

**HIGH ELEVATION SAND DEPOSITION AND RETENTION
FROM THE 1996 SPIKE FLOW: AN ASSESSMENT FOR
CULTURAL RESOURCES STABILIZATION
FINAL REPORT**

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December 1996

Abstract

In the spring of 1996, the Bureau of Reclamation conducted a historic event: an experimental manmade flood event was released from Glen Canyon Dam through Glen and Grand Canyons. This high flow experiment was conducted in order to test a number of hypotheses relating to the long term management of natural and cultural resources along the Colorado River. As part of this research, the Hopi Tribe examined the effectiveness of the high flow to elevate sediment into the mouths of four ephemeral arroyos that drain the margin deposits along the River. These types of arroyos have been identified as one of the contributing sources to the erosion of cultural resources along the Colorado River. At three out of the four study locations, the Palisades site, and the Furnace Flats #2 and #1 sites, sediments were in fact deposited in the mouths of the arroyos. While the fourth site, the Lee's Ferry site, received no deposition, it even more significantly did not experience erosion which potentially could exacerbate arroyo downcutting.

Preliminary Observations:

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The following provides a preliminary look at some of the results of the 1996 High Flow Experiment (HFE) based on the research conducted by the Hopi Tribe. This research seeks to identify the effectiveness of occasional, scheduled, high flows to deposit sand in the mouths of the ephemeral arroyos that cut through the margin deposits. The formation and expansion of these arroyos has been identified as one of the major sources of erosion to cultural resource sites along the Colorado River corridor. The postulated benefit of occasional high flows is to mimic, to a degree, the pre-Glen Canyon Dam spring flows that would overtop the margin deposits and fill the ephemeral arroyos with new sediment deposits. The infusion of new sediments will essentially reset the erosion processes along the channel margins, thereby limiting erosional impacts to the cultural resource sites contained within the margin deposits. Since the dam has been in place, the nearly annual deposition of new sediments has not occurred resulting in a sediment deficit throughout the river corridor in Grand Canyon. This has allowed the development of the ephemeral arroyos to continue unabated to the point where they are now threatening the cultural resource sites located in the margin deposits. Occasional high flows are seen as a potential Canyon-wide method of redistributing the existing sediment resources into locations more suitable for resource protection.

The results that follow are preliminary; they are primarily qualitative in nature based on direct observations preceding and following the HFE. Once the data are fully analyzed, quantitative results will refine our understanding of the actual magnitude of change seen at the study sites.

Methodology

The original Hopi proposal identified 7 study locations, within established GIS reaches, as potentially being appropriate for addressing the research goals; these were located at river miles -4, -0.5, 65.5, 70.7, 71.3, 207, and 209. During the course of the pre-flow work, a number of these sites were rejected as not being suitable for addressing the research questions. Specifically, arroyo mouths were either well above the level of the river, or, they had cut through sediment deposit that would not be overtopped at the level of the high flow. The final selected sites consisted of arroyos at river miles -0.5, 65.5 (two arroyos), 71.2, and 71.3.

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Introduction

In the spring of 1996, the Bureau of Reclamation conducted a historic event: an experimental manmade flood event was released from Glen Canyon Dam through Glen and Grand Canyons. This high flow experiment was conducted in order to test a number of hypotheses relating to the long term management of natural and cultural resources along the Colorado River. These hypotheses centered around the ability of planned high flows to redistribute sediment for such management purposes as maintaining beaches, maintaining or enhancing wildlife habitats, and stabilizing cultural resource locations. In order to ascertain the effectiveness of the high flow to achieve these management objectives, an intensive scientific effort surrounded the high flow experiment and as part of these studies, the Hopi Tribe conducted research aimed at identifying the effectiveness of the high flow to elevate sediment into the mouths of ephemeral arroyos that drain the margin deposits along the River. These arroyos have been identified as one of the contributing sources to the erosion of cultural resources along the Colorado River.

Background

Cultural Resources and the Habitat/Beach Building Flow

The high flow experiment provides a critical test of the assumption that occasional, planned high flows can be employed to redistribute sand stored in low elevation channel deposits to higher elevation margin deposits, above the high water stage of normal Glen Canyon Dam operations. This assumption, in part, is what drove the inclusion of the Beach/Habitat building flow in the preferred alternative of the Glen Canyon Dam Environmental Impact Statement (EIS). The value of these high elevation sand deposits ("beaches") is multiple, including providing camping and recreation opportunities, a foundation for the riparian zone, and perhaps a buffer against the erosion to the pre-dam terrace deposits that lie behind the beaches.

Many of the cultural resource sites rely on the stability of the pre-dam terrace deposits for their preservation; as these deposits erode, so too do the cultural sites contained within them. Now, the single most pervasive element threatening the preservation of cultural resources in the Colorado River corridor through the Grand Canyon is the lack of seasonal sediment re-deposition that regularly occurred prior to the completion of Glen Canyon Dam. Without replenishment of the sediments flanking the river, particularly at higher stages, there will inevitably be a continual erosion of many cultural resources located in the old river terraces. The EIS noted the problem in this way:

Archaeological sites once protected by sandbars and terraces have become increasingly exposed to erosion by the river and rainfall-induced terrace erosion. (Bureau of Reclamation 1995:263)

and:

Because the dam traps sediment and reduces floods, little or no sediment is deposited at the mouths of small ephemeral tributary streams, which makes the situation [terrace erosion] worse (Bureau of Reclamation 1995:263).

Altering the day-to-day operations of the dam may increase or decrease the rate of this erosion, but can not correct the root cause of the erosion. Site specific remedial efforts (such as check dams, etc.) that essentially mimic the effect of natural sediment deposition by artificially raising the base level can be undertaken, but these activities are labor intensive and not feasible on a Canyon-wide basis. Scheduled high flows, however, may be one of the few aspects of dam operation that could provide a direct, system-wide benefit for the preservation of cultural resources within the river corridor:

Adding sediment at the mouths of tributaries and creating sandbars at slightly higher elevations is a systemwide approach to rebuilding and stabilizing the high terraces upon which the sites depend. Although more research is needed on the success of these flows, creation of stable sandbars - even at lower levels - could result in a more stable situation for predam terraces (emphasis added, Bureau of Reclamation 1995:264).

Previous Research

Although erosion of cultural resource sites has been noted since closure of the dam, it was with the 1983-1985 flooding that the rate of erosion became substantial (Fairly et al. 1994:ix). With the instigation of Phase II of the Glen Canyon Environmental Studies, and the complete inventory of cultural resources in the Grand Canyon corridor, it became apparent the degree to which erosion had become pervasive at cultural resource sites throughout the canyon. Logic dictated that this rate of erosion must be a relatively new phenomenon, otherwise the sites would not have survived through the many hundreds, or even thousands of years previous. In order to examine causes for this recent episode of increased erosion, geomorphological studies were carried out in conjunction with some of the cultural resource work. What came out of that work (Hereford et al. 1993) was the realization that daily operations of the dam had relatively little direct effect on the erosion that was occurring at the sites and that the presence of the dam itself, and the concomitant loss of sediment in the system, was allowing natural erosive forces to proceed to a new equilibrium. Prior to the dam, high elevation sediment was regularly deposited during the high sediment-laden spring flows. The frequent replenishment of these deposits served to offset the erosive actions of rainfall occurring on the terraces, effectively maintaining a high base level for the ephemeral terrace drainages; they rarely cut to the mean level of the Colorado river (Hereford et al. 1993:44). Because of the mechanism for deposition of these high elevation sediment deposits ended with the construction of the dam, the effective base level that these ephemeral drainages are able to obtain has been lowered. In the process of cutting to this lower base level through deepening, lengthening, and expansion, these ephemeral drainages are exposing previously buried cultural deposits.

In addition to the geomorphological studies, research has also been conducted that examined the dynamics of the beach deposits, both the exposed and underwater portions, in relation to the river flows (Kaplinski et al. 1995). These studies have focused on the sand deposits within the hydrologically active zone that form in the major eddy complexes. While these deposits are some of the most important for creating aquatic habitat and for recreational uses, they are commonly not the deposits that may be important to preservation of cultural resource sites. Similarly, this study does not focus on the relation of these beach deposits to the predam terrace deposits behind them.

Though not a primary focus of either of these research efforts, both identified that high, post dam flows have the capacity to rebuild high elevation sediment deposits if there is enough sand in the system (Hereford et al. 1993:43, Kaplinski et al. 1995:54). This was the assumption made in the EIS:

that occasional high flows could redeposit high elevation sand deposits that were desired for multiple purposes. In particular, the EIS recognized that in the case of cultural resources, no normal operating flow regime could completely mitigate the changes to the system brought on by the construction of the dam (Bureau of Reclamation 1995:263). Instead, the common elements of reduced (natural) flood frequency and habitat/beach building flows were thought to provided the greatest potential for preserving the cultural deposits *in situ*. Essentially, if effective, the habitat/beach building flow would fill in the mouths of river-based arroyos, converting them temporarily back into terrace-based arroyos with the concomitant raising of the effective base level. At a higher base level, the downcutting of the arroyos into the predam terrace deposits should be reduced and the impacts to the cultural resources lessened. Because of the potential for obtaining a system-wide decrease in erosion rates at cultural resource sites, monitoring the effectiveness of the high flow experiment is of primary importance, both in the short and the long term. Should the high flow not be effective at filling the mouths of the ephemeral arroyos and achieving temporary elevation of arroyo base-level, then the ramification is that the habitat/beach building flow would likewise be a poor tool for achieving the same effect. This would result in the necessity of employing more labor intensive and costly means of mitigating the effects of the dam, and its operations, on the cultural resources.

Research Goals/Hypotheses

The primary research goal of the Hopi Tribe during this experiment is to examine the effectiveness of the high-flow experiment to create high elevation sand deposits in selected river-based arroyos along the margins of the river. This research goal is framed in the following hypotheses:

H₀: the null hypothesis is that no sediment deposition will be realized in the arroyo mouths that are being studied.

H₁: sediment will be deposited in the arroyo mouths being studied.

Assuming deposition of high elevation sand deposits is achieved, secondary goals that address the ultimate motive for these deposits will be examined under the long term monitoring program. That is, will these new deposits re-establishing a higher effective base level in the river-based arroyos, what is the effective life span of these new deposits, and will they be efficacious at stabilizing the terrace deposits and ultimately the cultural resource sites.

H_{0(A)}: sediment deposited in the arroyos will not be retained during fluvial episodes on the terraces that the arroyos drain, causing the arroyo systems to return to downcutting, river-based systems.

H_{1(A)}: sediment deposited in the arroyos will be retained during fluvial events, temporarily maintaining a higher effective base level in the arroyo systems.

and:

H_{0(B)}: the rate of erosion of the terrace deposits does not decrease due to the spike flow sediment deposition.

H_{1(B)}: the erosion rate of the terrace deposits slow due to the spike flow sediment deposition.

Methodology

Site Selection

The original Hopi proposal identified 7 study locations, within GIS reaches, as potentially being appropriate for addressing the research goals; these were located at river miles -4, -0.5, 65.5, 70.7, 71.3, 207, and 209 (Yeatts 1996). During the course of the pre-flow work, a number of these sites were rejected as not being suitable for addressing the research questions. Specifically, arroyo mouths were either above the level of the proposed high flow (45,000 cfs), or, the arroyos had cut through sediment deposit that would not be overtopped at the level of the high flow. The final selected sites consisted of arroyos at river miles -0.5, 65.7 (two arroyos), 71.3, and 71.4 (Figure 1 and Table 1). In the remainder of the document, the arroyo at -0.5 mile is referred to as the Lee's Ferry site; the arroyos at 65.7 mile are referred to as the Palisades site; the arroyo at 71.3 mile as the Furnace Flats #2 site; and the arroyo at 71.4 mile as the Furnace Flats #1 site.

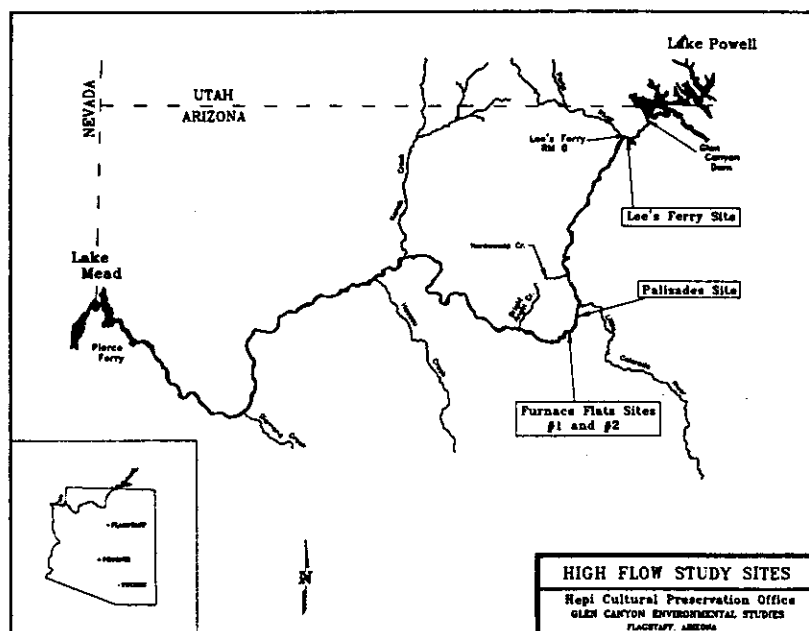


Figure 1. Locations of study sites.

