Monitoring Arroyo Erosion of Pre-Dam River Terraces in the Colorado River Ecosystem, 1996-1999, Grand Canyon National Park, Arizona

Draft Final Report

Joseph E. Hazel, Matt Kaplinski, Mark Manone, and Rod Parnell

Department of Geology
Northern Arizona University
Flagstaff, AZ 86011-4099

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ABSTRACT

This study describes changes over a 3.5-year period at four arroyos that drain terraces along the Colorado River in Grand Canyon National Park. Sediment deposited in the arroyo mouths, by the 1996 controlled flood from Glen Canyon Dam, was largely retained during the study period. Lower dam releases, such as the steady flows in 1997, eroded deposits from the terrace margins but did not significantly impact the arroyo systems. Following the 1996 controlled flood, wind deposition lessened or inhibited arroyo-cutting during the study period. The relatively infrequent occurrence of local rainfall and resultant surface flow was not sufficient to downcut the arroyos to the pre-1996 flood condition.

INTRODUCTION

This study examines four arroyos that drain high elevation alluvial terraces along the Colorado River in Grand Canyon (Figure 1). The river terraces are composed of sand-sized and finer sediment that were deposited by sediment-laden floods before closure of Glen Canyon Dam in 1963. Small, ephemeral tributary streams that drain higher catchment areas have incised or eroded through the terraces in order to reach the Colorado River. In wide reaches of Grand Canyon, archaeologic sites are associated with these alluvial terraces. In easternmost Grand Canyon, the density of prehistoric cultural sites is greater than five per kilometer, most of which are on or in high-elevation terrace alluvium (Fairly et al., 1994). Arroyo incision of the terrace deposits has impacted and exposed many of these sites (Carothers and Brown, 1991; Fairley et al., 1994) and Glen Canyon Dam operations have been implicated in having accelerated terrace erosion in the post-dam era (Fairley et al., 1994; Hereford et al., 1993).

An important hypothesis listed in the Glen Canyon Dam-Environmental Impact Statement (GCD-EIS) is that occasional high flows could rebuild high elevation sand deposits and potentially preserve the cultural deposits *in situ* (U.S. Department of Interior, 1995). It was theorized that deposition in arroyo mouths would lessen or slow arroyo-cutting and thus reduce impacts to cultural resources. The first test of a controlled flood as described in the GCD-EIS occurred in spring 1996, with a seven-day release of 1,274 m^3/s (Webb et al., 1999). Physical process studies showed that sand was entrained from the river bed and redistributed to the channel margin, thereby aggrading high-elevation sand deposits and beaches (Schmidt, 1999). Topographic mapping of four arroyo systems before and after this experiment indicated that sediment was deposited in the arroyo mouths (Yeatts, 1996). In the present study, we continue the arroyo monitoring initiated by Yeatts (1996; 1998). We reanalyze the data collected in 1996 and 1997, compare the data with surveys collected in 1998 and 1999, and describe arroyo stability over a 3.5-year period.

Background

Alluvial terraces are typically associated with large tributary debris fans along the Colorado River in Grand Canyon (Howard and Dolan, 1981). Large boulders are transported to and deposited on the fans at the mouths of tributary streams by debris flows (Webb et al., 1989; Melis et al., 1994). Because the river is unable to move the debris except during floods, the channel is constricted, forming rapids and zones of recirculating water (eddies) upstream and downstream from the fans. Alluvial depositional sites are created by eddies because the slower water velocities promote deposition of suspended sediment (Schmidt and Graf, 1990). In the post-dam era, fine-grained sand deposits in eddies are extremely dynamic features and are subject to erosion and deposition as a result of changes in discharge, sediment supply, and debris fan modification. Under pre-dam conditions, this alluvial depositional setting increased in size, extent and elevation, as discharge varied over two orders of magnitude during the annual spring and early summer flood (Howard and Dolan, 1981; Schmidt, 1990). Sand and silt deposited in eddies or along the channel margin during these floods created large bars, the erosional remnants eventually becoming high terraces that in places contain cultural resources. Because regulated flows have lowered the level at which river sand bars are deposited, these terraces are not replenished with sediment and are subject to bank retreat and gully erosion.

Arroyos that incise the high terraces and now drain to the Colorado River have been characterized as “river-based streams” by Hereford et al. (1993). They proposed that flow regulation from Glen Canyon Dam effectively lowers base level (the elevation below which arroyos cannot erode) such that the base level for ephemeral drainages now cut to the mean base level of the Colorado River. Before the dam, the replenishment of these deposits by large floods offset arroyo erosion that occurred during infrequent rainfall events and as a result, a higher base level was maintained for the ephemeral terrace drainages. "Terrace-based streams" were those that terminate on a pre-dam alluvial terrace rather than at the Colorado River base level. This "base-level hypothesis" developed by Hereford et al. (1993) continues to be the subject of much debate among managers and researchers, especially the implication that river terrace erosion has accelerated since emplacement of Glen Canyon Dam and that dam operations are partly responsible. Recently, studies have been devised to test this hypothesis and alternative hypotheses that explain gully erosion processes (Thompson and Potochnik, 2000).

Yeatts (1996) showed that the 1996 controlled flood deposited sand into the mouths of the four arroyos that he studied. He examined the arroyos a year later to determine whether or not the new deposits were retained in the arroyos. He concluded that sand infilling during the flood remained in April 1997, following a two-month period of steady high flows. There had not, however, been any significant rainfall events during the one-year period following the 1996 controlled flood. Based on qualitative observations during on-site visits in 1997 and 1998, Yeatts (1998) concluded that infilling by wind deposition or slumping arroyo walls, had partially replaced sand lost to rainfall runoff events. He suggested that the well-sorted sand deposited in the arroyo bottoms, being porous, caused runoff to infiltrate and percolate rather than remain as surface runoff, thus decreasing erosion. Thompson and Potochnik (2000) also showed that eolian processes transport sand to high terraces and periodically infill gullies.

While temporary infilling by controlled floods and eolian redistribution of flood sand deposits is clearly important in slowing arroyo enlargement, it is not so clear that by reducing rates of gully erosion, the arroyos revert from a stream-based to a terrace-based system as proposed in the "base-level hypothesis". The present study is not designed to test this hypothesis but rather was funded solely to continue measurement of established arroyo monitoring sites. We examine whether or not gully incision resumed following the 1996 controlled flood, the effects of other dam operations such as the 1997 test flow, and the relative importance of eolian processes in inhibiting further arroyo-cutting.

Purpose and Objectives

This study has the following objectives:

(1) Compare the surveys of Yeatts (1996; 1998) to surveys we conducted in 1998 and 1999, in order to develop a 3.5-year time series of arroyo change.

(2) Determine the long-term retention of sediment deposited in the arroyo mouths by the 1996 controlled flood.

(3) Determine if other dam operations such as the 1997 test flow and rainfall events have impacted the arroyos.

(4) Ascertain the effect of sand retention in the arroyo mouths on terrace erosion rates.

Streamflow During the Study Period

Releases from Glen Canyon Dam during the study period were generally high and steady following the 1996 controlled flood (Figure 2). Between May 1996 and October 1999 mean daily flow was 508 m^3/s and the average daily fluctuation ranged from 446 to 554 m^3/s. Power plant capacity is approximately 900 m^3/s. The 1996 controlled flood was a 7-day release of 1,274 m^3/s from March 26 to April 2 (Webb et al*.,* 1999).

Two high flow events of note occurred in 1997. During February and March 1997, reservoir drawdown priorities resulted in steady discharges of about 771 m^3/s for 21 days and 689 m^3/s for 30 days. In November 1997, following a series of large Paria River floods the "1997 test flow" was conducted (Hazel et al., 2000; Topping et al., 2000). This flow began on November 3 and consisted of a rapid increase in discharge from 479 m^3/s to a steady flow of 878 m^3/s for 48 hours, followed by a slow decrease to 480 m^3/s on November 6. Periods of low flow occurred during fall and early spring 1996, 1998, and 1999**,** when the daily mean flow averaged between 300 and 400 m^3/s.

METHODS

We repeated the arroyo survey conducted by Yeatts (1996; 1998) in October 1998 and 1999, using methods described below. The timing of these surveys in relation to Glen Canyon Dam flow releases is shown in Figure 2. The surveys were conducted shortly before and after the 1996 controlled flood, after the high steady flows in February and March 1997, and once yearly beginning in October 1998.

Site Descriptions

The study sites are located in easternmost Grand Canyon, Arizona, downstream from the confluence with the Little Colorado River (Figure 1). The sites are entirely with the "Furnace Flats" geomorphic reach of the Colorado River defined by Schmidt and Graf (1990; Table 1). The Furnace Flats reach is characterized by a relatively wide, shallow channel. Bedrock at river level is mainly the Precambrian Dox Formation and overlying Cardenas Basalt, and cemented Quaternary gravels (Huntoon et al., 1986). Alluvial terraces in this reach date from before 770 B.C. to slightly before 1890 (Hereford, 1996; Hereford et al., 1996). There are no archaeological sites exposed in the study arroyos.

