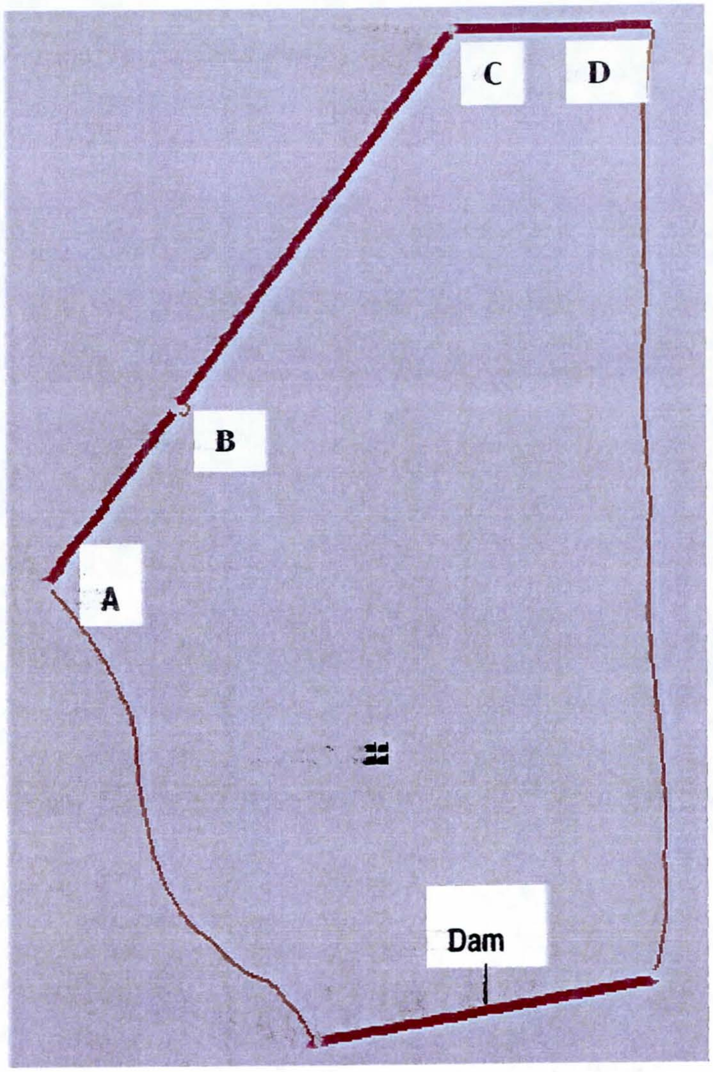


Figure 1-G. The upstream boundary has a north section (C to D) and a northwest section (A to C) which is divided into a lower part (A to B) and an upper part (B to C).

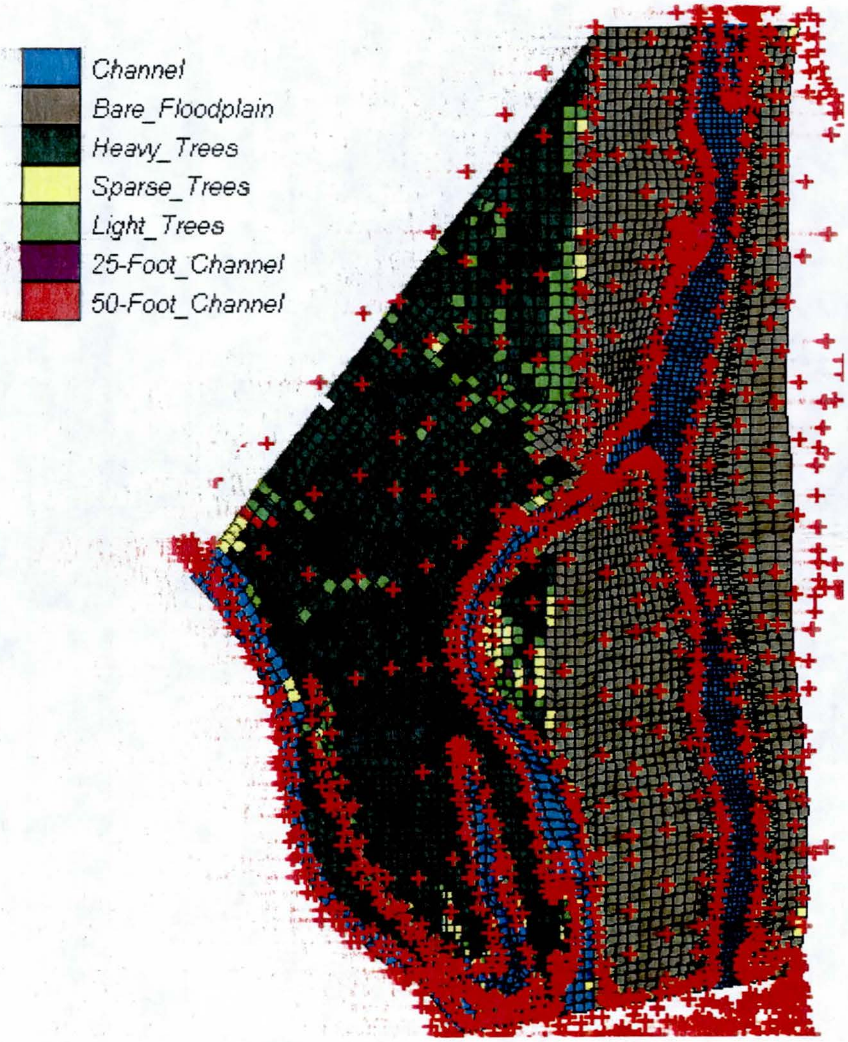


Figure 2-G. Map showing the location of digital terrain mapping points (red plus marks) along with materials coverage for the 1993 Model.