The final selected sites consisted of arroyos at river miles -0.5, 65.7 (two arroyos), 71.3, and 71.4 (Figure 1 and Table 1). In the remainder of the document, the arroyo at -0.5 mile is referred to as the Lee's Ferry site; the arroyos at 65.7 mile are referred to as the Palisades site; the arroyo at 71.3 mile as the Furnace Flats #2 site; and the arroyo at 71.4 mile as the Furnace Flats #1 site.

Table 1. Study site locations.

STUDY SITE	GIS REACH	RIVER MILE *	ARIZONA STATE PLANE COORDINATE LOCATION **	
			North	East
Lee's Ferry	2	-0.5 L	650410	243350
Palisades	5	65.7 L	569680	222360
Furnace Flats #2	5	71.3 R	564350	217820
Furnace Flats #1	5	71.4 R	564320	217670

* Mileages are approximate and based on the Belknap guide. R is river right; L is river left.

** Units are meters. The datum is NAD83.

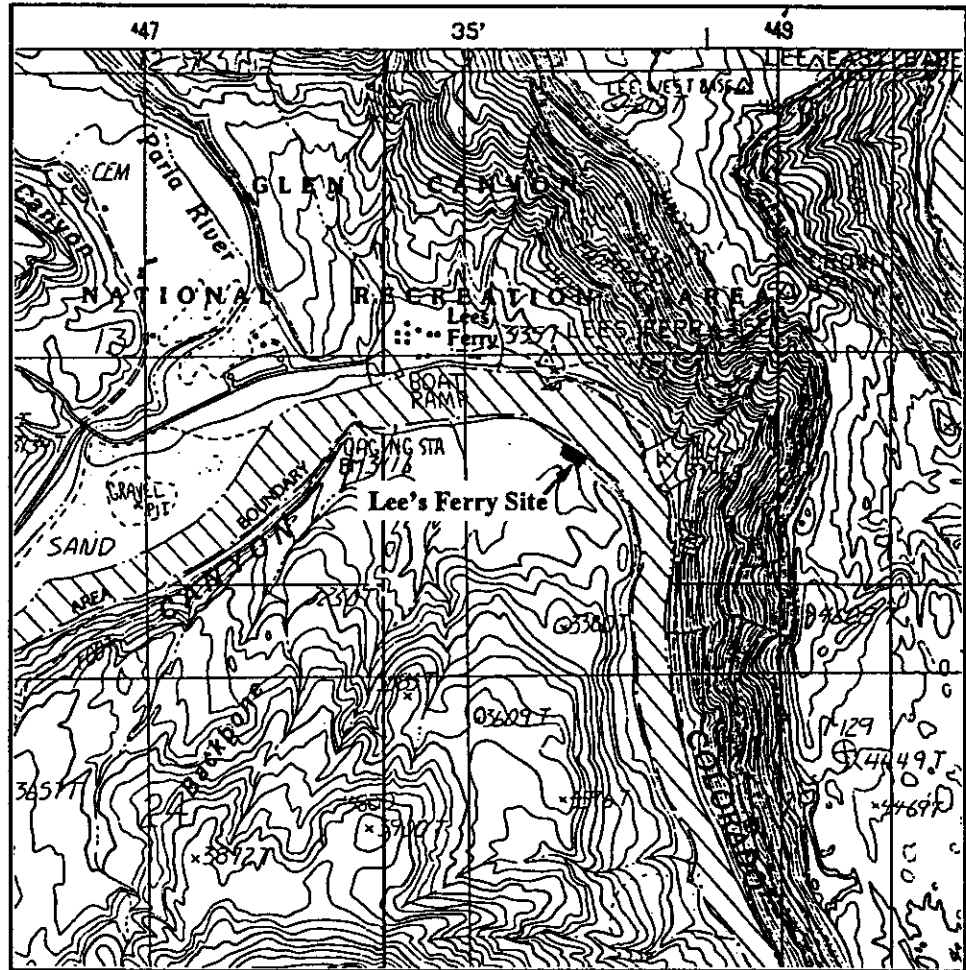
The Lee's Ferry site is located at the lower end of the Glen Canyon reach of the River on the left bank; in GIS reach 2 (Figure 2). This arroyo was selected in order to assess the impacts of the essentially clear water release, a situation felt to predominate in the Glen Canyon reach. This study site also was viewed as providing a baseline for the other arroyos as little to no sediment deposition was

expected.

The site is located on the inside bank of a gentle left bend in the river and does not have an eddy in front of it. A dense growth of tamarisk (*Tamarix chinensis*) and arrowweed (*Tessaria sericea*) occurs over most of the site with the arrowweed covering the lower zone along the river. From the edge of the river, the river bottom drops away at a steady though relatively gentle slope. The substrate is primarily sand with few large rocks noted. There are some submerged tamarisk stumps at the upriver end of the study site.

The arroyo system enters the river at a relatively shallow slope with a small abrupt drop at about the 45,000 cfs level. Nickpoints in this drop could potentially migrate upstream given flows out of the arroyo.

The soil at the mouth of the arroyo seems to have a relatively high clay content and is fairly cohesive as indicated by the vertical drop at the 45,000 cfs level. This higher clay fraction may help maintain the stability of this arroyo system at its current state.



These two arroyo systems are the only ones in this study that discharge into a well defined eddy complex. Both of the arroyos enter the large eddy on the left below Lava-Chuar rapid, formed by Palisades and Lava creeks. The lower portions of both arroyos enter the river over a sand/cobble matrix and are less than 0.50 meters deep within the study area. The eddy into which the arroyos empty is relatively shallow for a considerable distance from shore; the bottom is a variously sand or cobbles.

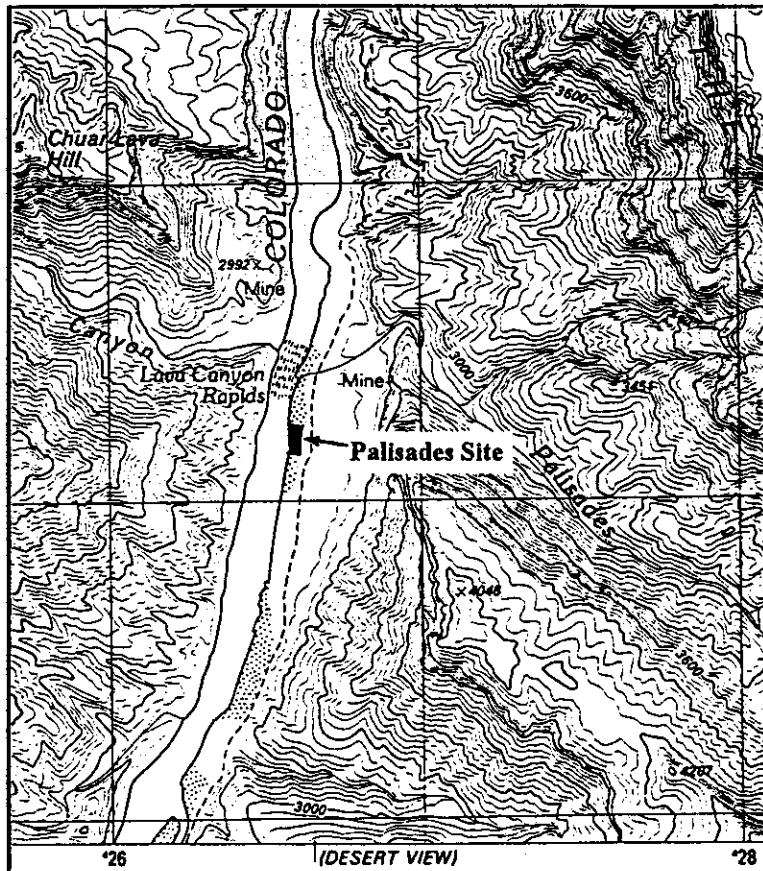


Figure 3. Palisades study site. USGS Cape Solitude, Arizona, 1988 provisional edition, 7.5' series map.

The margin deposits are relatively unconsolidated, consisting primarily of silt and sand interspersed with some colluvial material from the Dox formation. These deposits slope relatively steeply into the river and appear to continue downward as the bed of the river. The arroyo has headcut to the point where it encounters Dox bedrock.

The margin deposits through which the arroyo cuts are densely vegetated by tamarisk at the water edge, and arrowweed behind. The density is such that movement across the site is difficult or virtually impossible in areas. There is some wet marsh forming at the edge of the river.

The final arroyo, the Furnace Flats #1 site, is located about 150 meters to the west of the previous site, at about river mile 71.4, also in GIS reach 5 (see Figure 4). This site is in a similar

Vegetation at this location is sparser than at any of the other sites. There is a small number of tamarisks bordering the edge of the river (ca. 20,000 cfs). Behind the tamarisks is a relatively broad area, extending to the back of the study site, of arrowweed, camelthorn (*Alhagi camelorum*), and herbaceous plants. The density of vegetation on this site is unlikely to be great enough to have a marked effect on surface flows.

The Furnace Flats #2 site is located on the right side of the river at approximately river mile 71.3, within GIS reach 5 (Figure 4). This site is on a relatively straight section of river with no significant eddies near the arroyo mouth. Adjacent to the site, the river bottom drops quite abruptly from the shore.

The arroyo system at this site has cut through a relatively narrow band of riverine margin deposits forming a deeply entrenched (nearly 2 meters), "V" shaped gully.

geomorphic setting as the Furnace Flats #2 site. It is wholly on river margin deposits and the arroyo heads in the Dox formation. Likewise, the vegetation density and assemblage is similar to the previous site. The two principle differences between this and the previous arroyo system are that the arroyo is much less entrenched and empties into slack water that likely becomes a small eddy at high water. The river bottom drops relatively steeply from the shore and is primarily sand, the exception being the downstream end of the study site where a bedrock shelf projects into the river.

It is interesting to note that this arroyo has not downcut to the degree that the previous one has. This may be due to the presence of a more cohesive substrate, a vegetation "checkdam" that has formed near the mouth of the arroyo, or a combination of the two factors. Both this, and the previous study location, should provide a representation of the effectiveness of high flows at AZ:C:13:10, a highly impacted archaeological site in the area.

Survey Methods

Both the pre-flood and post-flood mapping methodology consisted of the collection of detailed topography within the area that was expected to be inundated by the high flow as well as the area above the inundation level. The rationale for collecting information above the level of inundation, an area of essentially no change, was to provide a relative assessment of error inherent in the mapping.

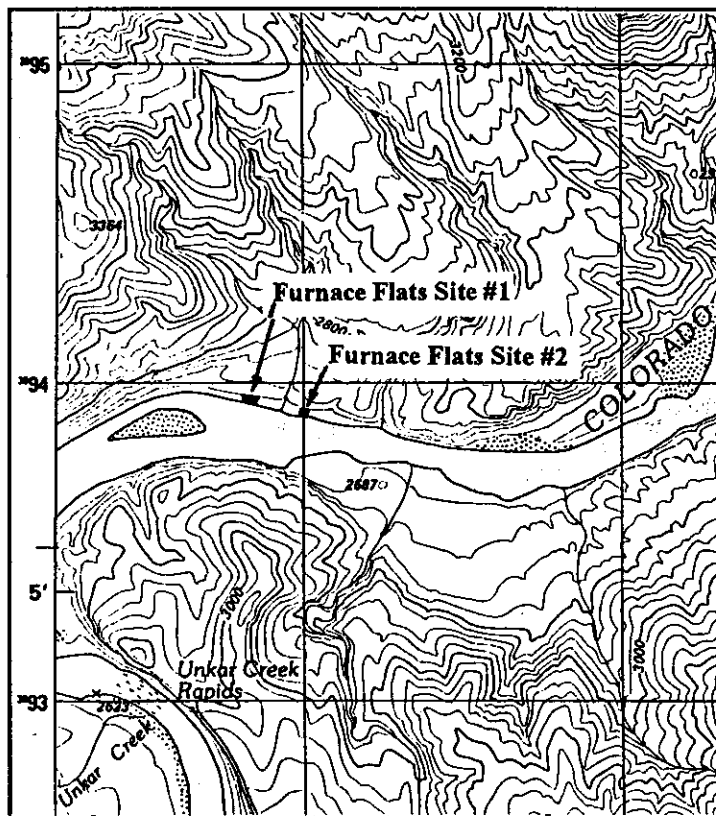


Figure 4. Furnace Flats study sites. USGS Desert View, Arizona, 1988, 7.5' series map.

The mapping was carried out at a level of intensity necessary to generate contour information accurate to a 0.25 meter interval, a level felt precise enough to identify and quantify the degree of change to features within the study sites and address the research hypotheses. While emphasis was placed on defining the arroyo systems at each of the sites, a surrounding zone was also characterized in order to define the overall deposition/erosion environment in which the arroyos are situated. Mapping was carried into the river to about 0.75 meters below the water surface; this equated to less than 2 meters from shore at some sites and nearly 10 meters at others. In general, mapping proceeded by defining breaklines at the site and then filling in the ground surface judgementally in other areas with individual points; a grid system of points across the site was not established.