The first site was termed the Palisades site by Yeatts (1996) and contains two adjacent arroyo systems located at river mile 65.7 (65.7 miles downstream from Lees Ferry, Arizona) on the left bank (as viewed in a downstream direction). Incision of the arroyos probably occurred between 1973 and 1984, based on analyses of aerial photographs (Hereford et al,, 1993). The arroyos differ in size and extent but both have been the focus of remedial stabilization efforts. Approximately 70 check dams have been constructed in the arroyos from the catchment areas to the termination with the Colorado River (Yeatts, 1996). Both arroyos are located on the downstream side of an aerially extensive, low-gradient debris fan formed at the mouths of Palisades and Lava Creeks. This type of geomorphic setting was categorized as a "deltaic fan" by Thompson and Potochnik (2000). Inundation of the low-relief fan surface by large, pre-dam floods resulted in extensive terrace deposits. The local catchment drains from a playa lake-coppice dune complex on the top of the highest terrace (Hereford, 1996). The arroyos were considered river-based, not terrace-based by Yeatts (1996). At higher flows, when the fan is inundated, a sand deposit classified as a separation bar by Schmidt and Graf

(1990) is deposited at topographic levels adjacent to the river. Downstream from the arroyos an ephemeral reattachment bar is typically present at river level. Oblique and aerial photographs taken in the last century show that the sparsely vegetated terrace deposits were open high-elevation sand bars in the pre-dam era (Grams and Schmidt, 1999). The upper terraces at the site, however, were interpreted to have been deposited in overbank channels by flows in excess of 2,700 m^3/s (Hereford, 1996).

The arroyos are informally named Palisades #1 and #2, respectively (Figure 3). The upstream arroyo, Palisades #1, is the least developed of the two arroyos and is less than 0.75 m deep. Arroyo 2 is better defined but is still less than 1.5 m deep. The arroyos are more that 100 m in length and extend high onto the catchment area located on the broad fan surface. Vegetation is relatively sparse and consists of a small number of tamarisk (*Tamarix chinensis*) bordering the river margin with arrowweed (*Tessaria sericea*) and herbaceous plants elsewhere (Yeatts, 1996).

The second site was named Furnace Flats by Yeatts (1996) and contains two arroyo systems located on the right side of the river at river mile 71.3 (Figure 4). The area is not located near a tributary debris fan; it is a geomorphic setting categorized as "talus slope" by Thompson and Potochnik (2000). In this type of catchment, the headwater areas are bedrock close to the river and are characterized by very high runoff during rainfall events. The terrace deposits probably originated as a type of bar, termed a channel margin bar by Schmidt and Graf (1990), deposited by bank irregularities that create minor flow obstructions during flooding. The terrace is composed of unconsolidated fine-grained silty sand. In contrast to the Palisades site, the Furnace Flats terrace is colonized by vegetation composed *tamarisk* and dense thickets of arrowweed.

The upstream arroyo was named Furnace Flats #2 by Yeatts (1996). This arroyo is the widest and deepest of the four gullies studied. Arroyo-cutting has entrenched nearly 2 m into the narrow terrace deposit. The length of the arroyo is about 35 m and the width is much as 3.5 m. Nickpoint migration has progressed to a steep bedrock slope composed of erodible sandstone, siltstone and shale of the Dox Formation (Figure 4). The second arroyo, Furnace Flats #1, is located about 150 m downstream. This arroyo also heads in the Dox Sandstone, is approximately the same length as Furnace Flats #2, but is not as wide and deep. There have been no remedial stabilization efforts at these two arroyos.

Survey Methods and Accuracy

Topographic change at each site was measured by field survey with electronic total stations. The mapping was focused on the area between the river's edge and the elevations reached by flows in excess of approximately 1,700 m^3/s. Similar field methods were also used by Yeatts (1996; 1998), but our analysis techniques differ (described below). In general, field surveys were conducted by defining break lines along each arroyo edge and along the bottom thalweg. Other areas were covered with individual points so that a regular point spacing encompassed the entire site. The point density required depended on arroyo complexity and as many as 800 ground points were collected during each survey. This typically corresponded to a point density of one point per 3 to 5 m^2 for the entire site with a greater density of one point per 0.75 m^2 concentrated in the arroyos. The point data accuracy is on the order of ± 0.1 m horizontally and ± 0.05 m vertically. Survey accuracy in the field was maintained by horizontal and vertical checks of positional error between known reference points in the Arizona State Plane Coordinate System.

Digital elevation models (DEM's) were created from surface modeling software using the triangulated irregular network method for contouring. The ground points were collected with the intention of accurately representing the topography with a contour interval of 0.20 m. In contrast, topographic accuracy standards utilized by the Army Core of Engineers for archaeologic or structure site detail mapping are performed to the 0.003-0.15 m levels with an intended contour interval accuracy of .03-.30 m (USACE, 1994).

Analysis

The DEM's were used to generate cross sections, comparison maps, and area and volume calculations. Locations of computational boundaries and cross sections are shown in Figures 3 and 4. Boundaries that encompassed the area of each arroyo were used to calculate regions of cut (erosion) and fill (deposition) between surveys. We calculated arroyo cut and fill between the 566 m^3/s stage elevation and the elevation reached by a flow of approximately 1,700 m^3/s. To accurately describe the amount of net downcutting or infilling along the length of each arroyo, changes in bed elevation along the arroyo thalweg were calculated for each time period. At each site, stage-discharge relationships were developed, using the methods of Kaplinski et al. (1995), to estimate the stage elevations reached by dam releases of interest and the degree of indundation by the 1996 controlled flood (these relationships have an accuracy of ± 0.05 m).

Our analysis differs from that of Yeatts (1996; 1998) in that we separate volume change in each arroyo from the surrounding region and as a result, reported volume changes differ. In addition, because only portions of the terrace areas at the Palisades and Furnace Flats sites were surveyed, we limit the analysis to quantifying rates of arroyo change. The data focus on processes within each arroyo. They were not collected to describe and analyze the physical processes that rework terraces and deposit or erode sand bars during flooding or during periods of lower peak flow magnitude. In addition, because rain gages were not installed at any of the sites, there is little information available on the intensity, duration, or occurrence of local rainfall events.

RESULTS

Changes as a Result of the 1996 Controlled Flood

The 1996 controlled flood considerably modified the study sites by depositing and eroding sand from the terraces and by infilling the arroyo mouths. Changes along the length of the arroyos are shown in Figure 5a and b for the Palisades arroyos and Figure 5c and d for the Furnace Flats arroyos, respectively. Changes in minimum bed elevation are with reference to a common datum defined by the pre-1996 flood arroyo thalweg elevation in February 1996; points above the solid line indicate deposition, points below erosion. Changes in arroyo width, infilling, and erosion are depicted by cross-sections shown in Figures 6-9. Pre-flood topography is shown with the solid line.

In general, sand deposition filled the arroyo mouths and scour removed topographic highs along the arroyo edges and terrace margins. Net deposition occurred in all four arroyos, ranging from 2.4 to 12.0 m^3 of sand, and was greatest at Furnace Flats #2 (Table 1). Figure 5 shows that the depth of fill was greatest at or near the arroyo mouths. In the lower part of the arroyos there was complete or nearly complete infilling of up to 1 m of sand (Figures 6a, 8a, 9a). The average depth of fill between the stage elevations reached

Table 1. Volume of arroyo material scoured and filled at the study sites

Palisades #1

Comparison Interval	Scour (m^3)	Fill (m^3)	Net Change (m^3)
960217 - 960512	-3.1	6.2	3.1
960512 - 970422	-2.6	2.5	-0.1
970422 - 981014	-5.5	2.2	-3.3
981014 - 991007	-1.1	1.9	0.8
960217 - 991007	-3.9	5.4	1.5

Palisades #2

Comparison Interval	Scour (m^3)	Fill (m^3)	Net Change (m^3)
960217 - 960512	-3.9	7.5	3.6
960512 - 970422	-3.9	3.6	-0.3
970422 - 981014	-1.9	3.9	2.0
981014 - 991007	-2.9	1.6	-1.3
960217 - 991007	-2.4	6.5	4.1

Furnace Flats #1

Comparison Interval	Scour (m^3)	Fill (m^3)	Net Change (m^3)
960218 - 960513	-0.9	3.3	2.4
960513 - 970423	-2.2	0.8	-1.4
970423 - 981014	-0.5	3.7	3.2
981014 - 991007	-1.4	0.8	-0.6
960218 - 991007	-0.8	4.1	3.6

Furnace Flats #2

Comparison Interval	Scour (m^3)	Fill (m^3)	Net Change (m^3)
960218 - 960513	-1.7	13.7	12.0
960513 - 970423	-3.2	2.8	-0.4
970423 - 981014	-5.0	4.4	-0.6
981014 - 991007	-0.9	5.7	4.8
960218 - 991007	-2.3	16.4	14.1

by 566 and 1,274 m^3/s ranged from 0.07 m at Palisades #1 to 0.42 m at Furnace Flats #2 (Figure 5). Even in the higher parts of the arroyos, at terrace elevations not completely inundated by 1,274 m^3/s, there was considerable deposition (Figure 9b). Two of the checkdams at Palisades #2 were completely buried with sediment (Figure 5b).

Erosion occurred along the terrace margins and topographic highs were leveled or flattened (Figures 7a and 8a). Widening of the arroyos was also observed at terrace elevations not completely inundated by the flood (Figures 7b and 8b). Bank collapse and arroyo widening may have been caused by saturation and undermining of the sediment composing the terrace from water ponded in the arroyos during the flood. There was little or no change observed above the flood line (Figures 5 and 9c).