DTM Points

Figure 2-G shows the locations of the digital terrain mapping points (DTM) used to develop the topography for the elements. The DTM points tend to cluster at the edges of water existing at the time of the photograph. In dry areas away from the water, the density of mapping points is less.

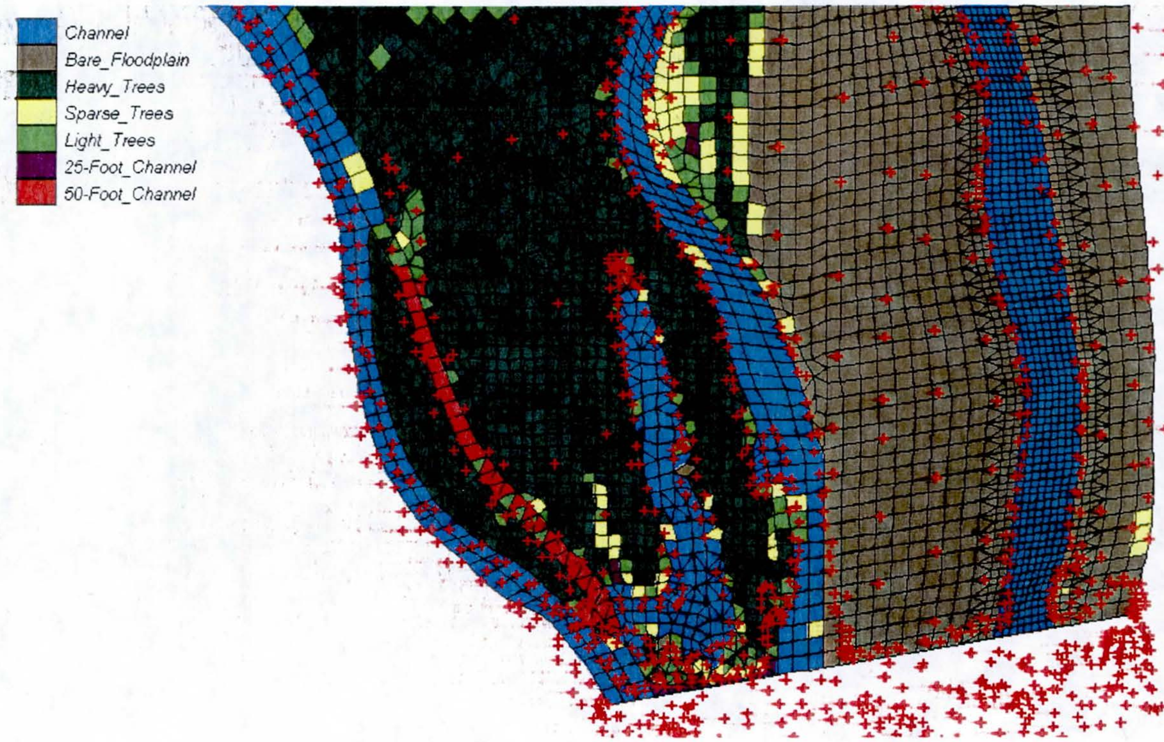


Figure 3-G. Map showing the location of digital terrain mapping points (red plus marks) along with materials coverage for the lower portion of the 1993 Model.

Figure 3-G shows more clearly that DTM points were taken along the edge of areas covered with water, with no points taken in the water. This is because ground elevations could not be determined under the water surface. Because the model topography was developed directly from the DTM points, it means that the modeled channels do not have the actual depth they had in the field. The channels assume a bottom elevation about equal to the measured ground elevation at the sides of the channel. Where the channels are deeper, they carry more flow and have higher unit discharges. Not only were pre-flood channels deeper than indicated by pre-flood DTM points, one of the purposes of the cleared corridor was to promote channel scour during higher flows (FCD 1993), which would make channel areas even deeper compared to vegetated areas. Therefore, models that use the DTM data without adjustment for depth of the channels underestimate the flow and unit discharge in the channels. The One-Mile Models all use unadjusted channel depths and underestimate flow concentration in the channels.

Mesh

The blue (channel) elements in the vicinity of the breach at the dam are 25 feet wide, the brown floodplain elements are about 50 feet wide. The model was developed primarily with rectangular elements that are 50 feet on a side. In the channel area upstream from the dam, rectangular elements that are 25 feet on a side were used. The smaller elements were used to provide additional detail in the critical area of the breach, and to provide the capability to have a long 25-foot wide channel in the 1981 Model.

In the 1980, 1981, and 1993 models, the material coverages were mapped to the mesh elements based on the available photographs. One exception was the upstream end of the 25-foot channel in the 1981 Model, which was placed in the center of the 1993 channel to be at the lowest local elevation and to maintain continuity of the channel down the mesh column.