Each of the sites was mapped from a known point that had been previously established for control within the GIS reaches by the GCES survey department. As these points are already georeferenced, it allowed the study areas to automatically be referenced in real-world coordinates (in

this case the Arizona State Plan Coordinate System, central zone) and for incorporation into the GCES-GIS. Similarly, because of the locational control, it allowed remapping efforts to be undertaken without the necessity of placing any on-site datums or establishing physical boundaries around the study areas; all adjustments and area definition could be made in the office using Terramodel®, the mapping software. All data collection was accomplished using total stations.

Field Work

The pre-flood work was conducted on February 5, 1996 for the Lee's Ferry site, February 17, 1996 for the Palisades site, February 20, 1996 for the Furnace Flats #2 site, and February 19, 1996 for the Furnace Flats #1 site. Mapping was conducted by Chris Brod, Michael Yeatts, and Nina Swidler at the Lees Ferry and Palisades sites, and by Chris Brod and Michael Yeatts at the Furnace Flats sites.

The post-flood work was conducted on April 5, 1996 for the Lee's Ferry Site, May 11-12, 1996 for the Palisades site, and May 12-13, for the two Furnace Flats sites. The mapping was conducted by Chris Brod and Michael Yeatts at the Lees Ferry, and Furnace Flats sites and by Chris Brod, Michael Yeatts and Craig Hagood at the Palisades site.

On August 30, and September 1, 1996, the Palisades site, and both Furnace Flats sites, were examined, respectively, in a qualitative assessment of the stability of the new sediment deposits by Michael Yeatts. No mapping was conducted at this time; only a visual examination was made. Photos of the Furnace Flats sites were also taken.

Flow Level Interpretation

As an aside to the primary goal of assessing the results of the experimental high flow to create high elevation sediment deposits, the research provided an opportunity to collect information regarding the stage-discharge relationship at the study sites. During each of the mapping episodes, the water edge was mapped in order to provide an actual elevation for the given flows. While the flows at the Lee's Ferry site, and for the 45K flow could easily be determined from the Lee's Ferry gauge and the high water mark, the other flows needed to be estimated based on the United States Geological Survey discharge routing model (Wiele and Smith 1996). Table 2 provides a tabulation of the various flows and their associated elevations at each of the sites. For input into the model, flows were routed from the Little Colorado River gage station. As no

Table 2: Stage discharge relationships at the study sites.

LOCATION	FLOW (cfs)	ELEVATION *
Lee's Ferry	16,300	949.85
Lee's Ferry	8,000	949.25
Lee's Ferry	45,000	951.25
Palisades	15,500	817.00
Palisades	17,200	817.50
Palisades	45,000	818.70
Furnace Flats #2	18,200	800.25
Furnace Flats #2	14,900	800.00
Furnace Flats #2	45,000	802.00

* Units are meters above mean sea level, NAVD 29.

significant runoff was occurring in the Little Colorado River, a baseflow value of 225 cfs was used for the tributary contribution. At the time that the model was run, the gage values were still provisional, and therefore, the interpolated values are likewise provisional.

Results

Data Analysis

Analysis of the survey data provides the basis for the interpreting the effects and the effectiveness of the high-flow experiment. Therefore, an effort was made in the analysis of the data to identify those components of the data that were due to stochastic variability in the mapping rather than from real changes due to the high flow.

From the mapping data, a digital terrain model (DTM) of each of the sites was created using Terramodel® surveying software. From the DTM, contour maps and surface models of the sites were produced and from the comparison between the pre- and post-high flow DTMs, interpretation of changes to the surfaces and volumes of material at the sites were made. Locations of cutting or filling at the sites can easily be identified in the resulting data.

In order to ascertain that changes at each site following the high flow were due to a real processes and not an artifact of the mapping, several comparisons were made between the area inundated at each of the sites and the area above the inundation zone, an area that should not show significant change. First, a simple "ratio of change" was calculated for the area above and below 45,000 cfs for each of the sites (Table 3). This was accomplished by dividing the total volume of change (derived from the DTMs), both positive and negative, by the area over which the change occurred. This in essence standardized the values at each site so as to allow comparison between the inundated and non-inundated zones, and to allow a means to compare relative depositions between the different sites. Examining the

values, it becomes apparent that in the area above 45,000 cfs, where no change should have occurred, an absolute value of up to nearly "2" can be attributed to volume changes resulting from mapping inaccuracies. It is also obvious that at all sites other than the Lee's Ferry site, the inaccuracies in mapping are not enough to have produced the volume changes identified within the inundated zones. Therefore, a real volume change must have occurred due to the high flow experiment, the Lee's Ferry site being the exception as discussed later. Also apparent from these figures is the proportional amounts of deposition that occurred on each site. The Furnace Flats #1 site received the greatest amount of deposition per unit area, followed by the Furnace Flats #2 site, and then the Palisades site. This may be due to differing amounts of deposition, erosion, or a combination of the two factors. This issue will be discussed further under the individual sites.

Table 3: Ratio of Change. *

LOCATION	BELOW 45,000 cfs	ABOVE 45,000 cfs
Lee's Ferry	1.16 (+)	1.82 (+)
Palisades	3.63 (+)	0.69 (-)
Furnace Flats #2	16.45 (+)	1.45 (-)
Furnace Flats #1	41.67 (+)	0.38 (+)

* Total volume of change/area of change.

A second avenue pursued to evaluate the error level in the data resulting from imprecision in the mapping was to examine the percentage of total change expressed by depth of change. The mapping was targeted to accurately represent the terrain at a 0.25 meter level; features less than 0.25 meter would likely not show up on a contour map or be accurately reflected in the DTM. Therefore, examining the distributions of changes between the pre- and post-high flow data by amount of change will yield a picture of real change versus mapping variability. Depositional or erosional changes of greater than 0.25 meters are most likely to represent real changes whereas those within the 0.25 meter range have a greater likelihood of being a construct of the mapping. This is not to say that all of the changes that are less than 0.25 meters are fictitious, as obviously there is real change within this range. It is just that the mapping can not completely distinguish this from the stochastic variability inherent in the measurement process. By comparing the distributions of change between the inundated and non-inundated zones at each site, an evaluation can be made regarding the reality of the measured change in the inundated zone.

Table 4 presents this information for each of the sites. This data supports the results of the previous discussion: that there is real change at all of the sites other than the Lee's Ferry site.

Table 4: Distribution of change by depth of cut or fill.

LOCATION		AMOUNT OF FILL OF CUT			
		< 0.25 m	0.25-0.50 m	0.50-1.00 m	> 1.00 m
Lee's Ferry	above 45K	92.37%	7.38%	0.25%	0.00%
	below 45K	93.93%	5.26%	0.81%	0.00%
Palisades	above 45K	99.73%	0.27%	0.00%	0.00%
	below 45K	85.54%	13.39%	1.07%	0.00%
Furnace Flats #2	above 45K	98.73%	1.27%	0.00%	0.00%
	below 45K	71.19%	24.84%	3.97%	0.00%
Furnace Flats #1	above 45K	97.05%	2.98%	0.00%	0.00%
	below 45K	41.70%	22.80%	23.94%	11.55%

Virtually all of the change identified at each of the sites in the area unaffected by the high flow (above 45K) is within the 0.25 meter range. This, coupled with the values related to the amount of change, shown on Table 3, indicate that little change was occurring in the areas above the 45,000 cfs level; ie. the mapping technique was not introducing a great deal of error into the results.

Conversely, below the 45,000 cfs level, changes greater than 0.25 meters in depth occurred at all but the Lee's Ferry site. At the Lee's Ferry site, where no change was visually apparent, the distribution of values is nearly the same for the inundated and non-inundated zones.

One final analysis to be examined before discussing the results at each site individually is a summary of the level at which sand deposited relative to the high flow. The volume of material for

each successive 0.25 meter thick layer of material was determined for each site before and following the high flow. Each of these elevation ranges could be related to the elevation of the 45,000 cfs flow at the site, and from this, the level in which cutting or filling occurred could be identified. On average, the maximum amount of deposition occurred at about 1.4 meters below the 45,000 cfs stage with a small loss of sediment to about 0.6 meters below the 45,000 cfs stage. The distribution of sediment deposition about the maximum follows a relatively normal curve, although there is some deviation as will be discussed under the individual sites.

Site Specific Results

Lees Ferry Site

The Lee's Ferry site was the only study site that did not undergo any significant changes due to the high flow. Figures 5 and 6 present the pre- and post-high flow topography at this site. In terms of the mapping, the most obvious difference is the fact that following the high flow, the mapping effort was not extended to nearly as far from the river. This was because the inundated area was lower than expected and it was not felt necessary to map as much area. Only those areas that overlapped were included in the analysis. Figure 7 provides another view of the data, a 3-dimensional representation of the topography at the site, both before and following the high flow. These views were generated from the mapping data using Surfer® version 6 software. As with the topographic maps, there is really no significant change at the site other than the variation due to mapping variability. This is born out in Figure 8, a topographic representation of areas that were cut and filled by the high flow. Essentially, the changes are random both above and below the 45,000 cfs level, being an artifact of the mapping. This figure visually represents the information that was presented in Table 4.

In spite of the fact that there was no significant deposition or erosion at this site, the level of the 45,000 cfs flow was readily apparent. The layer of duff that had formed under the vegetation was removed up to the high water level. Very little if any soil was removed. This may be due to the relatively high clay content of the soil at this site.

Low grass at the site was flattened, and in areas with much current, it was flattened in the direction of the flow. At this site, the flow maintained a downstream trend; no eddy was formed. There was no scouring of larger vegetation at this location. It was noted that upstream of the site, where the slope enters the river at a much steeper angle, that there was a loss of material likely due to undercutting of the deposits, and then bank failure.

For this site, the null hypothesis (H_0) was met: there was no significant deposition of sediment in the arroyo mouth at this site. Therefore, the secondary hypotheses ($H_{(A)}$ and $H_{(B)}$) are no longer relevant as this is no new sediment to be maintained.

Palisades Site

Of all of the sites, the Palisades site was the most varied in response to the high flow. Some areas of the site eroded as much as 0.5 meters while other portions of the site received nearly 0.8 meters of deposition. Figures 9 and 10 show the pre- and post-high flow topography of the site and Figure 11 presents this information in a 3-dimensional perspective. There is a band of deposition approximately at the level of the 45,000 cfs flow. Behind and on this new sand is drift material

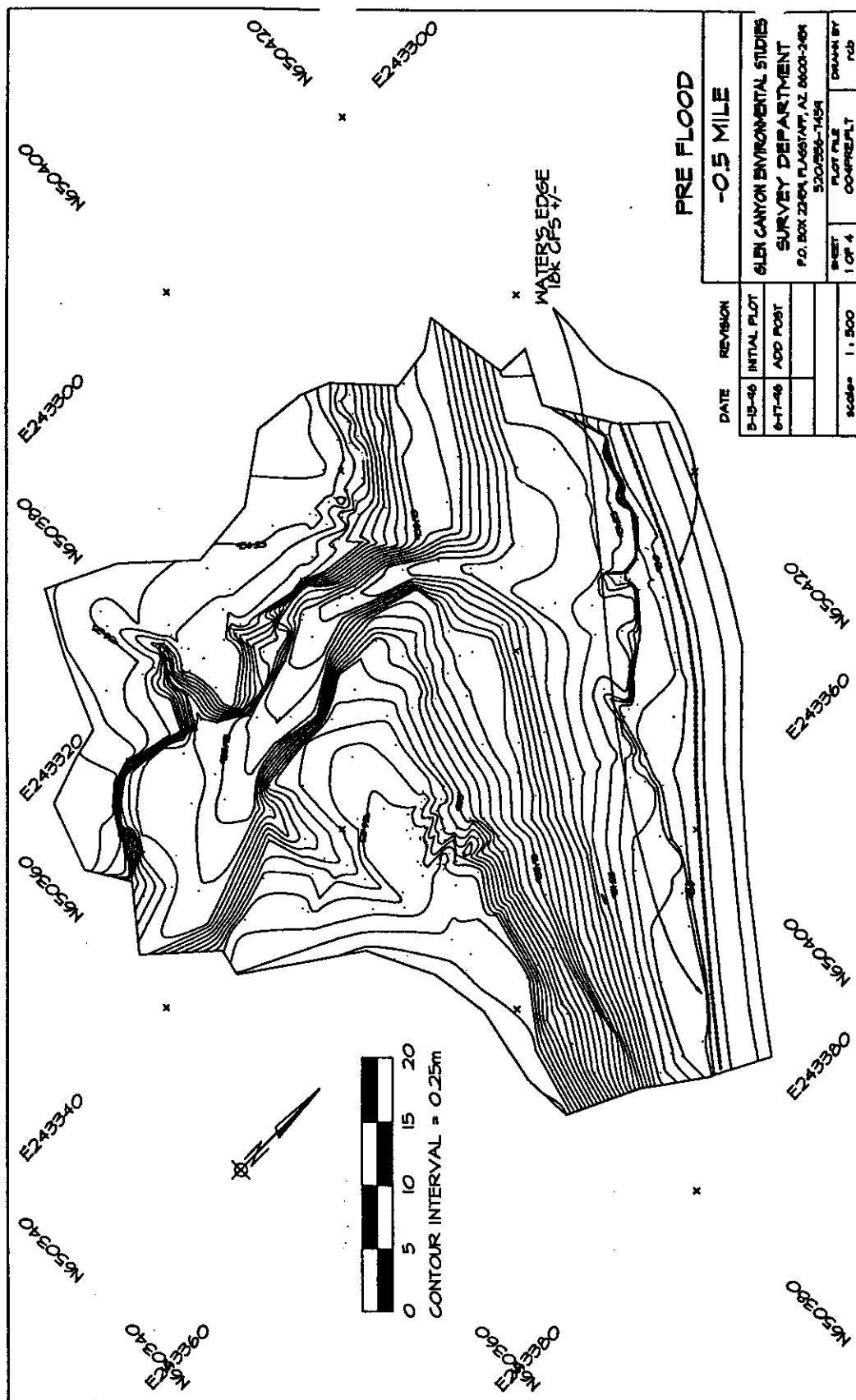


Figure 5. Lee's Ferry pre-high flow topography.