Changes Between May 1996 and April 1997

In the 11 months following the 1996 controlled flood, the arroyo changes were small compared to those caused by the flood. During this period, there were 2 months of steady high flows of ~771 m^3/s and ~689 m^3/s (Figure 2). Above the 566 m^3/s stage elevation, these flows had little effect on the sand emplaced in the arroyos during the 1996 controlled flood (Figure 5). Furnace Flats #1 was the only site that had a significant negative net change (Table 1). At this arroyo, reworking of the 1996-flood deposits below the 771 m^3/s stage elevation removed flood-deposition from the base of the terrace (Figure 5c). The only evidence for arroyo-cutting was at Palisades #2, where incision had removed part of the 1996-flood deposits (Fig. 7a). There was little or no change in arroyo width or depth near the arroyo mouths at the other three sites (Figures 6a, 8a, and 9a). With the exception of Palisades #2, there was no evidence to suggest that water had been flowing in the arroyos during the interval between surveys. However, above the 1,274 m^3/s flood line changes were variable, mainly along the arroyo bottoms (Figure 5). Minor deposition and erosion from redistribution of sediment appears to have occurred, possibly from wind reworking (Figure 6b). Yeatts (1998) reported that the terrace surfaces around the Palisades arroyos had been eroded during this period and attributed the scour to wind deflation.

Changes Between April 1997 and October 1998

In the 15 months following the May 1997 survey, the arroyos were relatively stable. Only one site had a net negative change in sand volume (Table 1). During this period, there were significant floods in both gaged and ungaged tributaries to the Colorado River and the release of the November 1997 test flow (Hazel et al., 2000; Topping et al., 2000) (Figure 2). Yeatts (1998) reported that rainfall events in September 1997, resulted in surface flow in all of the arroyos, particularly the Palisades site, where many of the checkdams were breached and flows reached the Colorado River. There was also active monsoon-thunderstorm precipitation in the region in August and September 1998.

The deposits emplaced in the arroyo mouths by the 1996 controlled flood were incised at 3 sites, but the arroyo channels were not eroded to depths that existed prior to the flood (Figures 6a, 8a, and 9a). Interestingly, there was no evidence for arroyo-cutting at higher elevations (Figure 5). Moreover, increases in net sand volume at 2 of the sites were similar to or greater than the magnitude of change measured following the controlled flood (Table 1). Sand was deposited in the arroyo bottoms, above both the elevations reached by the 1997 test flow and the 1,274 m^3/s flood (Figure 5). There was little change in arroyo width (Figures 7b, 8c, and 9c). In addition, the effects of inundation by the 1997 test flow could not be discerned a year after this dam release, except at Palisades #2, where the reactivated arroyo mouth observed in April 1997, was infilled (Figure 7a).

Changes Between October 1998 and October 1999

The arroyos remained relatively unchanged between October 1998 and October 1999. After the 1997 test flow, releases from Glen Canyon Dam never exceeded 708 m^3/s during this study. No significant rainfall events or runoff are known to have occurred at the study sites. Minor scour and fill was observed at the sites during this period from in-channel reworking (Table 1; Figure 5). The Furnace Flats #2 arroyo had a significant increase in sand volume. At this arroyo, there was further infilling of sand at elevations above the arroyo mouth (Figure 5d), which we attribute to eolian deposition. There was no slumping or collapse of the arroyo walls that could account for the volume change (Fig. 9c). At the other sites, cross sections located near the arroyo mouths indicate further incision suggesting that water had been flowing in the arroyos in the previous year (Figures 7a and 8a).

Temporal Longevity of the 1996 Controlled Flood Deposits

The surveys represent repeat observations of arroyo change for a 3.5-year period. To describe the changes observed between successive surveys, the minimum arroyo thalweg elevation was calculated for 0.20 m longitudinal increments in the part of each arroyo between the 566 and 1,274 m^3/s stage elevations. The resulting values were then subtracted from the pre-1996 flood values, which is considered the baseline condition, and then averaged (Figure 10). This method allows an estimate of arroyo cut and fill at each site compared to baseline conditions. It produces a time series of base level change.

The results shown in Figure 10 are consistent with the hypothesis that infilling of the arroyo mouths by the 1996 controlled flood established a new base level for the arroyos. Despite partial erosion of newly-deposited sand bars at the base of the terraces by the sustained high flows in 1997, the arroyos retained much of the fill [Figure 5; also see the comparison maps of cut and fill in Yeatts (1998)]. There were no rainfall runoff events during the following 3.5-years sufficient to cut the arroyos back to the pre-flood elevations. Runoff events in the arroyos were, however, observed to have occurred in 1997 and 1998 (Yeatts, 1998). Even so, the time series indicates that the new base levels were maintained in 1998 and 1999. Volume comparison indicates a net positive change at all four sites between 1996 and 1999 (Table 1). The deposits emplaced in the arroyo mouths by the 1996 controlled flood were never entirely removed and the higher parts of the arroyos either aggraded or remained unchanged. Sediment renewal in the arroyos was the direct result of wind deposition. Cross sections and cut and fill volumes suggest that this material was not derived from arroyo wall collapse.

DISCUSSION AND CONCLUSIONS

This draft report presents the results of field monitoring of 4 arroyo systems. Rates and amounts of erosion and deposition at each arroyo were quantified for a 3.5-year period. The 1996 controlled flood inundated the terraces at the study sites and deposited significant volumes of sand in the arroyo mouths. The arroyo mouth deposits were largely retained during the study period. Lower dam releases, such as the steady flows in 1997, eroded deposits from the terrace margins but did not significantly impact the arroyo systems. There was no significant channel deepening or widening. Rainfall runoff during the study period did not arroyo-cut to pre-1996 flood topographic levels. The relatively infrequent occurrence of intense rainfall and surface flow in the arroyos was offset or mitigated by eolian redistribution of sand. Furthermore, infilling of the arroyos by wind deposition, at terrace elevations higher than the arroyo mouth deposits, caused gully depths to progressively decrease through time (Figure 5).

The combination of flood inundation and arroyo infilling, followed by subsequent eolian deposition, lessened or inhibited arroyo-cutting during the study period (Figure 10). Eolian redistribution of 1996-flood deposits or wind deflation of sand from other areas are the only mechanisms that can explain the continued retention of sand in the arroyos. Through these two processes, the arroyos were stable during the study period.

The results of this study are limited in scope and should not be extrapolated to system-wide changes or used to systematically test the "base-level hypothesis" of Hereford et al., (1993). The arroyo infilling did create a base level increase, but up-drainage changes on higher terraces were not examined (higher terraces are present at the Palisades site but not at the Furnace Flats site). Thus, the effect of the base level increase on terraces that originated from higher river stages (ie., where most of the cultural sites are located) could not be determined. The gullies were still integrated with the Colorado River and this new base level effect is probably temporary. In time, a local rainfall event will likely result in catchment runoff sufficient to remove the infilling and reactivate the arroyos. Nonetheless, temporary base level effects from controlled flooding may still be important for short-term slowing of erosion rates. In addition, because the arroyos were relatively stable during the study period, we could not discern a difference in the pattern of change between arroyos that had checkdams emplaced to retard water flow, from those with no stabilization features.

The information generated from repeat mapping of selected arroyos can be useful for quantifying the effects of dam operations, erosion control methods, and rates of arroyo-cutting. There are currently different methods available to collect points for generating DEM's of topographic features of interest in Grand Canyon National Park. The accuracy levels of photogrammetrically derived small-scale maps used to depict topography at selected arroyos were found to vary by Thompson and Potochnik (2000). Comparison of photogrammetric techniques to conventional survey methods indicates that the accuracy of on-site surveying is higher than topography derived from aerial photography (Kohl, 2000). Arroyos are irregular and complex features and mapping requires high accuracy standards. We agree with the suggestion of Kohl (2000) that long-term monitoring of arroyo and related features should be mapped with a combination of aerial photography (or other remote sensing techniques) and conventional ground based methods (ie., total station surveys). This method will result in large site maps that encompass the entire length of arroyo and catchment areas, and the high density of well-defined points required to accurately depict arroyo width and depth.

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Figure Captions

Figure 1. Location of study area in eastern Grand Canyon. The location of the USGS streamflow-gaging station Colorado River near Grand Canyon is shown. Arroyo study site locations are highlighted by boxes on the lower, detailed map.

Figure 2. Daily mean discharge at the USGS streamflow-gaging station, Colorado River near Grand Canyon, Arizona, January 1996 to December 1999. Dots show the times when arroyo surveys were conducted.

Figure 3. Contour map of the Palisades arroyos. Flow in the arroyos is bottom to top and in the Colorado River right to left. Date of survey is October 7, 1999.

Figure 4. Contour map of the Furnace Flats arroyos. Flow in the arroyos is top to bottom and in the Colorado River right to left. Date of survey is October 15, 1998.

Figure 5. Changes in arroyo thalweg elevation. (A) Palisades #1. (B) Palisades #2. (C) Furnace Flats #1. (D) Furnace Flats #2. Changes in thalweg elevation are with reference to a common datum defined by the pre-1996 flood arroyo thalweg elevation measured in February 1996; data above the horizontal solid line at 0.0 m indicate deposition, data below indicate erosion.

Figure 6. (A) Palisades #1 cross-section 3, and (B) cross-section 4. Stage elevation for a discharge of 1,274 m^3/s is shown. Cross-sections are viewed in a down-gully direction. Locations are shown on Fig. 3.

Figure 7. (A) Palisades #2 cross-section 9, and (B) cross-section 7. Stage elevation for a discharge 1,274 m^3/s is shown. Cross-section are viewed in a down-gully direction. Locations are shown on Fig. 3.

Figure 8. (A) Furnace Flats #1 cross-section 4, (B) cross-section 5, and (C) cross-section 6. Stage elevation for discharges of 566 and 1,274 m^3/s are shown. Cross sections are viewed in a down-gully direction. Locations are shown on Fig. 4.