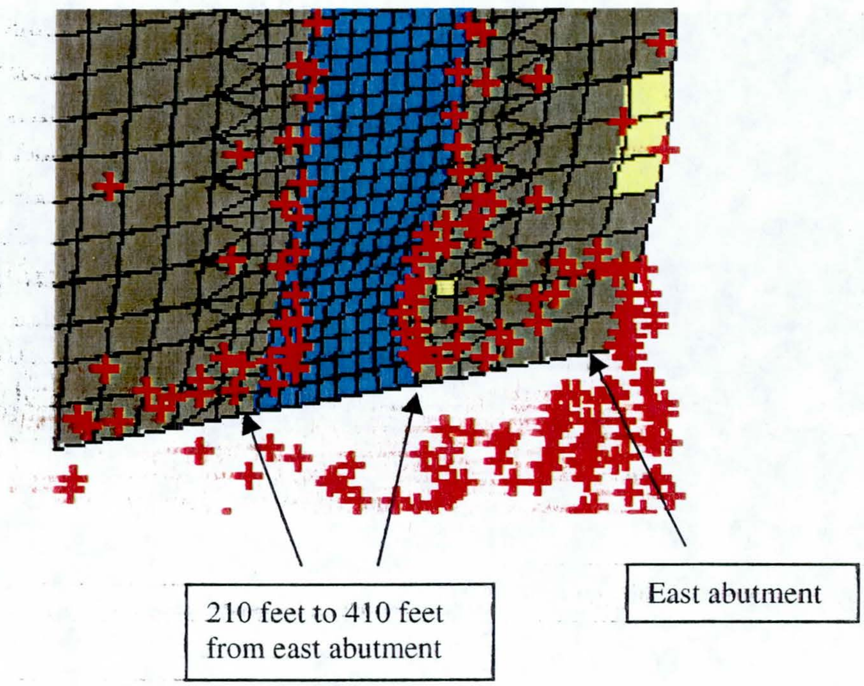


Figure 4-G. The location of the east channel in the 1993 Model.

Breach Location

The most probable location of initial failure was previously identified as Arch 12, which is 230 feet to 251 feet from the east abutment. The left (west) side of the first blue element on the right (east) side of the channel is 235 feet from the east abutment. This point is 275 from the east boundary of the model, including about 40 feet for the sluiceway. The area modeled as the east channel in the 1993 model spanned from 210 feet to 410 feet from the east abutment. The final breach spanned from 223 feet to 429 feet from the east abutment. The distances from each arch to the abutments are detailed in Table 3-G. Figure 4-G provides another indication of the location of the breach in relation to the channel and tree coverage. Figure 4-G is based on mapping by Aero-Graphics using a photograph date of September 9, 1991. At its narrowest point, the low-flow channel upstream of the dam in Figure 4-G is about 100-feet wide, centered about 250 feet from the east abutment (1,400 feet from the west abutment).

Table 3-G. Distances (feet) from Arches to Abutments.

Full Arch Number	Dist. from east side of arch to east abutment	Dist. from west side of arch to east abutment	Dist. from center of arch to east abutment	Dist. from east side of arch to west abutment	Dist. from west side of arch to west abutment	Dist. from center of arch to west abutment
1	0	20	9.5	1657	1637	1647.5
2	20	41	30.5	1637	1616	1626.5
3	41	62	51.5	1616	1595	1605.5
4	62	83	72.5	1595	1574	1584.5
5	83	104	93.5	1574	1553	1563.5
6	104	125	114.5	1553	1532	1542.5
7	125	146	135.5	1532	1511	1521.5
8	146	167	156.5	1511	1490	1500.5
9	167	188	177.5	1490	1469	1479.5
10	188	209	198.5	1469	1448	1458.5
11	209	230	219.5	1448	1427	1437.5
12	230	251	240.5	1427	1406	1416.5
13	251	272	261.5	1406	1385	1395.5
14	272	293	282.5	1385	1364	1374.5
15	293	314	303.5	1364	1343	1353.5
16	314	335	324.5	1343	1322	1332.5
17	335	356	345.5	1322	1301	1311.5
18	356	377	366.5	1301	1280	1290.5
19	377	398	387.5	1280	1259	1269.5
20	398	419	408.5	1259	1238	1248.5
21	419	440	429.5	1238	1217	1227.5
22	440	461	450.5	1217	1196	1206.5
23	461	482	471.5	1196	1175	1185.5
24	482	503	492.5	1175	1154	1164.5
25	503	524	513.5	1154	1133	1143.5
26	524	545	534.5	1133	1112	1122.5
27	545	566	555.5	1112	1091	1101.5
28	566	587	576.5	1091	1070	1080.5
29	587	608	597.5	1070	1049	1059.5
30	608	629	618.5	1049	1028	1038.5
31	629	650	639.5	1028	1007	1017.5
32	650	671	660.5	1007	986	996.5
33	671	692	681.5	986	965	975.5
34	692	713	702.5	965	944	954.5
35	713	734	723.5	944	923	933.5
36	734	755	744.5	923	902	912.5
37	755	776	765.5	902	881	891.5
38	776	797	786.5	881	860	870.5
39	797	818	807.5	860	839	849.5
40	818	839	828.5	839	818	828.5
41	839	860	849.5	818	797	807.5
42	860	881	870.5	797	776	786.5
43	881	902	891.5	776	755	765.5
44	902	923	912.5	755	734	744.5
45	923	944	933.5	734	713	723.5
46	944	965	954.5	713	692	702.5
47	965	986	975.5	692	671	681.5
48	986	1007	996.5	671	650	660.5
49	1007	1028	1017.5	650	629	639.5
50	1028	1049	1038.5	629	608	618.5
51	1049	1070	1059.5	608	587	597.5
52	1070	1091	1080.5	587	566	576.5
53	1091	1112	1101.5	566	545	555.5
54	1112	1133	1122.5	545	524	534.5
55	1133	1154	1143.5	524	503	513.5
56	1154	1175	1164.5	503	482	492.5
57	1175	1196	1185.5	482	461	471.5
58	1196	1217	1206.5	461	440	450.5
59	1217	1238	1227.5	440	419	429.5
60	1238	1259	1248.5	419	398	408.5
61	1259	1280	1269.5	398	377	387.5
62	1280	1301	1290.5	377	356	366.5
63	1301	1322	1311.5	356	335	345.5
64	1322	1343	1332.5	335	314	324.5
65	1343	1364	1353.5	314	293	303.5
66	1364	1385	1374.5	293	272	282.5
67	1385	1406	1395.5	272	251	261.5
68	1406	1427	1416.5	251	230	240.5
69	1427	1448	1437.5	230	209	219.5
70	1448	1469	1458.5	209	188	198.5
71	1469	1490	1479.5	188	167	177.5
72	1490	1511	1500.5	167	146	156.5
73	1511	1532	1521.5	146	125	135.5
74	1532	1553	1542.5	125	104	114.5
75	1553	1574	1563.5	104	83	93.5
76	1574	1595	1584.5	83	62	72.5
77	1595	1616	1605.5	62	41	51.5
78	1616	1637	1626.5	41	20	30.5
79	1637	1657	1647.5	20	0	9.5