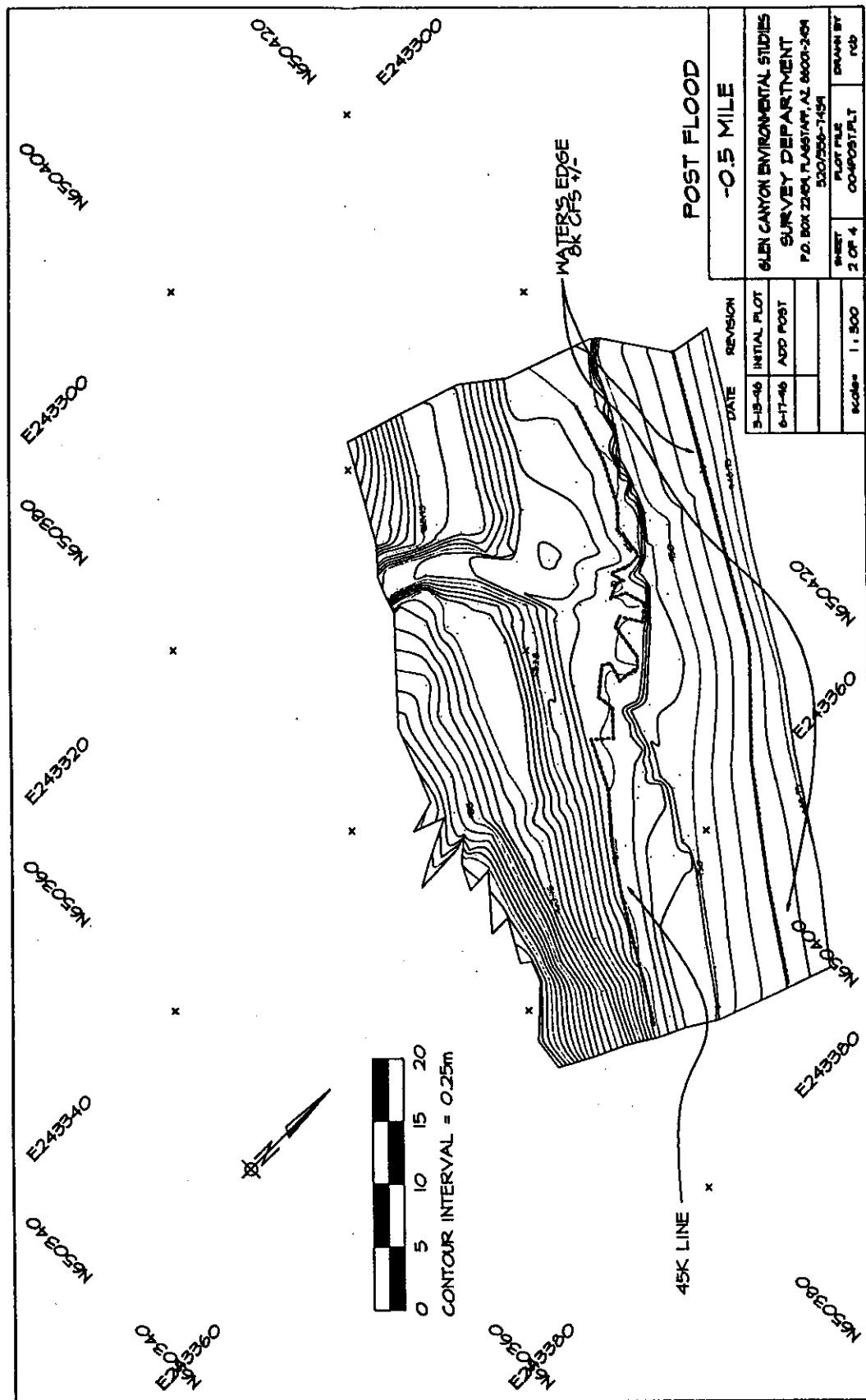


Figure 6. Lee's Ferry post-high flow topography.

LEE'S FERRY SITE

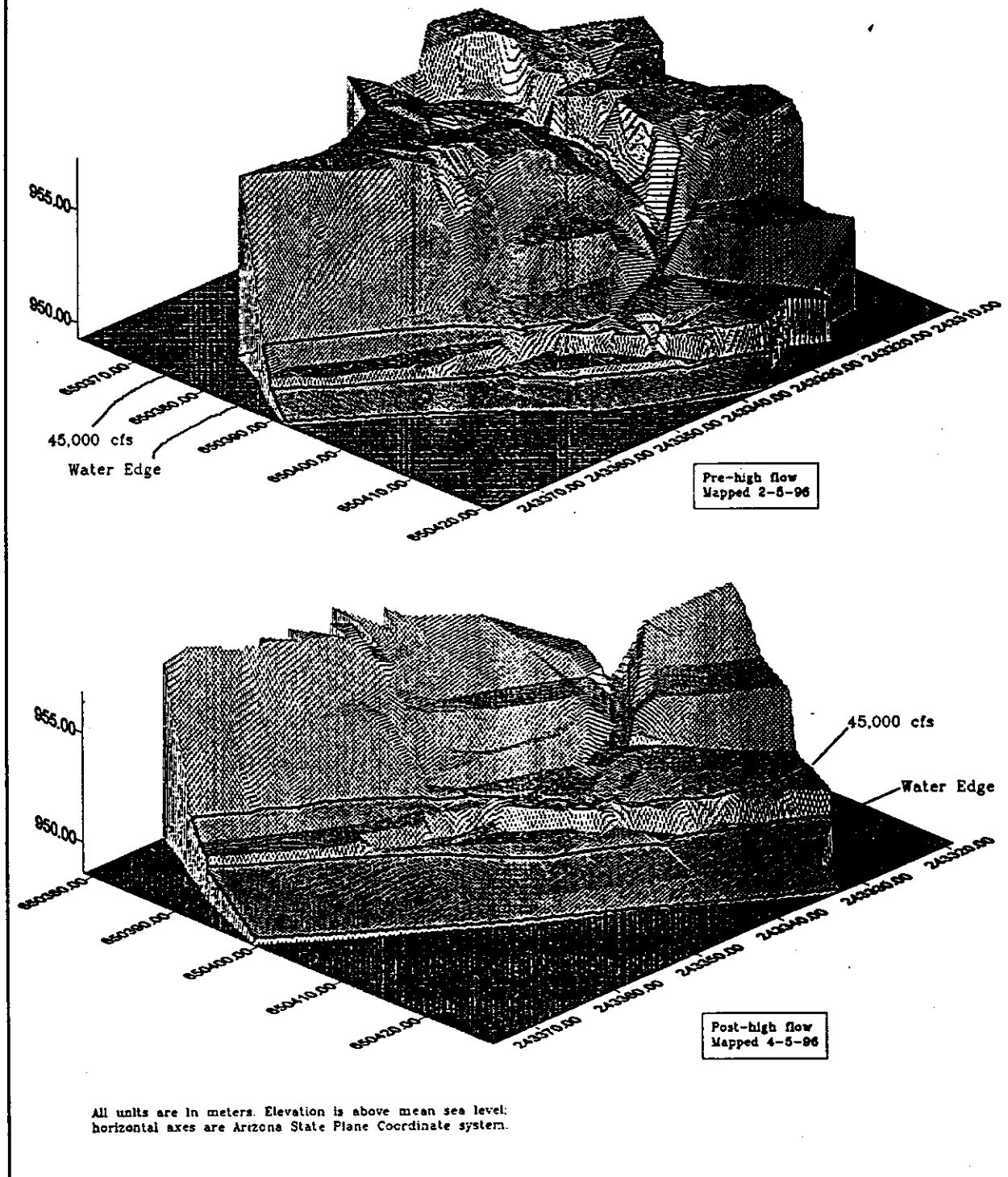


Figure 7. Lee's Ferry site, pre- and post-high flow topography in a 3-dimensional format.

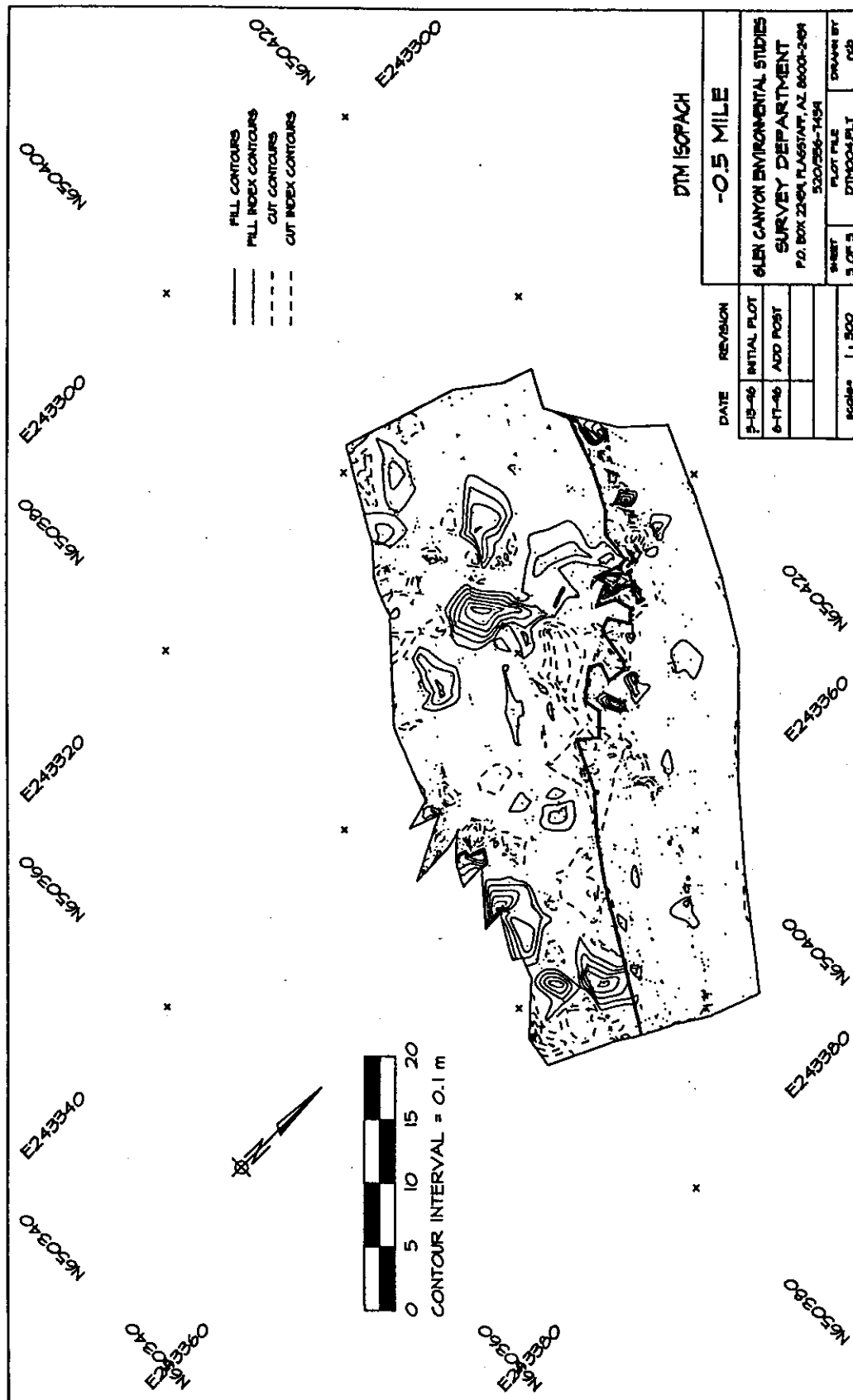


Figure 8. Cut and fill locations at the Lee's Ferry site.