Figure 9. (A) Furnace Flats #2 cross-section 1, (B) cross-section 2, and (C) cross-section 3. Stage elevation for discharges of 566 and 1,274 m^3/s are shown. Cross section is viewed in a down-gully direction. Locations are shown on Fig. 4.

Figure 10. Trends in average arroyo thalweg elevation between the discharges ranging from 566 to 1,274 m^3/s. Changes in thalweg elevation are with reference to a common baseline (the dashed horizontal line) defined by the pre-1996 flood arroyo thalweg elevation measured in February 1996.

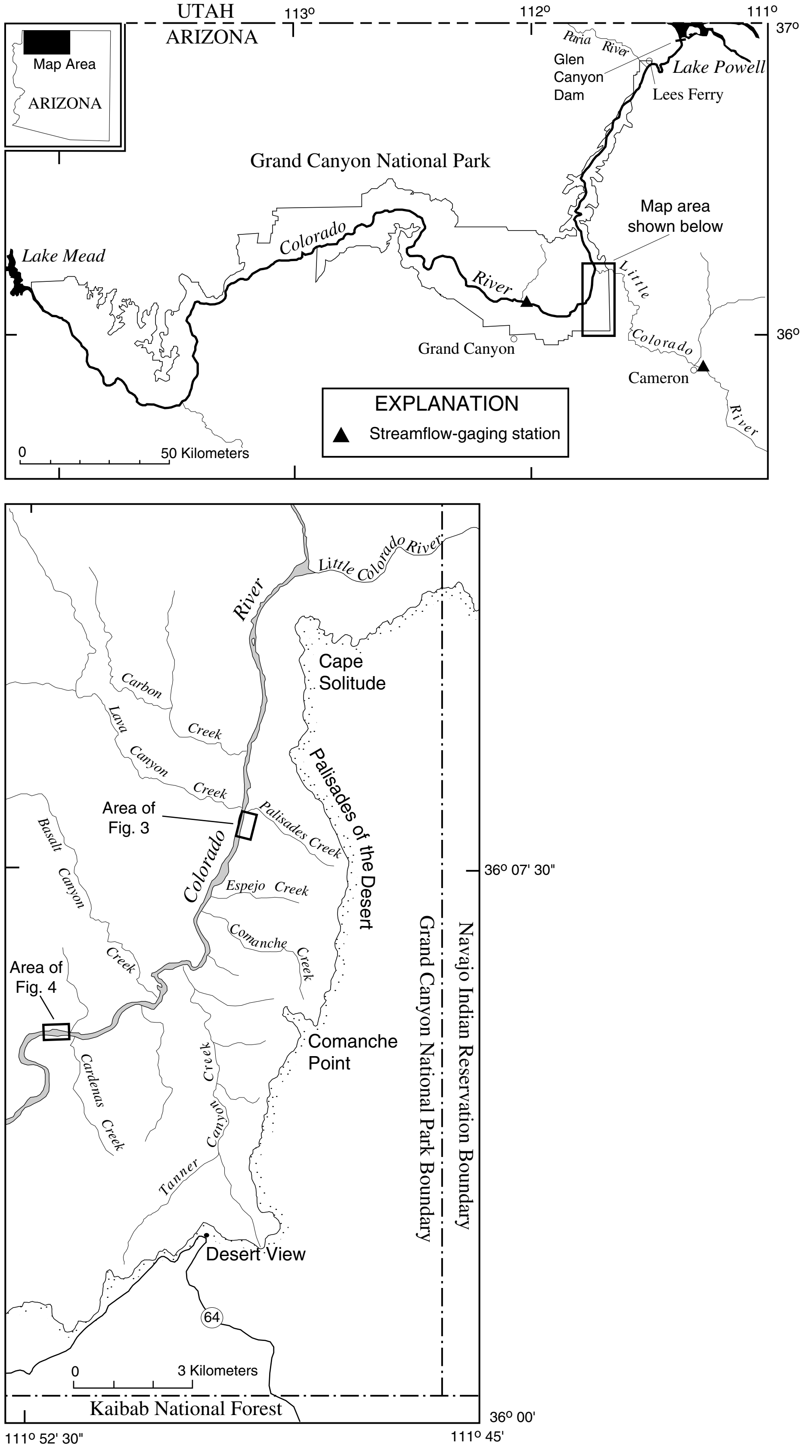

UTAH
ARIZONA
113°
112°
111°
37°
Map Area
ARIZONA
Paria River
Glen Canyon Dam
Lake Powell
Lees Ferry
Grand Canyon National Park
Map area shown below
Lake Mead
Colorado River
Little Colorado River
Grand Canyon
Cameron
36°
EXPLANATION
▲ Streamflow-gaging station
0
50 Kilometers
Little Colorado River
River
Carbon Creek
Lava Canyon Creek
Cape Solitude
Palisades of the Desert
Area of Fig. 3
Palisades Creek
Colorado
Espejo Creek
Basalt Canyon Creek
Comanche Creek
36° 07' 30"
Area of Fig. 4
Comanche Point
Cardenas Creek
Tanner Canyon Creek
Navajo Indian Reservation Boundary
Grand Canyon National Park Boundary
Desert View
64
0
3 Kilometers
Kaibab National Forest
36° 00'
111° 52' 30"
111° 45'

Figure 1.

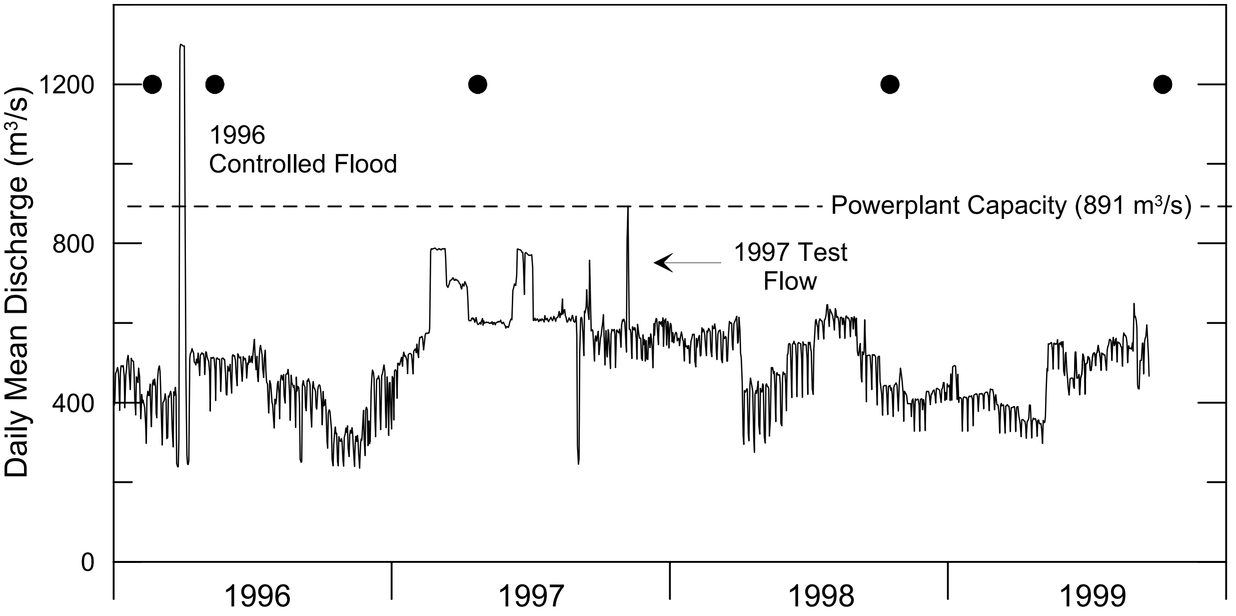

Daily Mean Discharge (m³/s)
1200
800
400
0
1996
Controlled Flood
Powerplant Capacity (891 m³/s)
1997 Test
Flow
1996
1997
1998
1999

Figure 2.