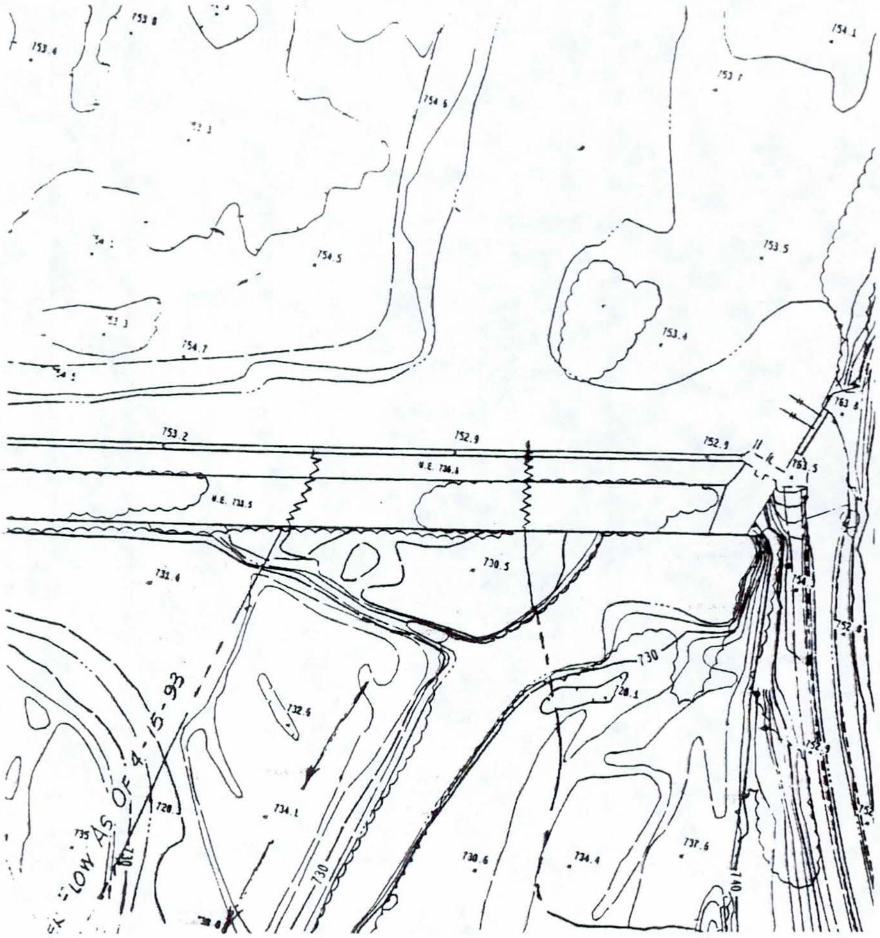


Figure 4-G. Drawing depicting Gillespie Dam with approximate breach location, pre-breach channels and trees.

Model Results

Model results for the full area covered in the One Mile Models is presented graphically as follows:

- Figure 5-G – Corridor (1993) Model
- Figure 6-G – 1980 Model
- Figure 7-G – 1981 Model
- Figure 8-G – All Trees Model
- Figure 9-G – All Bare Model

The graphical presentation for each modeled condition includes a photograph (if available) with boundary conditions, material coverage, flow velocity contours and direction, and unit discharge. The unit discharge is of particular importance, because it shows how flow is focused by the various material coverages, with shades of red indicating the most focused flow.

The 1993 model clearly indicates focused flow in the area that would be breached. The area of peak unit discharge is 235 feet to 272 feet from the east abutment, which encompasses Arch 12, Arch 13, and most of Arch 11.

A series of photographs, each a taken a few seconds apart, are available for the January 9, 1993 flood. Some discrete foam clumps, which are moving toward the dam with the flow, can be identified in more than one photograph. By measuring the distance between dam and the discrete foam clumps in each photograph and knowing the time difference between photographs, a flow velocity (feet per second) can be estimated. In the area upstream of the part of the dam that was breached, the photograph-measured velocity of four foam clumps averaged 12.7 ft/s with a range from 12.0 ft/s to 13.6 ft/s. The modeled velocities at the same points averaged 12.2 ft/s with a range from 11.3 to 12.8 ft/s. The highest velocity in both the photograph and model was nearest to the arch that initially failed. This close agreement between measured and modeled flow velocities in the breach vicinity provides one validation of the mathematical model.