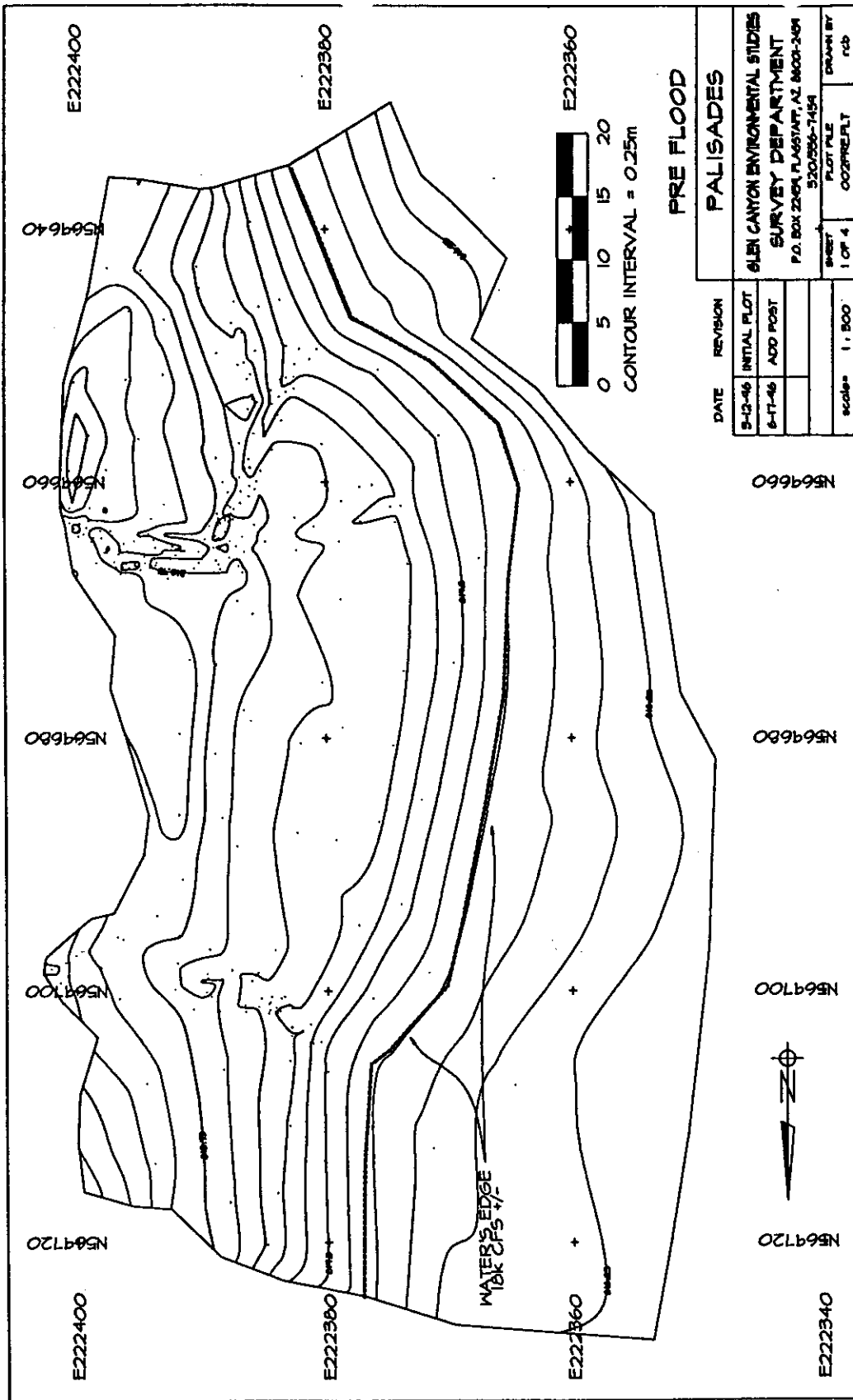


Figure 9. Palisades pre-high flow topography.

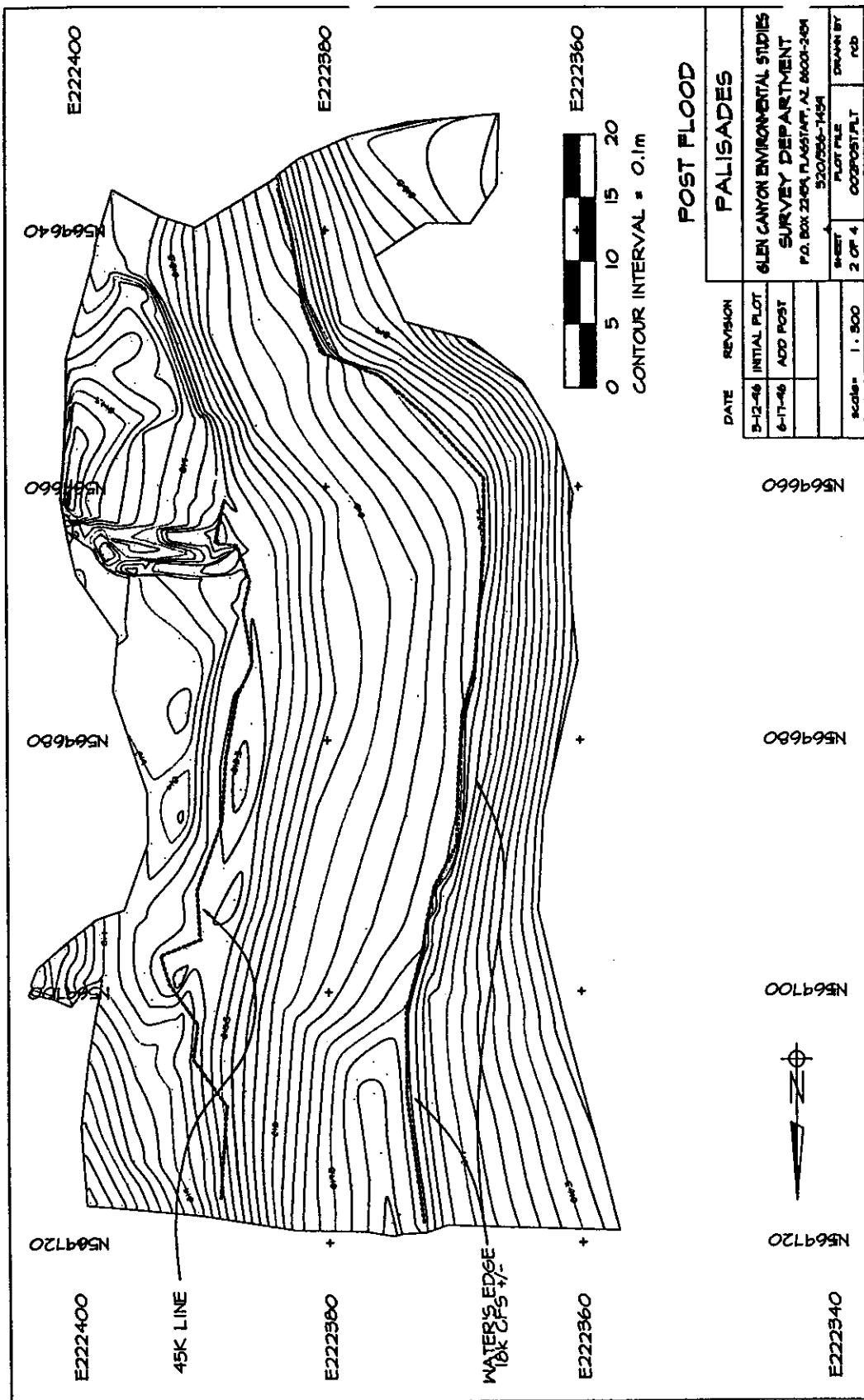
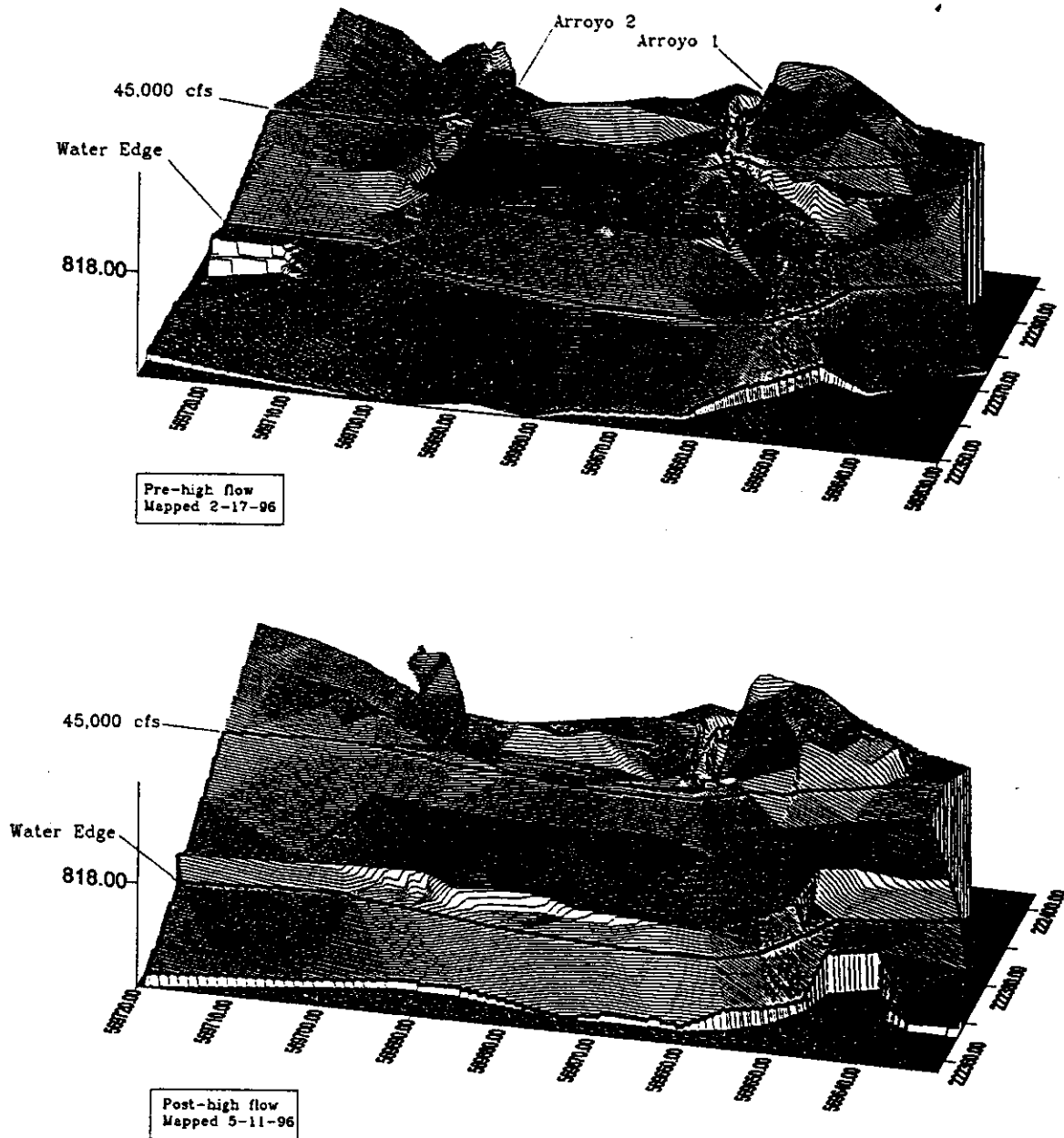


Figure 10. Palisades post-high flow topography.

PALISADES SITE



All units are in meters. Elevation is above mean sea level.
horizontal axes are Arizona State Plane Coordinate system.

Figure 11. Palisades site, pre- and post-high flow topography in a 3-dimensional format.

marking the highest extent of the flow. Between the new deposits and the river is an area that remained essentially the same, or was slightly eroded. The cobbles that form the substrate in this area appear to have been exposed to a greater degree by the high flow and may have also armored this region. The area just off shore received some of the more striking changes at this site. Much of the sandy substrate at the downstream end of the site was scoured out revealing a cobble bottom. At the upstream end of the site, a ridge was formed above water level that trapped a small pool behind it. This area had been a shallow, sandy bottomed cove prior to the high flow. Figure 12 shows all of these changes in the form of a topographic map showing the areas of cutting and filling. Overall, 202.4 cubic meters of material was deposited on this site and 124.6 cubic meters of material was eroded.

What appears to have happened at this location was the expansion of the large eddy that at the bottom of Lava-Chuar rapid up onto the site. This is collaborated by the fact that all of the small vegetation in the inundated zone was bent upstream. The scour zone may have been a higher velocity channel that with enough deposition would have formed a backwater.

As can be seen in Figures 9 and 10, the two arroyo systems at this site were completely filled with new deposits up to the 45,000 cfs level. Likewise, the lower check dams that had been constructed in the arroyos were covered by sand. Until some of the new deposits are eroded, there is no evidence whether the flow disturbed the arrangement of the check dams. This will be followed during the long term monitoring at this location.

Like all of the other study sites, there was very little change in the vegetation at this site. The duff layer as well as some of the smaller plants may have been removed, but by the return visit in September, 1996, the site was again covered with herbaceous plants, with camelthorn being particularly prevalent. There was no observable effect to any of the larger vegetation.

Apart from the increase in vegetation, there had been only minor changes at the site since the post-high flow mapping when it was visited in September, and most of these changes were in the areas immediately adjacent to the river. The sand ridge that had formed at the upstream end of the site had been reworked back to essentially the pre-high flow state (though this needs to be confirmed through remapping), and other new deposits had been rounded through aeolian reworking. Most significant for the cultural resources, however, was the fact that the deposits within the arroyos were still intact and none of the check dams that had been buried were exposed. It was clear that no flows had come down the arroyos since the high flow and therefore, there is no information yet on whether the new deposits will help create a high base level in the arroyo systems.