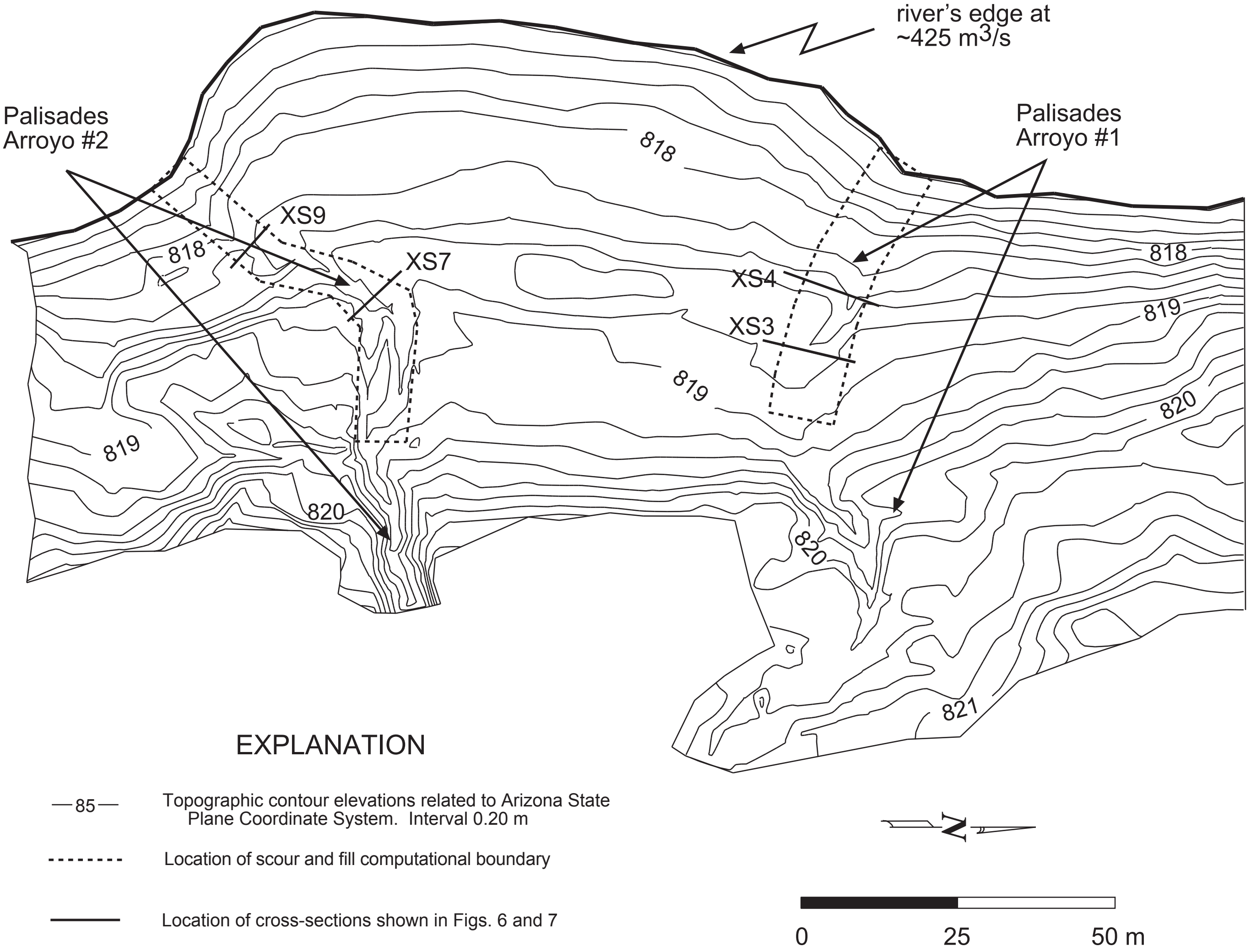

river's edge at
~425 m3/s
Palisades
Arroyo #2
Palisades
Arroyo #1
XS9
XS7
XS4
XS3
818
818
818
819
819
819
820
820
820
821
EXPLANATION
85
Topographic contour elevations related to Arizona State Plane Coordinate System. Interval 0.20 m
Location of scour and fill computational boundary
Location of cross-sections shown in Figs. 6 and 7
N
0
25
50 m

Figure 3.

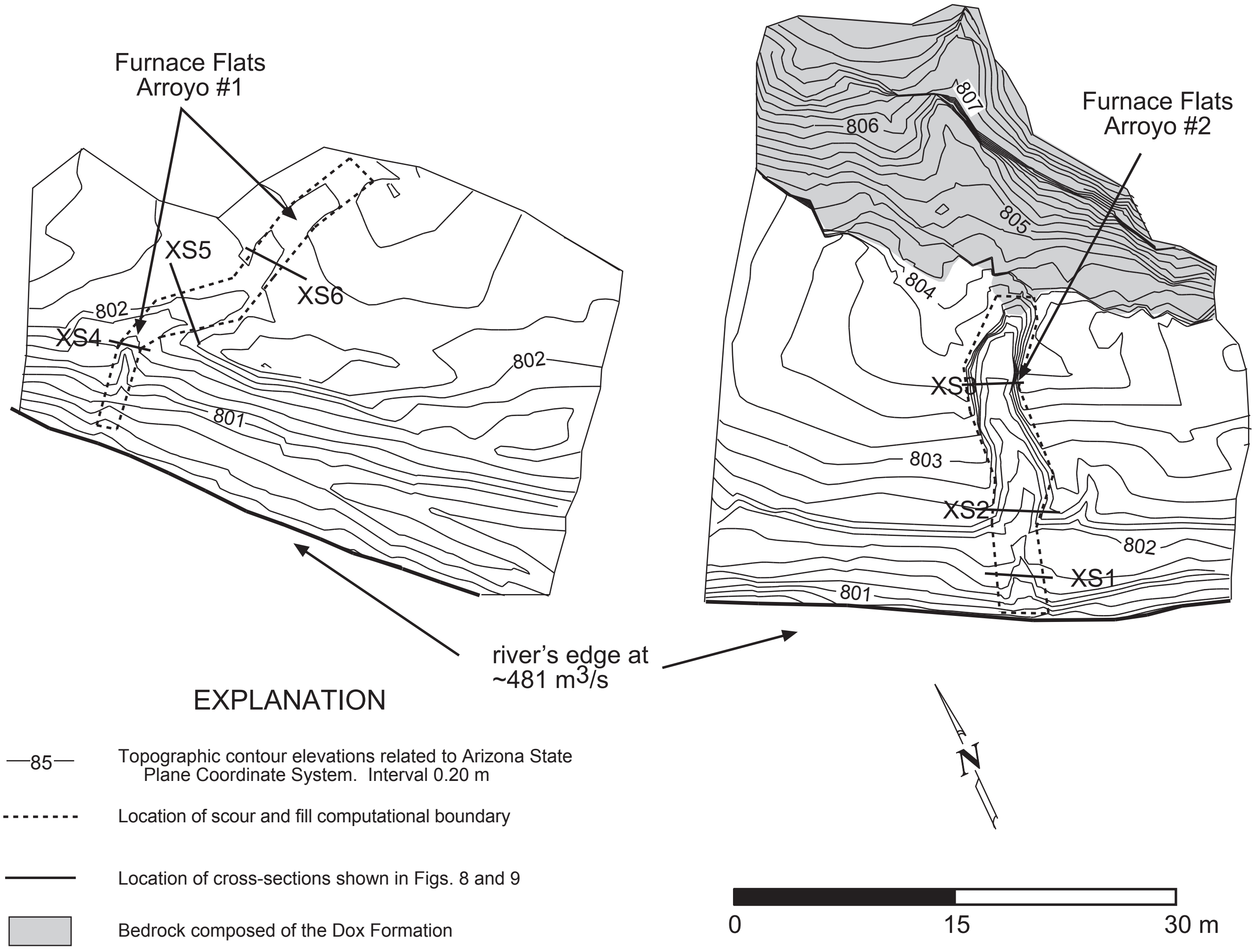
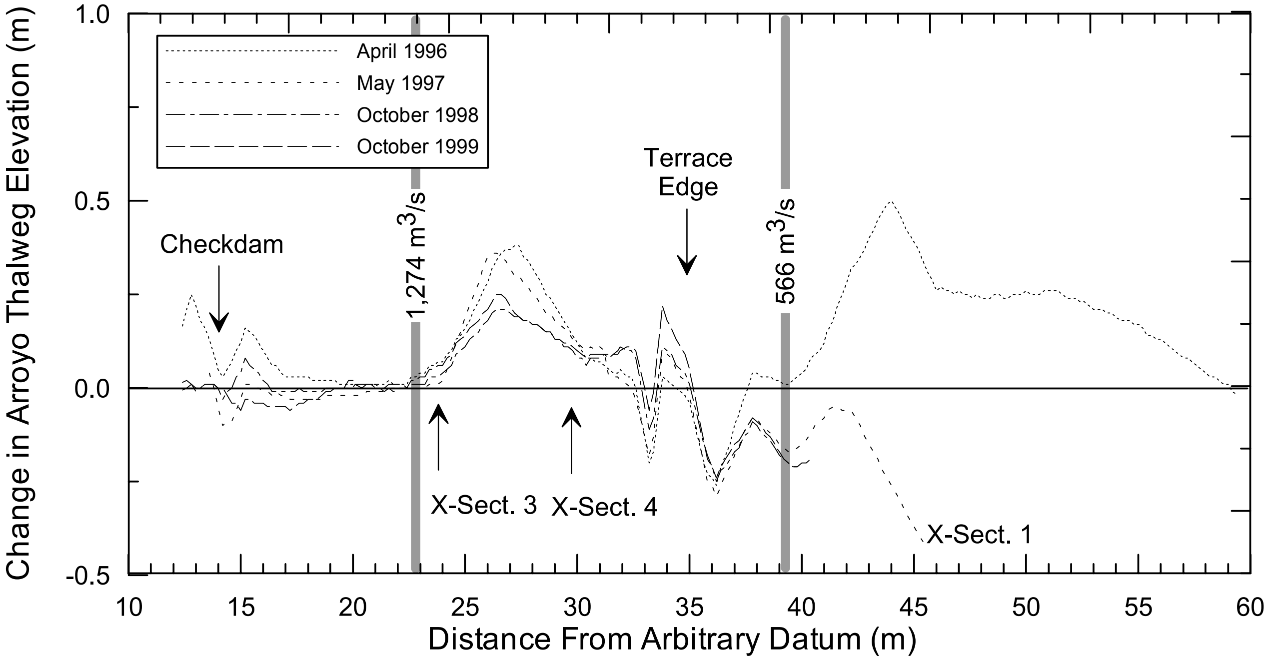

Furnace Flats Arroyo #1
XS5
XS6
XS4
802
802
801
Furnace Flats Arroyo #2
807
806
805
804
XS3
803
XS2
802
XS1
801
river's edge at ~481 m³/s
N
0
15
30 m
EXPLANATION
85
Topographic contour elevations related to Arizona State Plane Coordinate System. Interval 0.20 m
Location of scour and fill computational boundary
Location of cross-sections shown in Figs. 8 and 9
Bedrock composed of the Dox Formation

Figure 4.