The 1980 model indicates a focused flow near the center of the dam, which corresponds well with the 1980 photograph. The area of peak unit discharge is 885 feet to 935 feet from the east abutment, which includes all or part of Arch 43, Arch 44, and Arch 45. The magnitude of the peak unit discharge in the vicinity of Arch 43-45 in the 1980 Model is nearly the same as the peak unit discharge in the vicinity of Arch 11-13 in the 1993 Model.

The 1981 model shows a primary focused flow near the center of the dam at the same location as in the 1980 Model. To a lesser extent, flow is concentrated at the dam downstream of several other areas having relatively few trees.

With the uniform materials coverage provided by the Trees Model and the Bare Model, flow is distributed more uniformly at the dam. The minor non-uniformity of unit discharge at the dam is caused by upstream topography and by the narrowing of the floodplain at the dam.

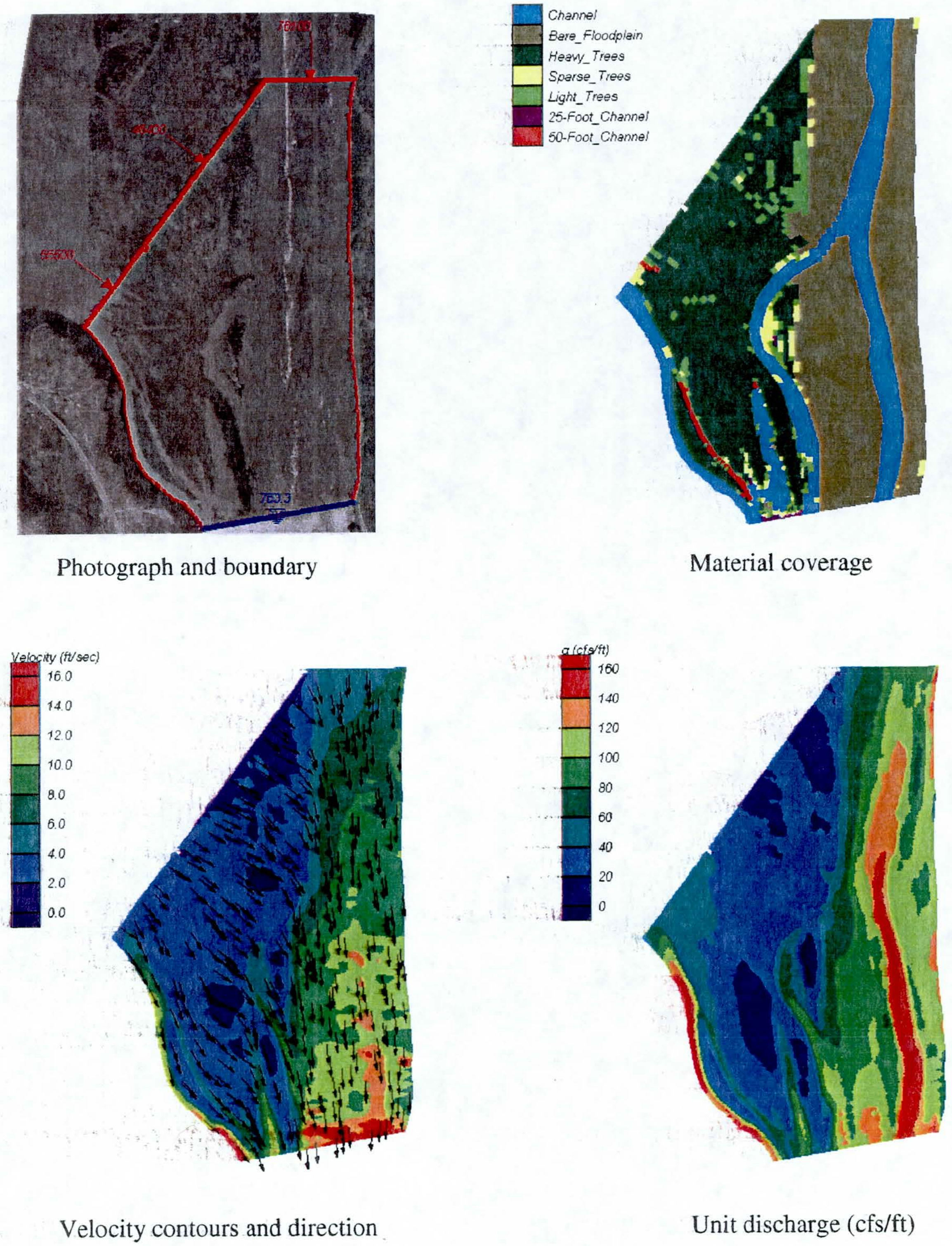
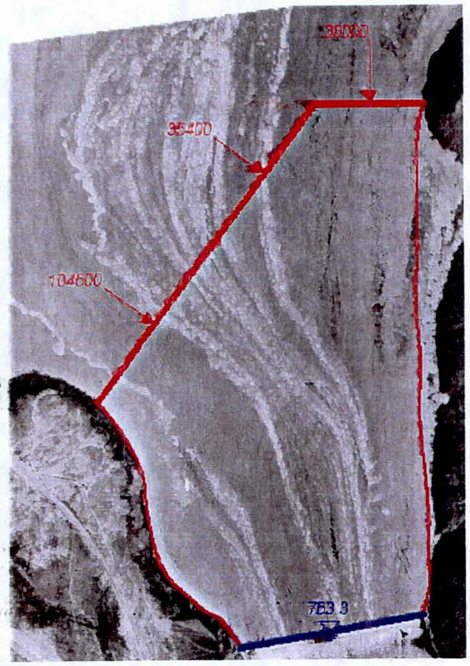
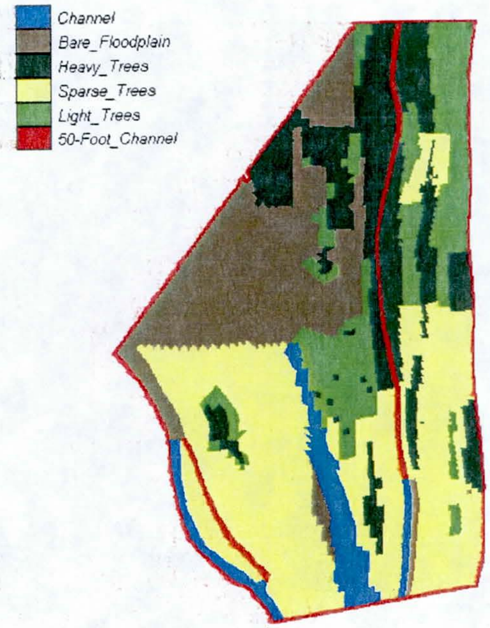