At this site, the null hypothesis was rejected as sand was deposited in the arroyos up to the 45,000 cfs level. Therefore, it will be necessary to examine the persistence of the new deposits through time, the goals of secondary hypotheses $H_{(A)}$ and $H_{(B)}$.

Furnace Flats #2

The Furnace Flats #2 site received the most prominent filling within the arroyo mouth of any of the study site. A shelf of new sediment was deposited the length of the study location parallel to the river, filling the mouth of the arroyo, and effectively damming the arroyo. Figures 13 and 14 show the pre- and post-high flow topography and Figure 15 presents a 3-dimensional view of the same data.

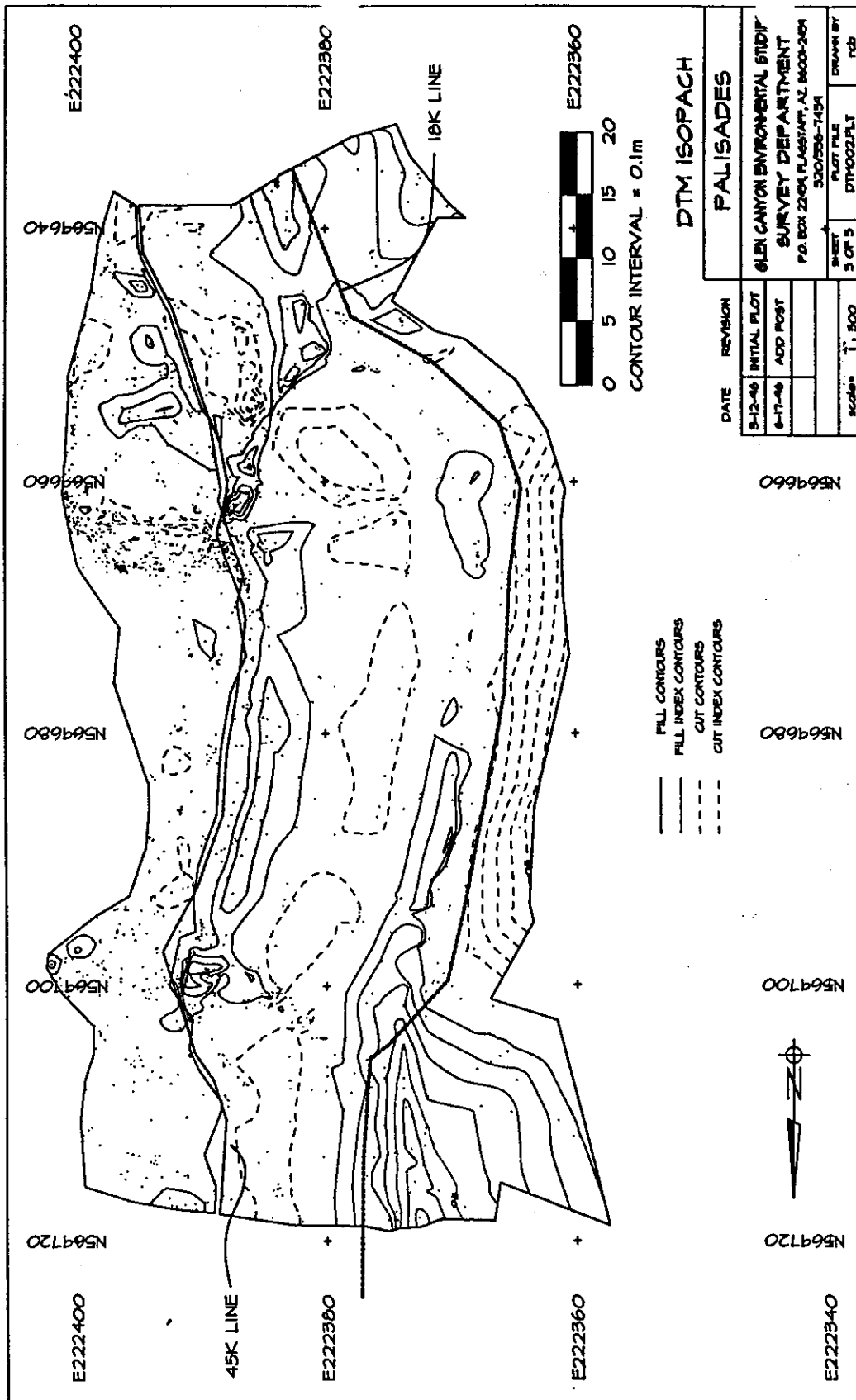


Figure 12. Cut and fill locations at the Palisades site.

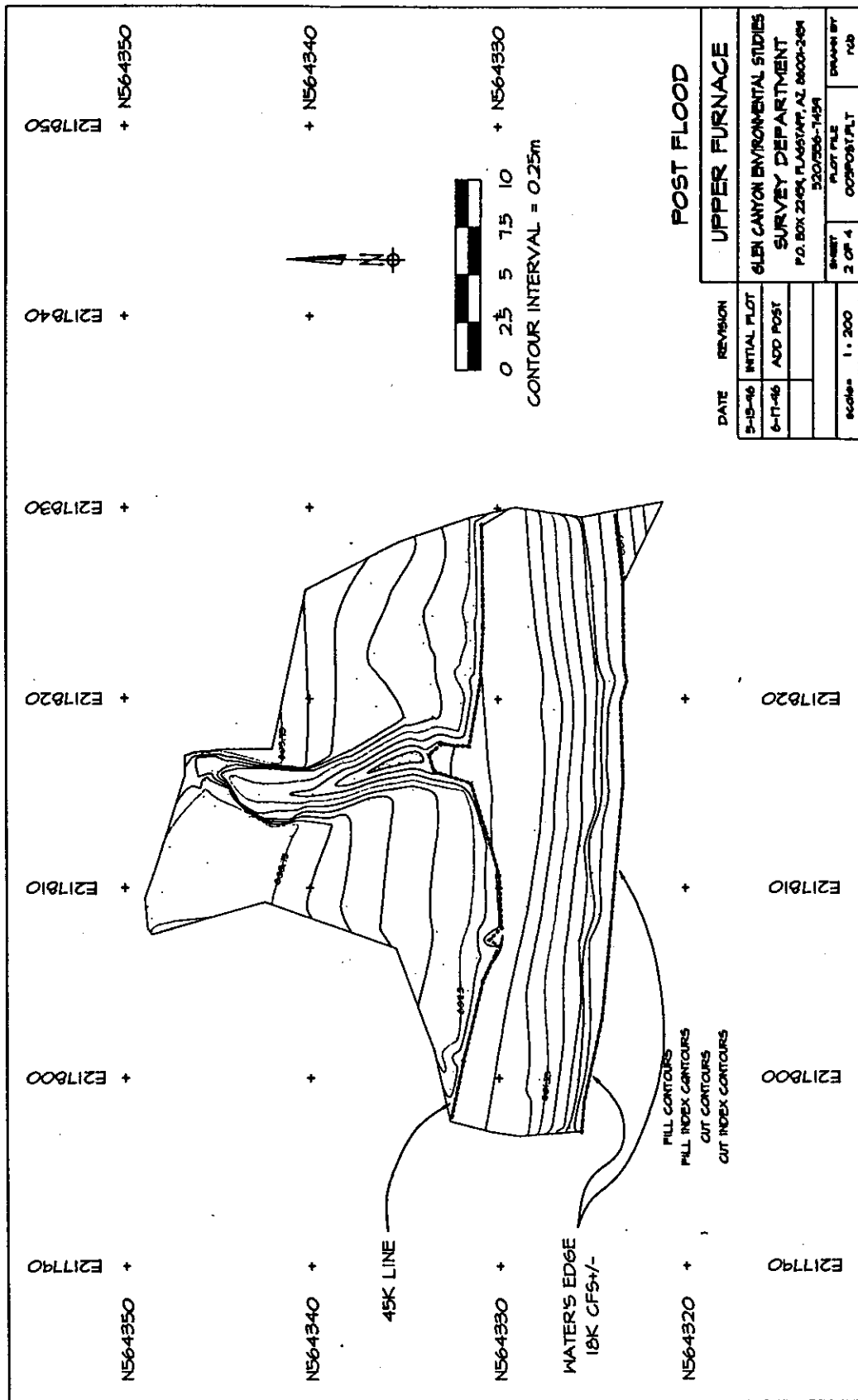
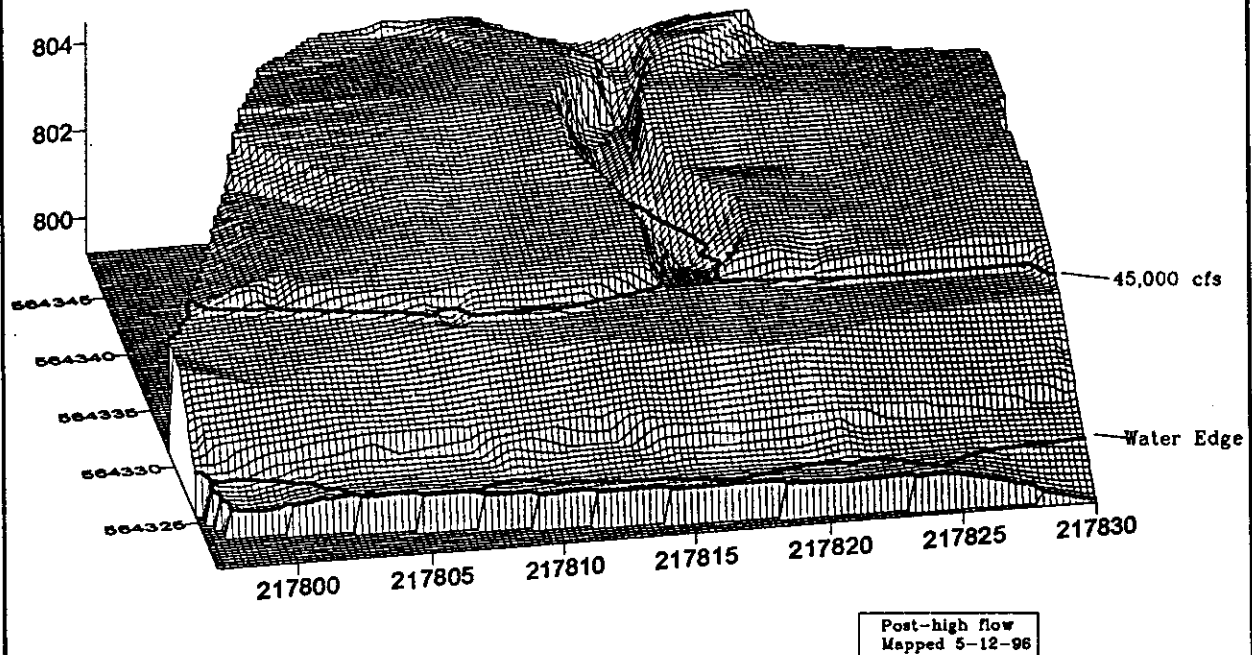
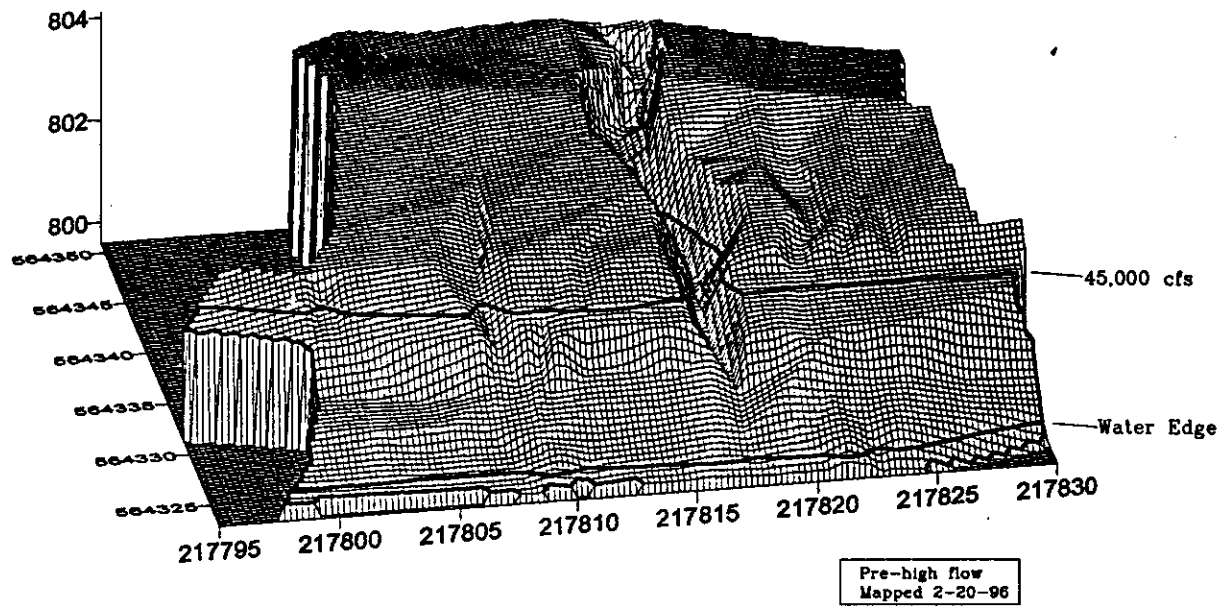


Figure 14. Furnace Flats #2 post-high flow topography.