A. PALISADES #1



B. PALISADES #2

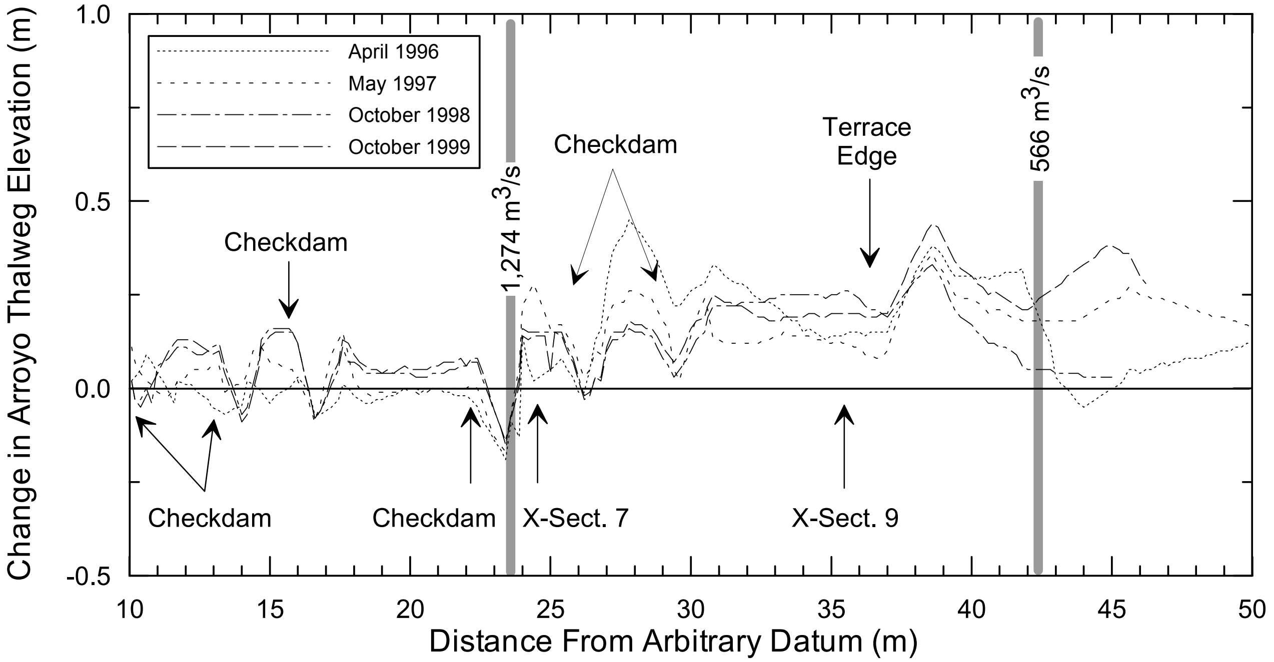
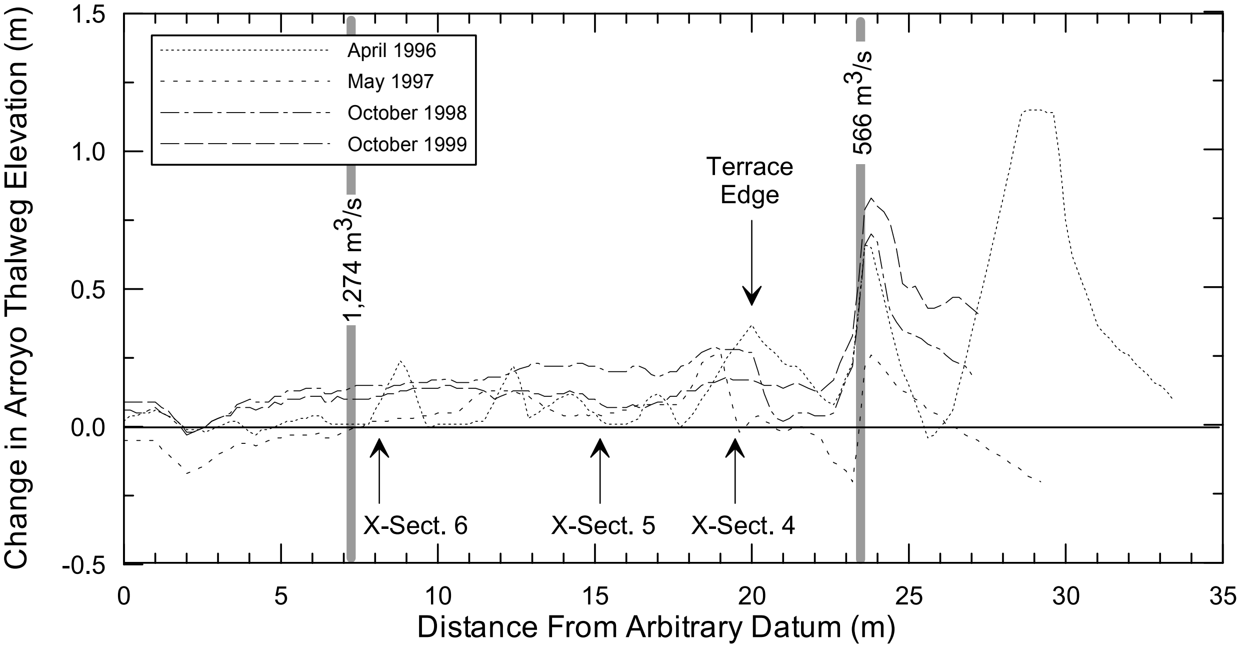


Figure 5.

C. FURNACE FLATS #1



D. FURNACE FLATS #2

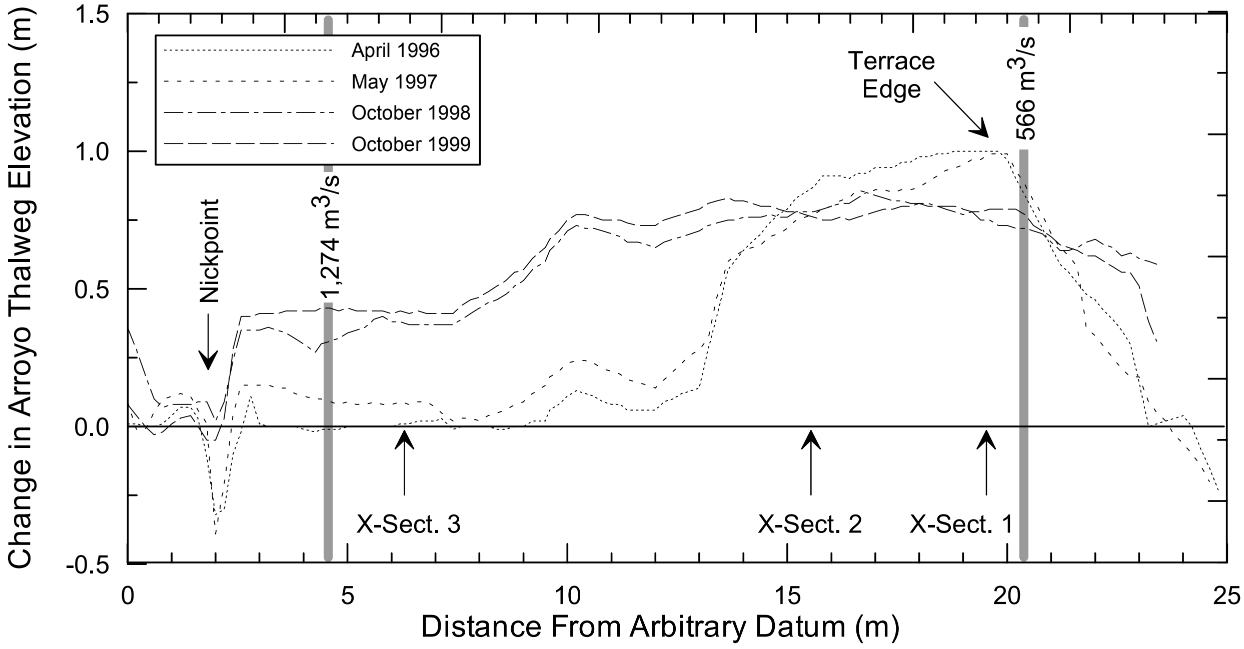


Figure 5 cont.