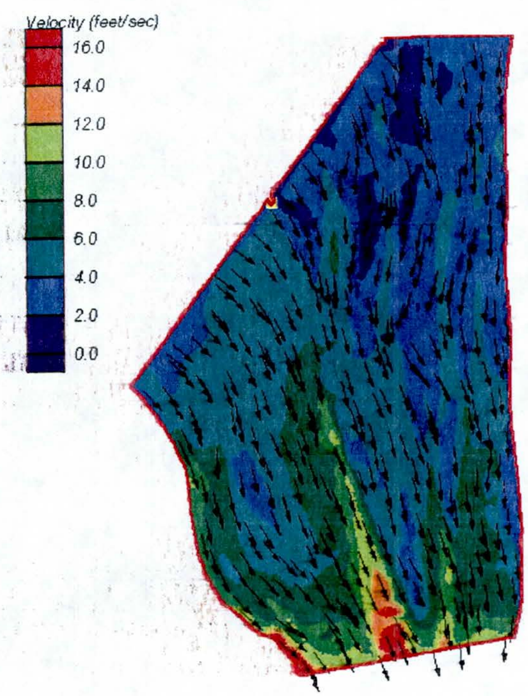
Figure 5-G. Corridor (1993) Model.



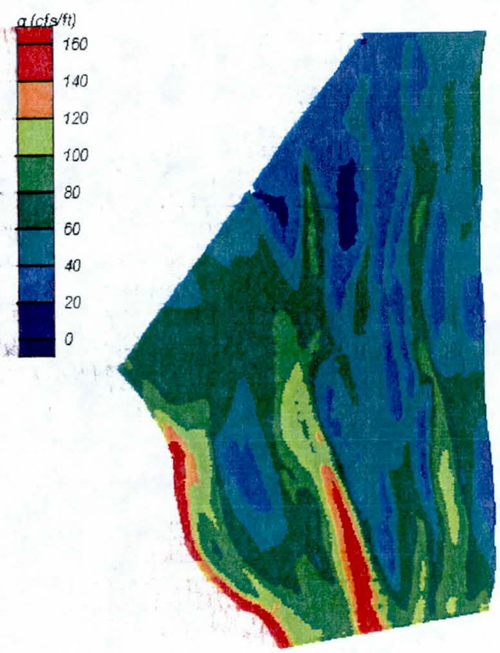
Boundary conditions and photograph



Material coverage

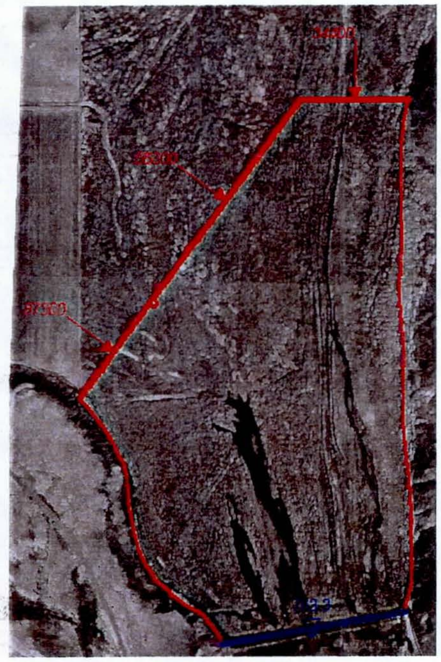


Velocity contours and direction

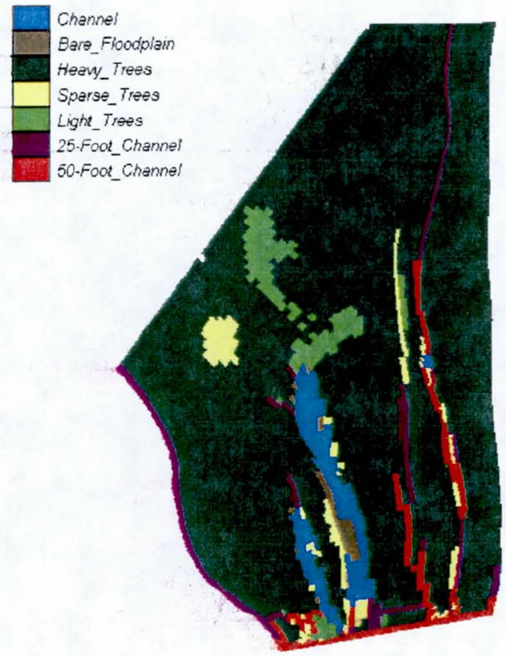


Unit discharge (cfs/ft)