FURNACE FLATS SITE #2



All units are in meters. Elevation is above mean sea level;
horizontal axes are Arizona State Plane Coordinate system.

Figure 15. Furnace Flats #2 site pre- and post-high flow topography in 3-dimensional format.

New sediment deposits ran from the edge of the river steeply up to the 45,000 cfs level where they formed a bench about 3 meters wide. The new deposits were laid down over the existing margin deposits with little scouring as evidenced by vegetation not being removed from the site (Figure 16 shows the cut and fill that occurred at the site). In fact, the arrowweed is sticking up through the new deposits while smaller vegetation was completely buried. Although this site had the second highest value for the volume of change (see Table 3), it appears to have received the greatest percentage of sediment on the existing margin deposits. The new deposits did not modify the shoreline as they did at the Palisades site or the Furnace Flats #1 site, discussed below, and therefore are likely to be retained longer. At this site, a total of 41.7 cubic meters of sediment was deposited on the site below the 45,000 cfs level and 6.2 cubic meters were eroded.

This study area did not become an eddy during the high flow. All evidence points to the flow maintaining a downstream direction, and yet considerable deposition was realized. It may be that the dense vegetation on the site contributed to a reduction in flow velocity at the site and improved the environment for deposition.

Reexamination of the site at the beginning of September, 1996 identified virtually no change. There may have been a small amount of erosion of the new deposits at the edge of the river and wind had rounded the upper edge of the deposit. The arroyo had not flowed at the time of the visit so the deposits still retained their integrity.

At the Furnace Flats #2 site, the null hypothesis ($H_{(0)}$) was rejected as sediment was deposited in the arroyo mouth. Now, the secondary hypotheses will need to be addressed through continued monitoring of the site. The September, 1996 revisit was a start, however, until a fluvial event occurs in the drainage, no relevant information for addressing the additional hypotheses can be collected.

Furnace Flats #1

While this site is located within 150 meters of the Furnace Flats #2 site, its reaction to the high flow was somewhat different. Like the previous site, sediment was deposited and the mouth of the arroyo was effectively filled (Figures 17, 18, and 19). In addition to the new sediment on the site, however, sediment also added out from the original shoreline. The location apparently became a small eddy at higher water and a ridge shaped dune formed out from the shore with a small return channel between the dune and the vegetated shore. This new deposit of sand is clearly seen in Figure 20, showing the areas cut and filled. Below the 45,000 cfs level, 151.8 cubic meters of sand was deposited and 4.8 cubic meters of material was eroded.

Within the vegetated zone, this site reacted similarly to the previous site. A bench of sand, 2-3 meters wide, was deposited parallel to the river. It filled in the arroyo mouth and buried some of the smaller vegetation. Again, there was no evidence of major scouring and the vegetation appeared unchanged.

This site showed considerable change when revisited in September, 1996. The dune that had formed off-shore had been reworked back into the river and the rock shelf that is located at the downstream end of the site, and which was buried by the high flow deposits, was again exposed. This indicates that the shoreline had returned to the pre-high flow condition, though this assumption needs to be confirmed through repeat mapping at the site. Considerable *Phragmites* sp. had colonized the sand

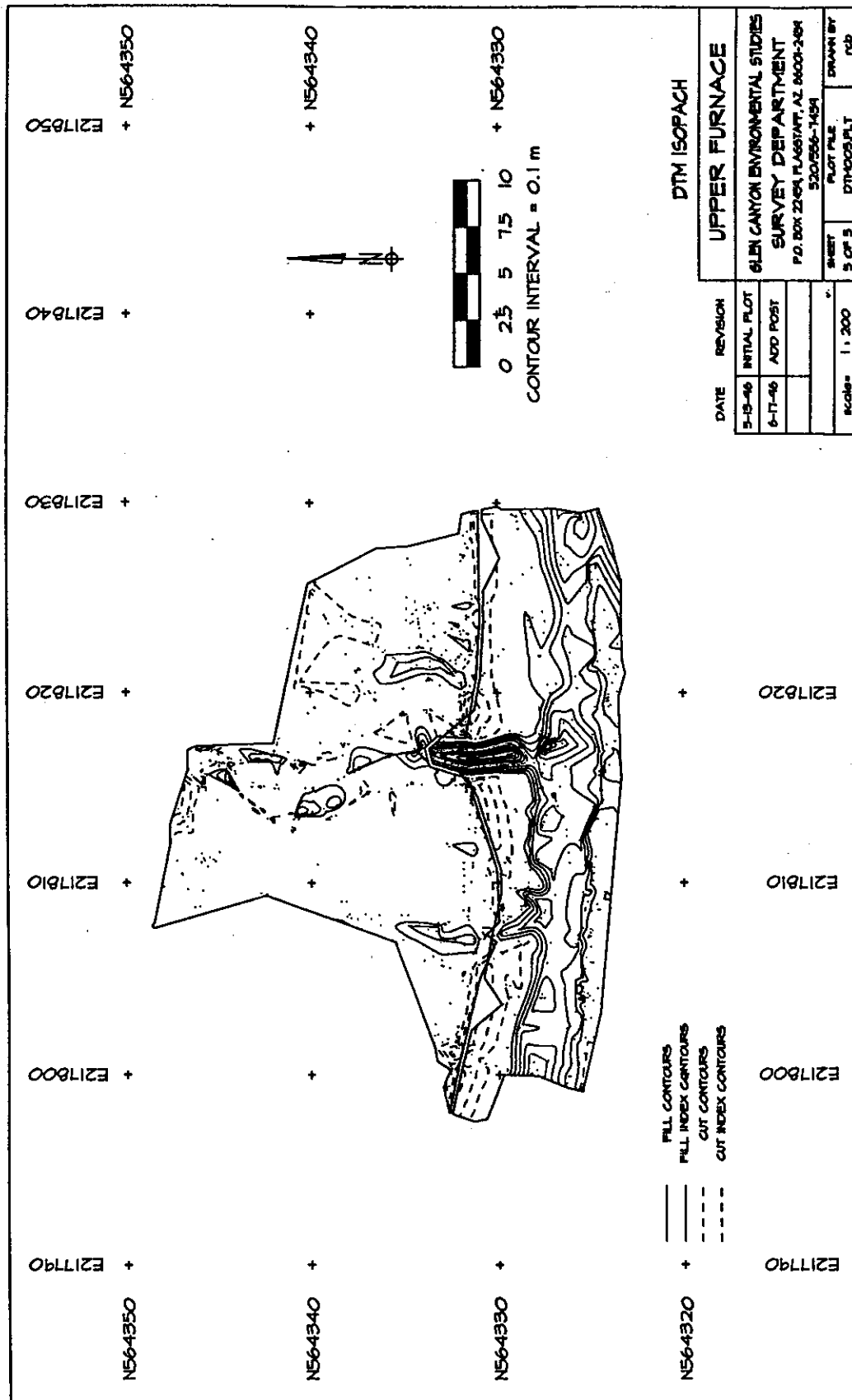


Figure 16. Cut and fill locations at Furnace Flats #2.

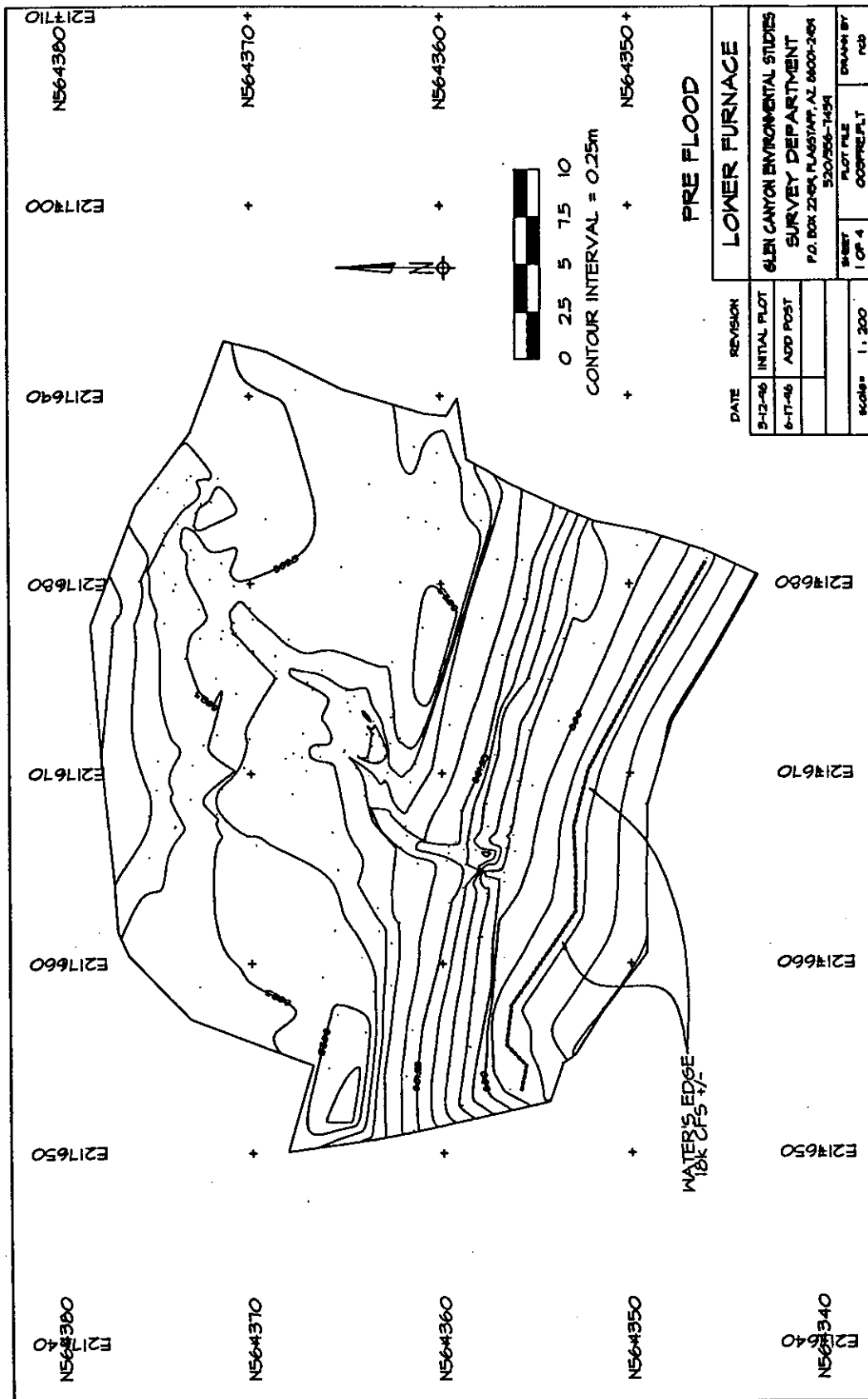


Figure 17. Furnace Flats #1 pre-high flow topography.

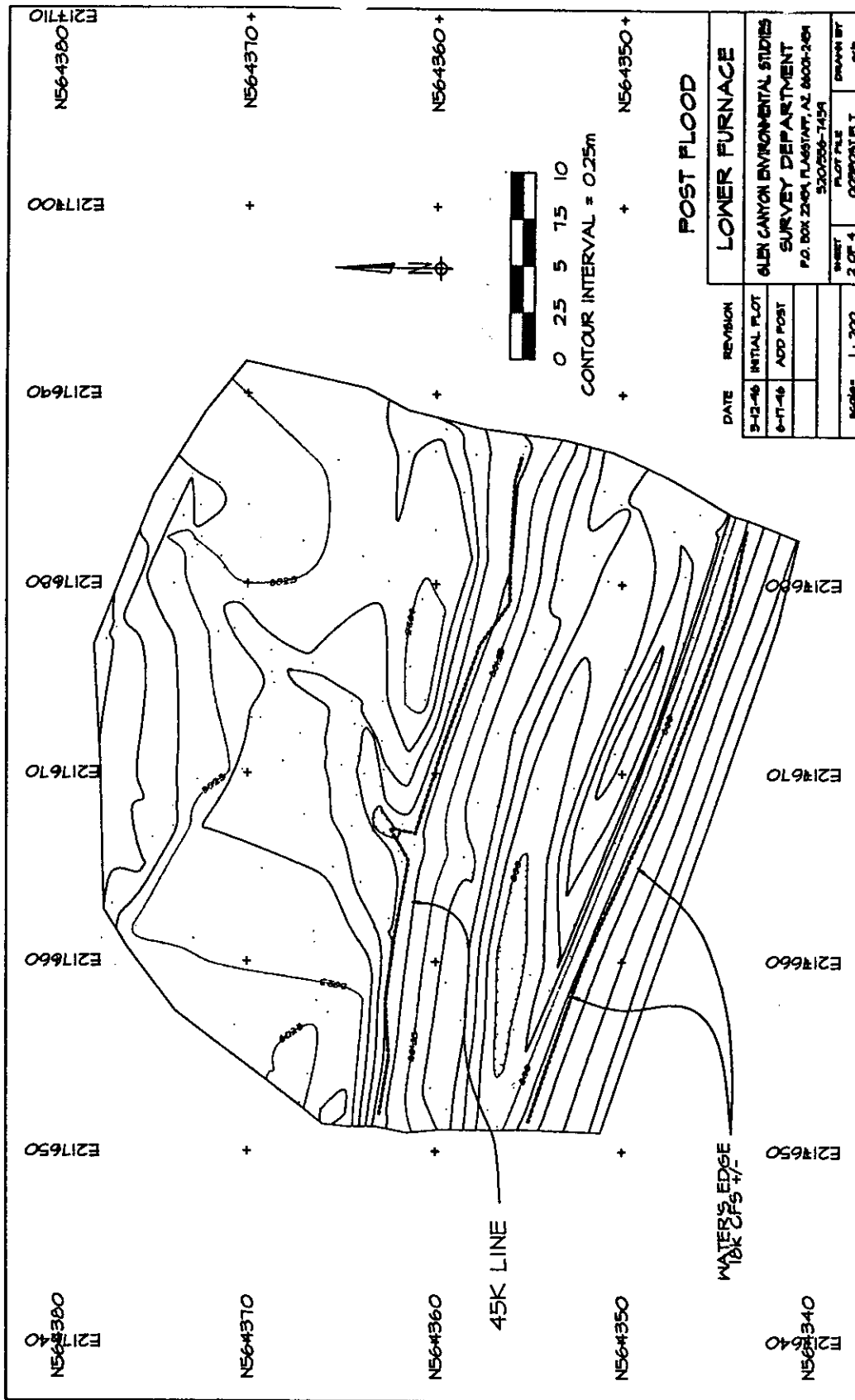


Figure 18. Furnace Flats #1 post-high flow topography.