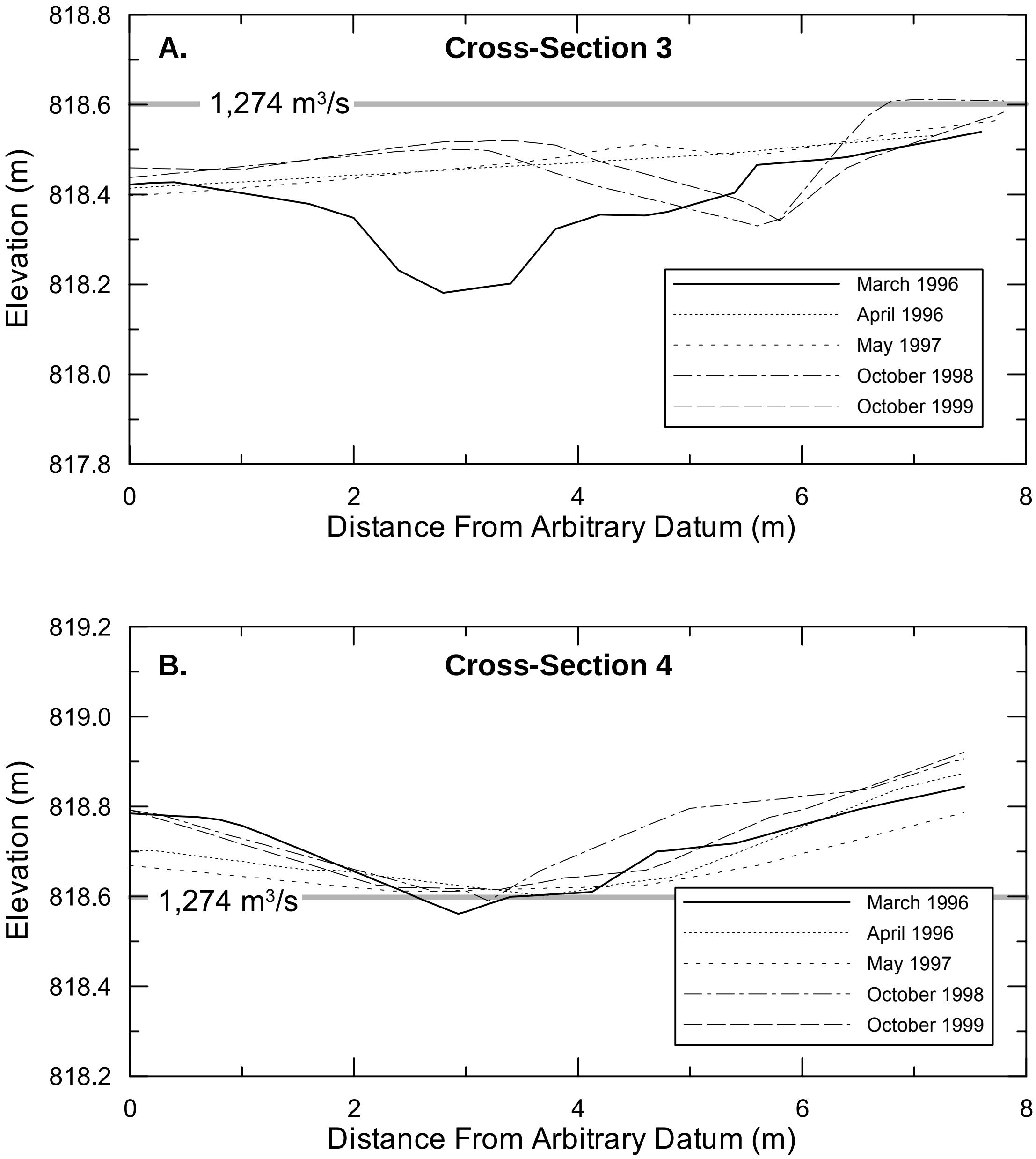

A.
Cross-Section 3
1,274 m³/s
818.8
818.6
818.4
818.2
818.0
817.8
Elevation (m)
0
2
4
6
8
Distance From Arbitrary Datum (m)
March 1996
April 1996
May 1997
October 1998
October 1999
B.
Cross-Section 4
1,274 m³/s
819.2
819.0
818.8
818.6
818.4
818.2
Elevation (m)
0
2
4
6
8
Distance From Arbitrary Datum (m)
March 1996
April 1996
May 1997
October 1998
October 1999

Figure 6.

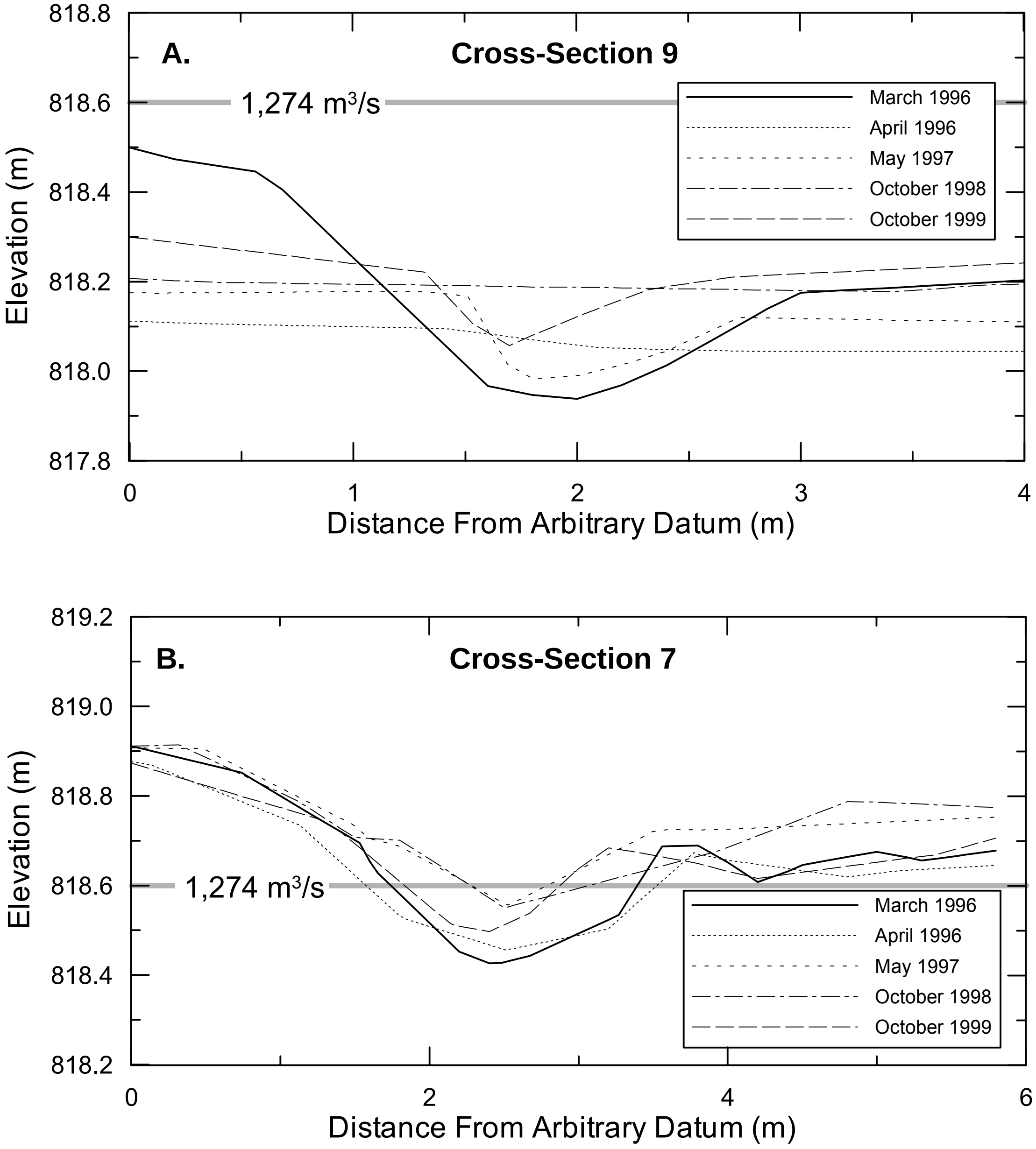

A.
Cross-Section 9
1,274 m³/s
March 1996
April 1996
May 1997
October 1998
October 1999
Elevation (m)
818.8
818.6
818.4
818.2
818.0
817.8
0
1
2
3
4
Distance From Arbitrary Datum (m)
B.
Cross-Section 7
1,274 m³/s
March 1996
April 1996
May 1997
October 1998
October 1999
Elevation (m)
819.2
819.0
818.8
818.6
818.4
818.2
0
2
4
6
Distance From Arbitrary Datum (m)

Figure 7.