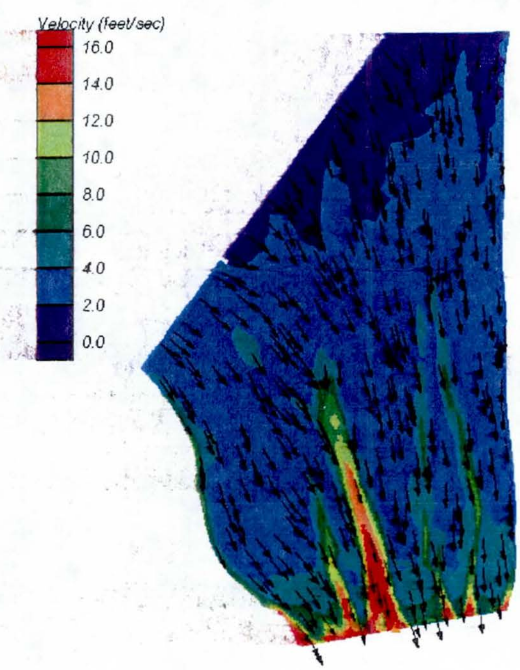
Figure 6-G. 1980 Model.



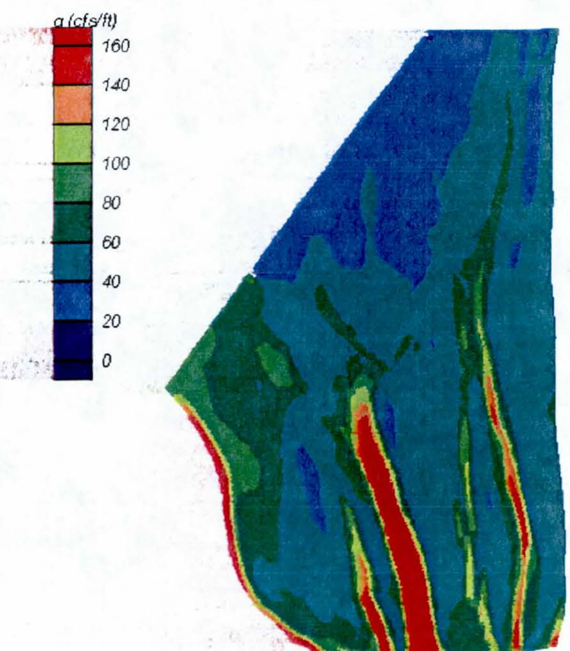
Boundary conditions and photograph



Material coverage



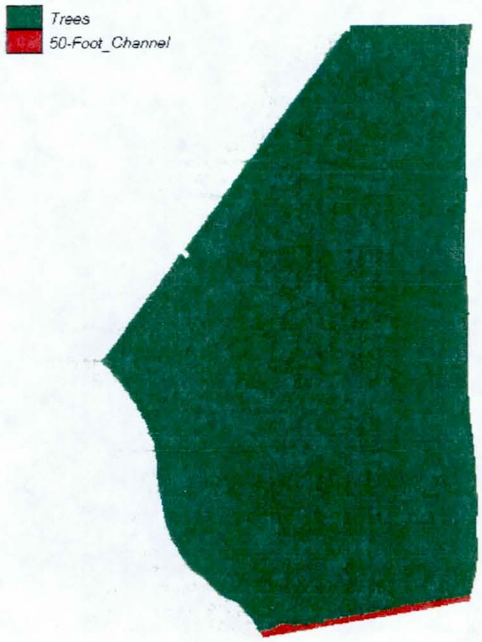
Velocity contours and direction



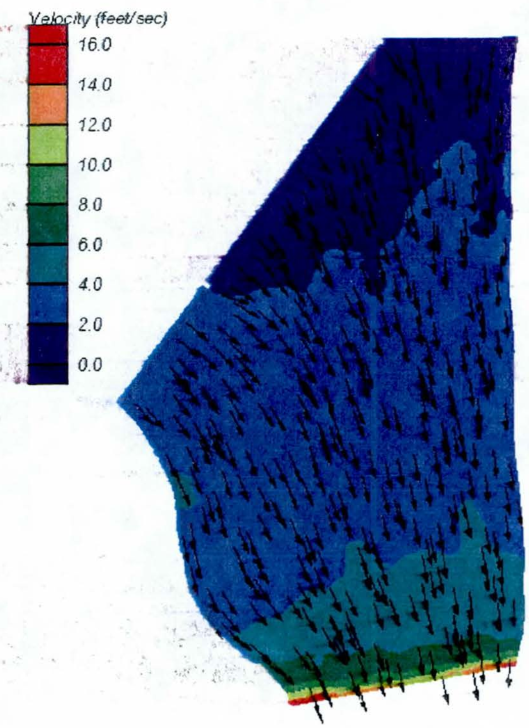
Unit discharge (cfs/ft)

Figure 7-G. 1981 Model.