FURNACE FLATS SITE #1

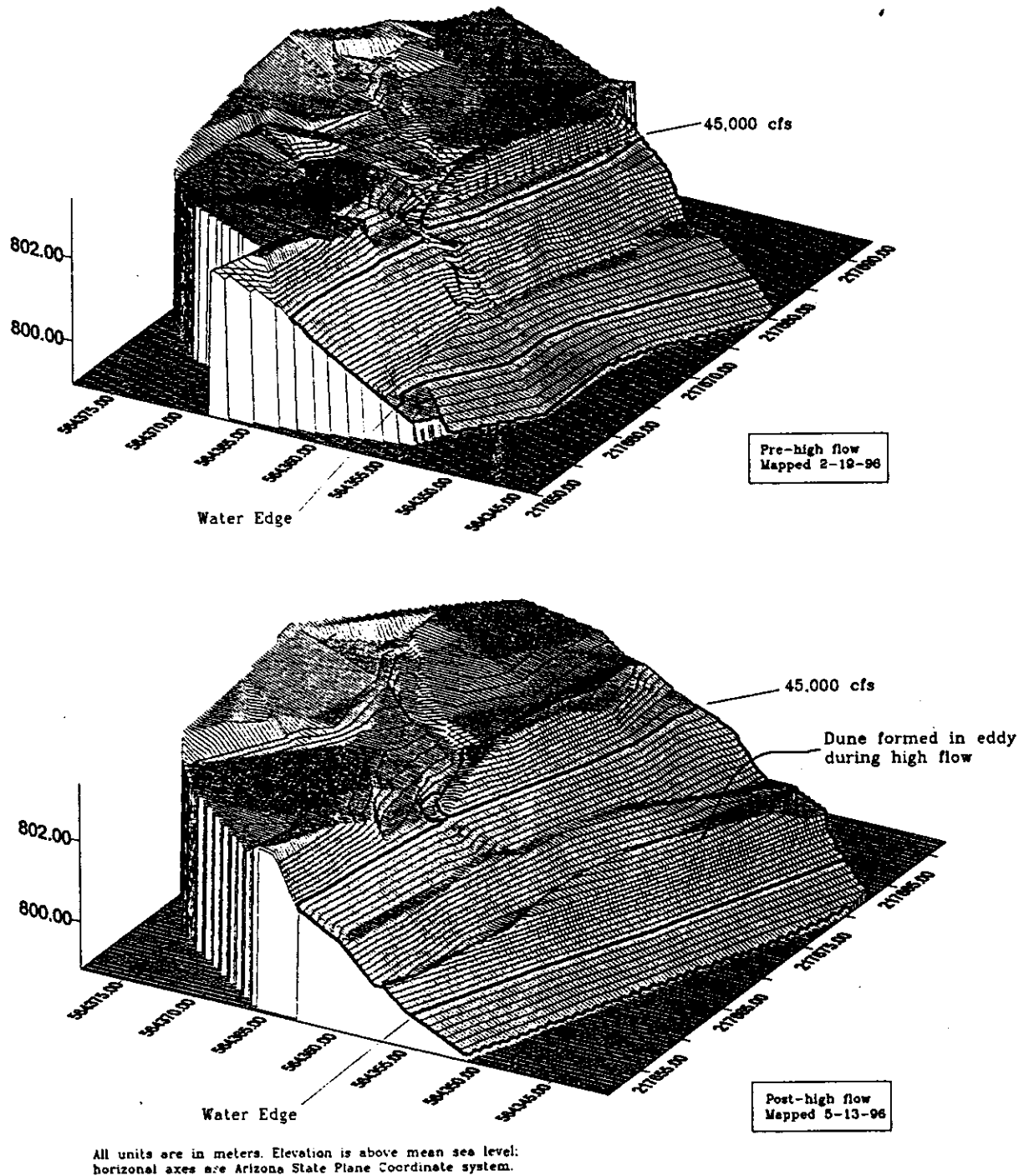


Figure 19. Furnace Flats #1 site pre- and post-high flow topography in 3-dimensional format.

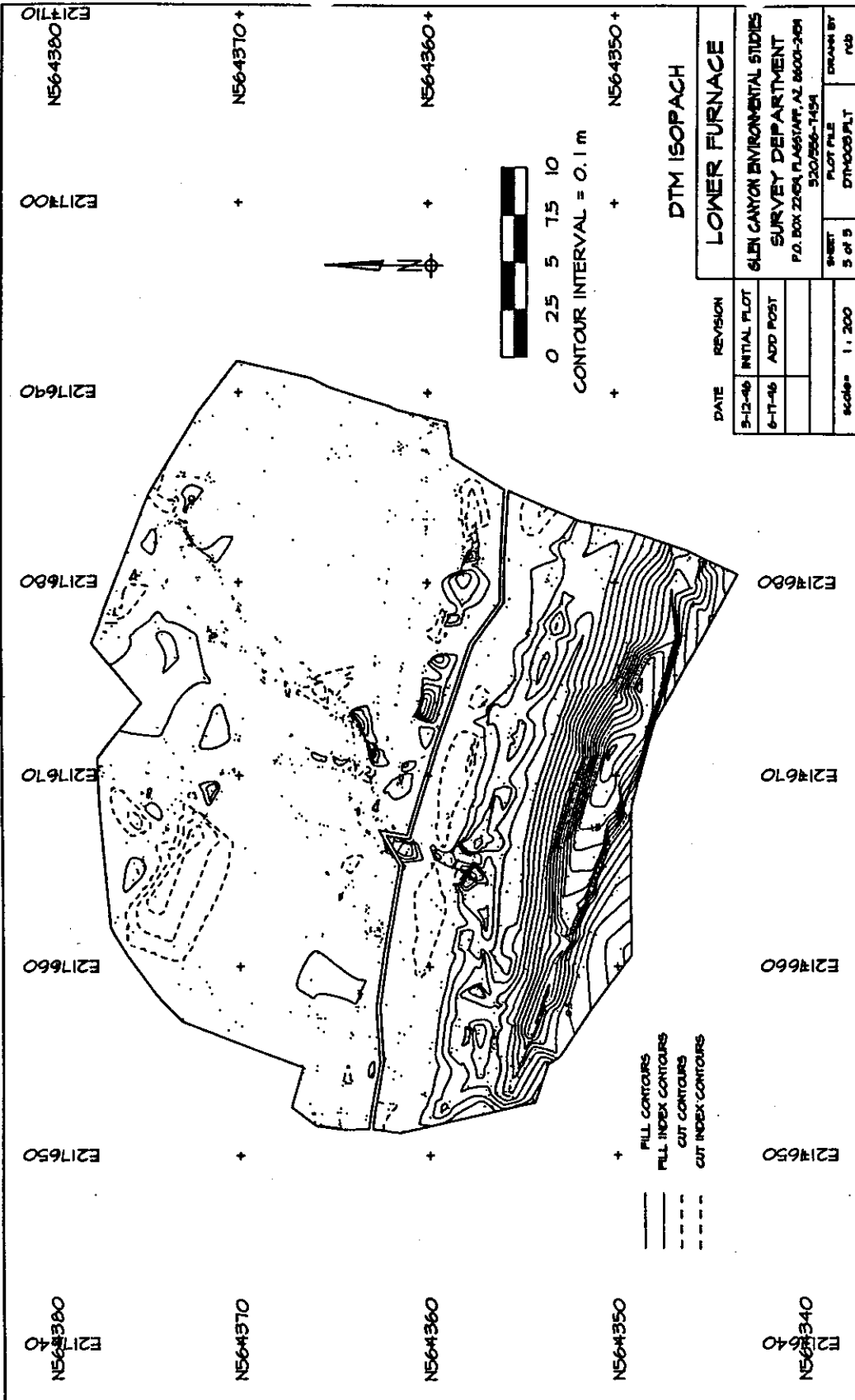


Figure 20. Cut and fill locations at Furnace Flats #1 site.

bordering the river along much of the shore. It was not clear whether this was on the high flow deposits or the original substrate.

The deposits within the vegetation zone, including those filling the arroyo channel, had not changed significantly since the post-high flow mapping. As no rain had yet fallen on the site, the deposits in the arroyo were still in place.

At the Furnace Flats #1 site, the null hypothesis ($H_{(0)}$) was rejected as sediment was deposited in the arroyo mouth. Now, the secondary hypotheses will need to be addressed through continued monitoring of the site.

Discussion and Conclusions

The primary research intent of this project has been realized, that being the identification of whether planned high flows could elevate sediments into the mouths of ephemeral arroyos, which have been implicated as a factor in the erosion of archaeological sites. At three out of the four study locations, the Palisades site, and the Furnace Flats #2 and #1 sites, sediments were in fact deposited in the mouths of the arroyos. While the fourth site, the Lee's Ferry site, received no deposition, it even more significantly did not experience erosion which potentially could exacerbate arroyo downcutting. Obviously, this is a very small sample of locations for a system as hydrologically complex as the Colorado River through the Grand Canyon and can not necessarily be generalized to other locations within the Canyon. During the post-high flow river trip, it was clearly apparent that erosion could occur immediately adjacent to an area in which deposition predominated. The results, however, substantiate the concept advanced in the EIS that high flows can be used as a management tool for system-wide stabilization of cultural resources.

One of the most critical aspects of the study that needs to be address through long-term monitoring is the duration that the deposits remain in the arroyos. Ultimately, if these deposits are not retained long enough to slow down the rate of erosion in the arroyo systems, then the goal for these deposits of stabilizing cultural resource sites will not be realized. Currently, a remapping of the downstream study sites is planned for the spring of 1997. Additionally, when opportunities present themselves for informal, qualitative visits to the sites, these will be made to record visual changes.

At all of the study sites, it was apparent that a 45,000 cfs flow was not large enough to remove much of the vegetation. From the standpoint of cultural resource preservation, this may be a benefit. The degree to which vegetation along the margins of the river help stabilize these deposits, and the degree to which it help deposition of sediment during high flows is not known, but may be significant. Conversely, the ability of even larger flows to raise sediment to a higher level and thereby fill in a larger portion of an arroyo system may offset any loss of vegetation. It will take a number of high flow episodes of different magnitudes to have any hope of identifying what is the optimal regime for cultural resource preservation.

As noted above, this study should be considered only a starting point of a long-term monitoring effort that seeks to address the underlying benefit of the high flow, that is, does it help stabilize the predam terrace deposits and the cultural resources that they contain. This aspect of the study needs to be a coordinated effort with the cultural resources monitoring programs of both GLCA and GRCA in

order to maximize interpretive results without duplication of effect. If the high flow is shown to be effective in the long term, then it greatly enhances our ability to provide proactive, system-wide protection without employing labor intensive mitigative strategies.

Acknowledgments

The research conducted by the Hopi Tribe surrounding the high-flow experiment could not have been realized without the contributions and efforts of many people. Without the coordinated efforts of Dave Wegner and the Glen Canyon Environmental Studies, Grand Canyon National Park, contractors, boatman, and volunteers, the work would have never occurred. Both Craig Hagood and Nina Swidler volunteered their services in connection with this project.

In this effort, the Hopi Tribe was greatly assisted by the expertise of the Glen Canyon Environmental Studies survey program, particularly the efforts of Chris Brod. His knowledge of survey methodology and technique produced the accurate characterization of the topography that was necessary to identify changes taking place due to the high flow. Additionally, he processed the field data to identify the volumes of materials involved and produced the topographic maps presented in this report. Without this effort, the project could not have been accomplished.

The Hopi Tribe is indebted to the efforts of Julia B. Graf, Research Hydrologist with the USGS for providing the flows values from the USGS discharge-routing model and to Bill Vernieu, BOR hydrologist for providing the flow values from the Lee's Ferry gage. Finally, we would like to thank those reviewers who provided comments on earlier drafts of this report.

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