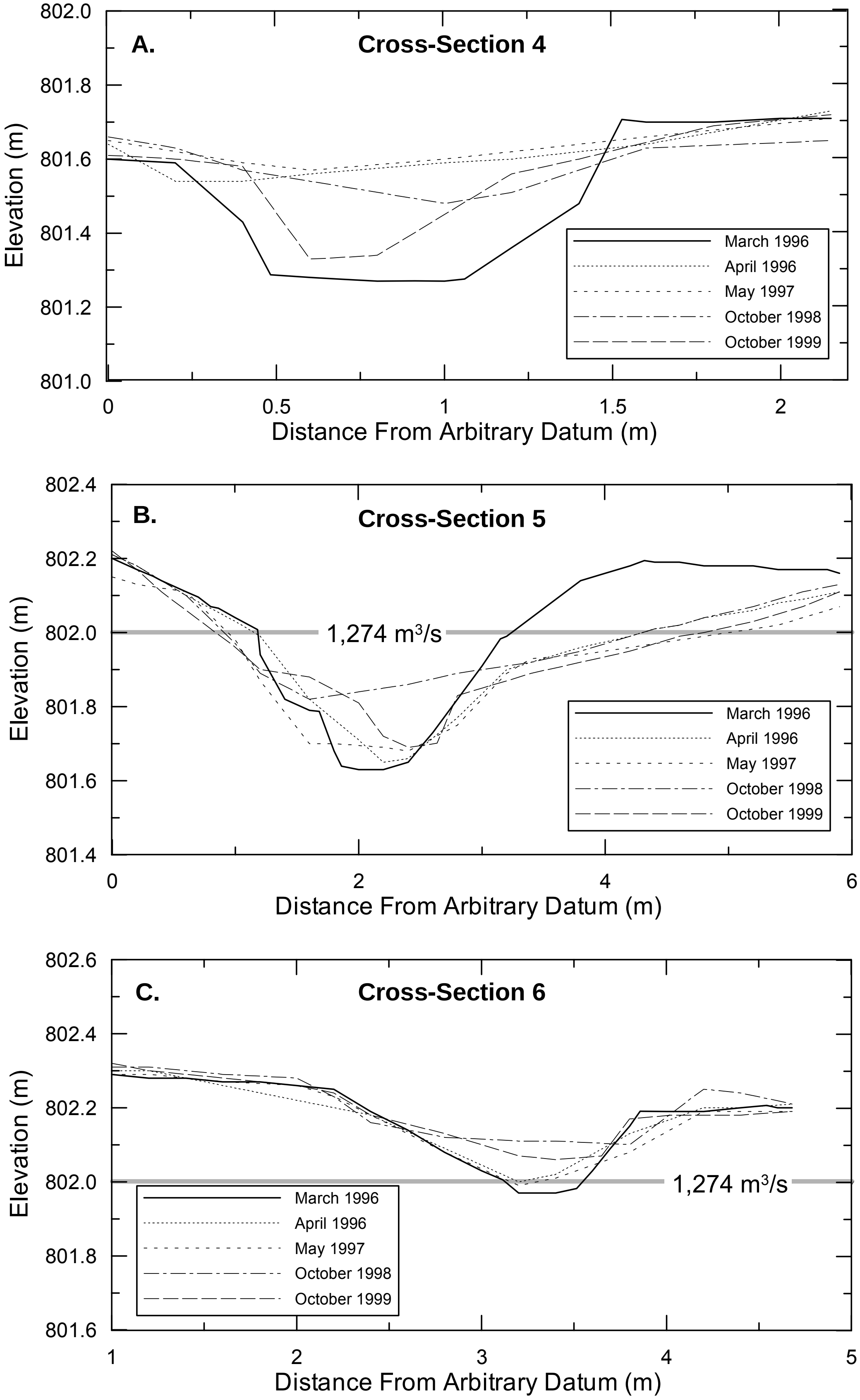

A.
Cross-Section 4
Elevation (m)
802.0
801.8
801.6
801.4
801.2
801.0
0
0.5
1
1.5
2
Distance From Arbitrary Datum (m)
March 1996
April 1996
May 1997
October 1998
October 1999
B.
Cross-Section 5
802.4
802.2
802.0
801.8
801.6
801.4
1,274 m³/s
0
2
4
6
C.
Cross-Section 6
802.6
802.4
802.2
802.0
801.8
801.6
1
2
3
4
5

Figure 8.

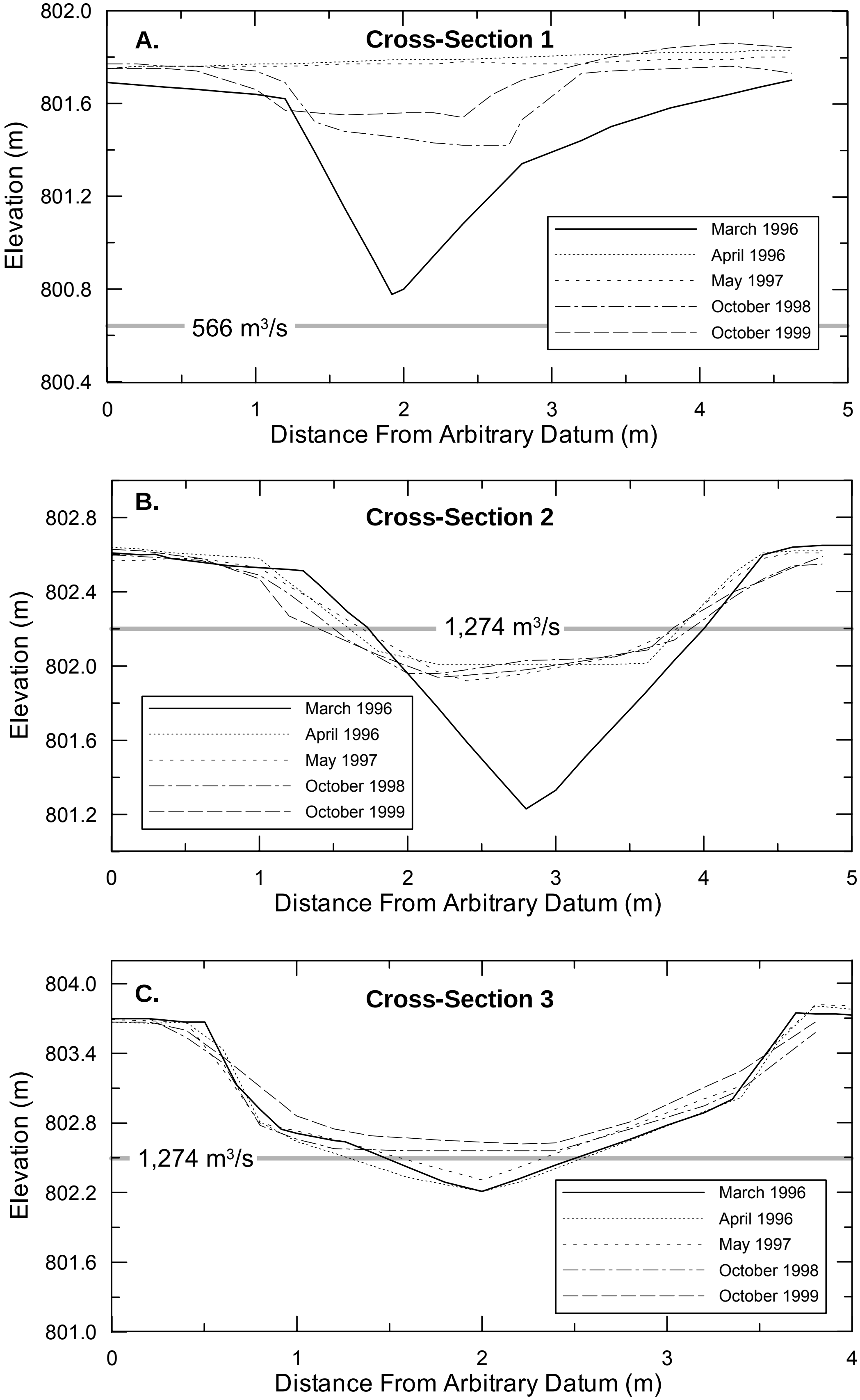

A.
Cross-Section 1
802.0
801.6
801.2
800.8
800.4
Elevation (m)
0
1
2
3
4
5
Distance From Arbitrary Datum (m)
566 m³/s
March 1996
April 1996
May 1997
October 1998
October 1999
B.
Cross-Section 2
802.8
802.4
802.0
801.6
801.2
Elevation (m)
0
1
2
3
4
5
Distance From Arbitrary Datum (m)
1,274 m³/s
March 1996
April 1996
May 1997
October 1998
October 1999
C.
Cross-Section 3
804.0
803.4
802.8
802.2
801.6
801.0
Elevation (m)
0
1
2
3
4
Distance From Arbitrary Datum (m)
1,274 m³/s
March 1996
April 1996
May 1997
October 1998
October 1999

Figure 9.

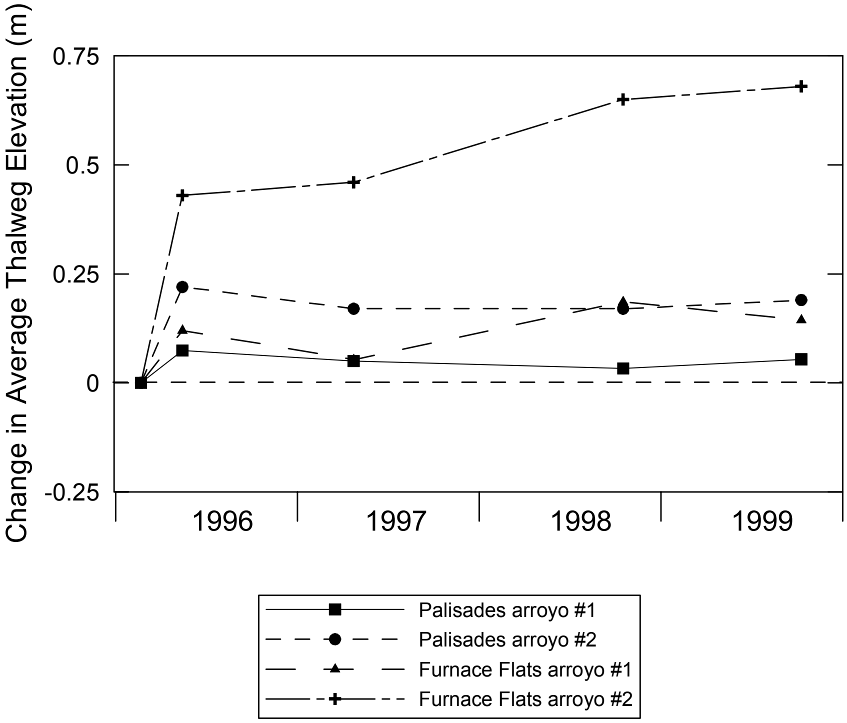

Change in Average Thalweg Elevation (m)
0.75
0.5
0.25
0
-0.25
1996
1997
1998
1999
Palisades arroyo #1
Palisades arroyo #2
Furnace Flats arroyo #1
Furnace Flats arroyo #2

Figure 10.