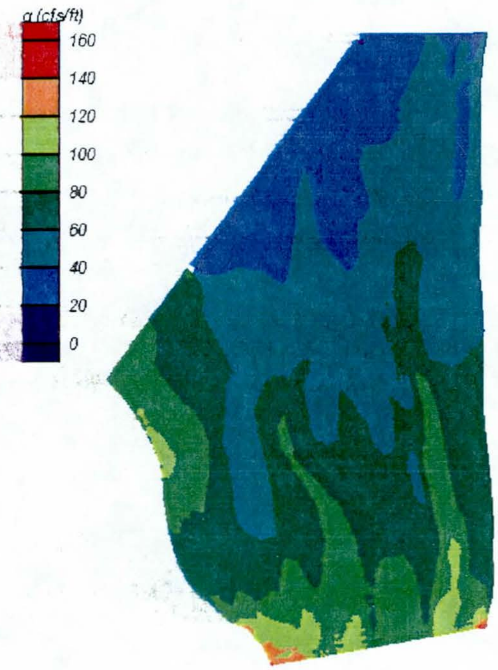
Boundary conditions



Material coverage

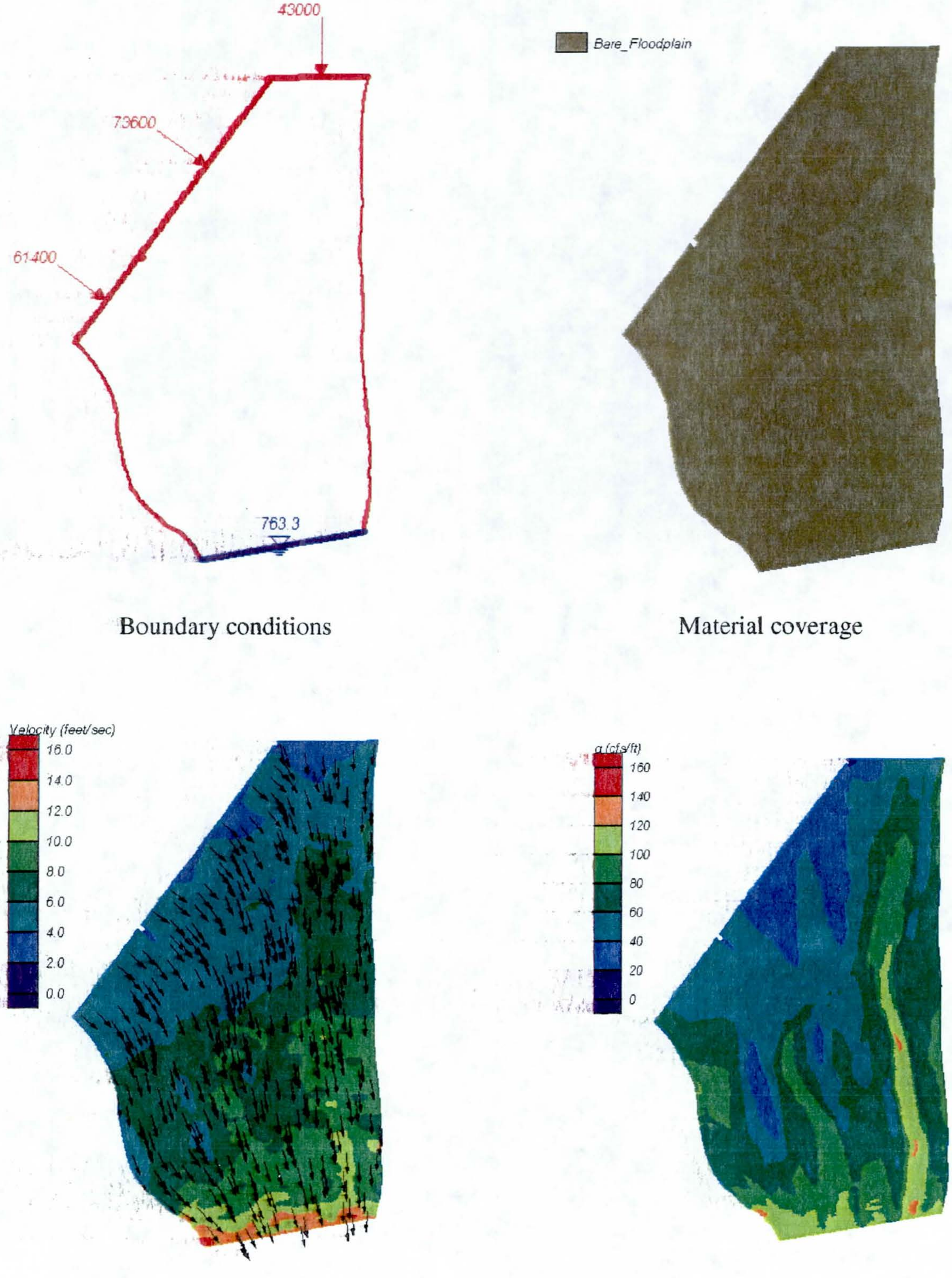


Velocity contours and direction



Unit discharge (cfs/ft)

Figure 8-G. Trees Model.



Boundary conditions

Material coverage

Velocity contours and direction

Unit discharge (cfs/ft)

Figure 9-G. Bare Model.